HDZZ CRPA

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IVANA TUCAKOVIĆ

KATJA MAGDIĆ KOŠIČEK

IVANA COHA

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Dragi članovi HDZZ-a, poštovani sudionici 14. simpozija,

Proteklo razdoblje od našeg posljednjeg susreta tijekom 13. simpozija u Poreču obilježeno je nizom značajnih aktivnosti Društva. Tijekom simpozija održana je redovna skupština Zbora članova HDZZ-a, na kojoj su raspravljene i prihvaćene promjene Statuta HDZZ-a te je izabrana nova počasna članica Društva. Za počasnu članicu izabrana je dr. sc. Mária Ranogajec-Komor, koja je od osnutka HDZZ-a 1979. godine aktivno doprinosila promociji Društva, unapređenju zaštite od zračenja i jačanju njegova ugleda. Tijekom njezina predsjedništva, HDZZ je steklo međunarodnu reputaciju u području zaštite od zračenja zahvaljujući znanstvenim aktivnostima, uspješnoj organizaciji regionalnih IRPA kongresa i suradnji s europskim društvima. Još jednom veliko hvala našoj Mariki na iznimnom doprinosu.

Krajem iste godine osvježena je web stranica Društva koja sadrži nove značajke i poboljšanja te moderan dizajn. Sve obavijesti mogu se pratiti na www.hdzz.hr.

Društvo je u proteklom razdoblju aktivno sudjelovalo na sastancima europskih društava, a nekoliko naših članova sudjeluje u radu Znanstvenog odbora Europske IRPA-e, čija će se konferencija održati sljedeće godine u Liverpoolu. Također, u 2023. godini raspisan je natječaj za najbolji znanstveni rad mladih autora, no nije bilo prijavljenih kandidata. Ove godine planiramo ponoviti natječaj uz nadu u bolji odaziv, potaknutu uspješnom organizacijom 4. skupa mladih HDZZ-a, održanog 1. ožujka 2024. na Institutu Ruđer Bošković. Skup je okupio više od pedeset sudionika, koji su imali priliku čuti 18 predavanja podijeljenih u tri tematske cjeline: radioterapija i radiološka dijagnostika, zračenje i okoliš te različiti aspekti rada s ionizirajućim zračenjem, uključujući edukaciju o znanosti o zračenju.

Društvo je također sudjelovalo u organizaciji drugog popularno-znanstvenog piknika medicinske fizike i zaštite od zračenja, održanog 15. ožujka 2025. u KB Dubrava, u suradnji s Hrvatskim društvom za medicinsku fiziku. Sudjelovalo je 150 sudionika, ponajviše srednjoškolaca i studenata, kojima je približen rad medicinskih fizičara i stručnjaka za zaštitu od zračenja. Veliki interes i pozitivni dojmovi potvrđuju potrebu za ovakvim događanjima i otvaraju mogućnost za uspostavu nove tradicije. Program je sadržavao četiri predavanja i šest radionica koje su pripremili naši članovi-volonteri, s različitih institucija, pod vodstvom dr. sc. Ivane Kralik.

Na svjetskoj i regionalnoj razini, članovi Društva aktivno sudjeluju u radu aktivnih IRPA radnih skupina, na raznim kongresima te na 32. simpoziju Društva za zaštitu od zračenja Srbije i Crne Gore u Budvi.

U ovoj godini Društvo organizira 14. simpozij, koji će obuhvatiti deset znanstveno-stručnih sekcija. Glavna tema ovog simpozija posvećena je izazovima u gospodarenju radioaktivnim otpadom. Ova problematika postaje sve značajnija u svijetu, pa tako i u Hrvatskoj, s obzirom na potrebu sustavnog zbrinjavanja radioaktivnog otpada što uključuje izazovan proces odabira lokacije i izgradnje skladišta odnosno odlagališta, zahtijeva unapređenje metoda obrade otpada i njegovog skladištenja, kao i usklađivanje s međunarodnim propisima. U Zborniku se nalazi 65 sažetka, a svi su sažeci objavljeni unutar predviđenog roka. Sažeci su pisani na hrvatskom i engleskom jeziku, a tehnički su uređeni prema standardiziranom predlošku. Ove godine novost su pozvani predavači iz zemlje i inozemstva, zbog čega su posterska priopćenja i usmene prezentacije pripremljene na engleskom jeziku, dok se izlaganja mogu održati na hrvatskom ili engleskom jeziku.

Podsjećamo da je službeno glasilo HDZZ-a znanstveno-stručni časopis *Arhiv za higijenu rada i toksikologiju* (http://hrcak.srce.hr/aiht), koji u 2024. godini ima faktor odjeka (Impact Factor) 1.7. Časopis redovito objavljuje informacije vezane uz rad Društva, a ovom prigodom pozivamo sve sudionike simpozija i članove Društva da proširene verzije svojih sažetaka objave u časopisu, pridonoseći tako njegovu daljnjem razvoju. Radovi prezentirani na Simpoziju mogu biti razmatrani za objavu pod uvjetom da nisu prethodno objavljeni te moraju biti uređeni prema smjernicama časopisa i proći znanstvenu recenziju. Vjerujemo da će ovaj Simpozij omogućiti kvalitetnu razmjenu iskustava i doprinijeti uspostavljanju novih te jačanju postojećih znanstvenih i stručnih suradnji. Organizatori zahvaljuju suorganizatorima, pokroviteljima, sponzorima i izlagačima na podršci i pomoći tijekom organizacije.

Na kraju, vjerujemo da će sudionici u ovom Zborniku pronaći vrijedne informacije i poticaj za daljnji znanstveni i stručni razvoj u području zaštite od zračenja. Želimo vam uspješan simpozij te ugodan boravak u Vodicama.

Ivana Coha , predsjednica HDZZ-a
Ivana Tucaković, predsjednica Znanstvenog odbora 14. simpozija
Katja Magdić Košiček, predsjednica Organizacijskog odbora 14. simpozija

Zagreb, travanj 2025.

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ISTRAŽIVAČKO PARTNERSTVO EUROPSKE UNIJE U PODRUČJU ZAŠTITE OD ZRAČENJA – PIANOFORTE, ŠTO JE TO U STVARNOSTI? - NOVOSTI

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Sažetak
Istraživačko partnerstvo PIANOFORTE teži unaprijediti znanje i promicati inovacije u području zaštite od zračenja za dobrobit javnosti, pacijenata, radnika i okoliša u svim scenarijima izloženosti ionizirajućem zračenju. Kroz znanstvene izazove kojima će se baviti, ovo partnerstvo ima za cilj doprinijeti prioritetnim europskim politikama kao što su borba protiv raka (Europski akcijski plan za suzbijanje raka), zaštita zdravlja od ekoloških rizika (Zeleni pakt za rast) i konačno poboljšanje predviđanja i otpornost u situacijama katastrofe (provedba Okvira iz Sendaija za smanjenje rizika od katastrofa). Unutar ovog partnerstva, objevljena su već tri poziva za dostavu istražiačkih prijedloga i koja su tvorena za cijelu europsku istraživačku zajednicu zaštite od zračenja. U fokusu su četiri istraživačke cjeline : poboljšanje zaštite pacijenata od zračenja vezanog uz uporabu ionizirajućeg zračenja u medicini; bolje razumijevanje varijabilnosti individualnog odgovora na izloženost ionizirajućem zračenju; proučavanje mehanizama uključenih u kroničnu izloženost niskim dozama ionizirajućeg zračenja; poboljšanje sposobnosti predviđanja i otpornosti u nuklearnim ili radiološkim kriznim situacijama i upravljanje nakon akcidenta. Posebna pozornost posvećena je uključivanju svih dionika (regulatore, civilno društvo, stručnjaci u području zaštite od zračenja, itd.) pri određivanju prioritetnih znanstvenih tema koje su predmetom otvorenih natječaja te prenošenju istraživanja u stvarno pojačanu zaštitu od zračenja uz korištenje novih tehnologija. Cilj je integriracija očekivanja širokog skupa dionika u zaštiti od zračenja. Partnerstvo također ima za cilj stvoriti poveznicu s istraživačkim aktivnostima koje se provode na europskoj razini u „ne-Euratom" područjima, posebno u zdravstvu. Osim ovih istraživačkih aktivnosti, PIANOFORTE doprinosi stvaranju održive i međunarodno priznate stručnosti u europskoj zaštiti od zračenja promicanjem dostupnosti, korištenja i dijeljenja postojećih najsuvremenijih istraživačkih infrastruktura na europskoj razini kao i provedbom aktivnosti obrazovanja i osposobljavanja. Partnerstvo, čije trajanje je produženo do 2029.g. se veže na prethodni zajednički rad, a posebno na rezultate europskog zajedničkog programa CONCERT (Program H2020). Također se veže na postignuća drugih europskih projekata koji su upravo završeni ili su u tijeku: MEDIRAD, HARMONIC, RadoNorm ili SINFONIA. Temeljem produljenja izvršni odbor konzorcija oslučio je u veljači 2025. raspisati i otvoreni natječaj za mlade istraživače doktorande u vrijednosti od 1.5 miliona €.
PIANOFORTE uključuje 58 partnera iz 22 zemlje EU-a te Ujedinjenog Kraljevstva i Norveške. Angažira javne istraživačke organizacije, tijela u području zaštite od zračenja, sveučilišta ali i šest europskih istraživačkih platformi u zaštiti od zračenja (MELODI, EURADOS, EURAMED, NERIS, ALLIANCE i SHARE). Očekuje se da će se ovaj inicijalni konzorcij i dalje proširivati dionicima koji će se odabrati otvorenim pozivima organiziranim tijekom trajanja partnerstva koje konzorcij namjerava kandidirati za drugi ciklus EURATOM radnog programa, sve do 20235.g. pod radnim nazivom FORTISSIMO

Ključne riječi: EU partnership, PIANOFORTE, radiation protection, Euratom

EUROPEAN UNION RESEARCH PARTNERSHIP IN THE FIELD OF RADIATION PROTECTION – PIANOFORTE, WHAT IS IT REALLY? – NEWS

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Abstract

The PIANOFORTE research partnership aims to improve knowledge and promote innovation in the field of radiation protection for the benefit of the public, patients, workers and the environment in all scenarios of exposure to ionizing radiation. Through the scientific challenges it will address, this partnership aims to contribute to priority European policies such as the fight against cancer (European Action Plan to Combat Cancer), the protection of health against environmental risks (Green Pact for Growth) and ultimately the improvement of forecasting and resilience in disaster situations (implementation of the Sendai Framework for Disaster Risk Reduction). Within this partnership, three calls for research proposals have already been launched and have been created for the entire European radiation protection research community. The focus is on four research topics: improving patient protection against radiation related to the use of ionizing radiation in medicine; better understanding the variability of the individual response to exposure to ionizing radiation; studying the mechanisms involved in chronic exposure to low doses of ionizing radiation; improving predictive ability and resistance in nuclear or radiological crisis situations and post-accident management. Special attention is paid to the involvement of all stakeholders (regulators, civil society, experts in the field of radiation protection, etc.) when determining priority scientific topics that are the subject of open tenders and transferring research into really enhanced radiation protection with the use of new technologies. The aim is to integrate the expectations of a broad set of stakeholders in radiation protection. The partnership also aims to create a link with research activities carried out at European level in „non-Euratom" areas, particularly in health. In addition to these research activities, PIANOFORTE contributes to the creation of sustainable and internationally recognized expertise in European radiation protection by promoting the availability, use and sharing of existing state-of-the-art research infrastructures at the European level as well as by implementing education and training activities. The partnership, whose duration has been extended until 2029, is related to previous joint work, and especially to the results of the European joint CONCERT program (Program H2020). It also links to the achievements of other European projects which have just been completed or are in progress: MEDIRAD, HARMONIC, RadoNorm or SINFONIA. Based on the extension, the executive board of the consortium decided in February 2025 to announce an open competition for young doctoral researchers worth 1.5 million €. PIANOFORTE involves 58 partners from 22 EU countries, United Kingdom and Norway. It engages public research organizations, bodies in the field of radiation protection, universities, but also six European research platforms in radiation protection (MELODI, EURADOS, EURAMED, NERIS, ALLIANCE and SHARE). It is expected that this initial consortium will continue to be expanded with stakeholders who will be selected by open calls organized during the duration of the partnership that the consortium intends to apply for the second cycle of the EURATOM work program, until 20235 under the working name FORTISSIMO.

Keywords: EU partnership, PIANOFORTE, radiation protection, Euratom

POLIMERNE NANOPREVLAKE NA BAZI DUGOLANČASTIH ALIFATSKIH MOLEKULA KAO PROSPEKT U MEDICINSKOJ NANOTEHOLOGIJI

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Samoorganizirajući molekulski slojevi (engl. SAM - *Self-assembled molecular*) molekularne su strukture koje se spontano formiraju na čvrstim podlogama adsorpcijom organskih molekula. Poznati po sposobnosti kontrole svojstava površine, poput vlažnosti, adhezije i reaktivnosti, SAM-ovi se široko primjenjuju u znanosti o površinama, nanotehnologiji i biomedicini. Međutim, njihova kemijska nestabilnost predstavlja ograničenje za praktične primjene.
Kako bi se prevladali navedeni izazovi, razvoj umreženih alifatskih molekula pojavio se kao transformativan pristup, osobito u biomedicinskim primjenama. Alifatski lanci, poznati po svojoj fleksibilnosti i hidrofobnoj prirodi, pružaju snažnu osnovu za razvoj materijala s poboljšanim mehaničkim svojstvima, biokompatibilnošću i kontroliranom razgradnjom. Umrežavanje omogućava novu razinu prilagodbe, omogućujući dizajn "pametnih" površina i biomaterijala prilagođenih specifičnim medicinskim potrebama.
Ionizirajuće zračenje jednostavna je, čista i učinkovita metoda za induciranje umrežavanja u alifatskim molekulama. Međutim, postizanje optimalnih rezultata zahtijeva pažljiv odabir uvjeta zračenja, jer oni utječu na svojstva dobivenog materijala, uključujući gustoću umrežavanja i mehaničke performanse. Različiti izvori zračenja i mediji mogu se koristiti za osiguranje uspješnog umrežavanja i kontrolu apsorbirane doze, što ovaj pristup čini svestranim i prilagodljivim različitim biomedicinskim kontekstima.
Ovaj rad istražuje napredak u optimizaciji gustoće umrežavanja i duljine lanaca za prilagodbu svojstava materijala. Takva optimizacija omogućava razvoj materijala s prilagodljivom razgradnjom za kontrolirano oslobađanje lijekova ili integraciju u tkiva.
Zaključno, umrežene alifatske molekule predstavljaju svestrano i obećavajuće rješenje za napredak u znanosti o biomedicinskim materijalima. Njihov potencijal za kombinaciju mehaničke čvrstoće, biokompatibilnosti i kontrolirane razgradnje otvara nove puteve za poboljšanje skrbi za pacijente i terapijskih ishoda.
Ovo istraživanje podržala je Hrvatska zaklada za znanost u sklopu projekta IP-2020-02-4344 pod nazivom „Irradiated Polymer Nano-Coatings for Metal Protection” (RadMeNano).

Ključne riječi: samoorganizirajući molekularni slojevi (SAM), umrežene alifatske molekule, biomedicinske primjene, modifikacija površine

POLYMER NANOCOATINGS BASED ON LONG-CHAIN ALIPHATIC MOLECULES AS A PROSPECT IN MEDICAL NANOTECHNOLOGY

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Self-assembled molecular layers (SAMs) are molecular assemblies that form spontaneously on solid substrates through the adsorption of organic molecules. Known for their ability to control surface properties like wettability, adhesion, and reactivity, SAMs are widely used in surface science, nanotechnology, and biomedicine. However, their chemical instability poses limitations for practical applications.

To address these challenges, the development of crosslinked aliphatic molecules has emerged as a transformative approach, particularly in biomedical applications. Aliphatic chains, known for their flexibility and hydrophobic nature, provide a robust platform for engineering materials with enhanced mechanical properties, biocompatibility, and controlled degradation rates. Crosslinking introduces a new dimension of customization, enabling the design of "smart" surfaces and biomaterials tailored to meet specific medical needs.

Ionizing irradiation is a simple, clean, and efficient method for inducing crosslinking in aliphatic molecules. However, achieving optimal results requires careful selection of irradiation conditions, as these influence the resulting material's properties, including crosslinking density and mechanical performance. Various radiation sources and media can be employed to control the absorbed dose and ensure successful crosslinking, making this approach both versatile and adaptable to diverse biomedical contexts.

This work explores recent advancements in this field, focusing on optimizing crosslinking density and chain length to fine-tune the material properties through examples of several biomedical applications. This allows for the development of materials with customizable degradation rates, enabling controlled therapeutic agent release or gradual integration into biological tissues.

In conclusion, crosslinked aliphatic molecules offer a versatile and promising solution for advancing biomedical materials science. Their potential to combine mechanical strength, biocompatibility, and controlled degradation opens new pathways for improving patient care and therapeutic outcomes. This approach not only enhances the functional capabilities of biomaterials but also contributes to the broader mission of advancing personalized and effective healthcare solutions.

This research was supported by the Croatian Science Foundation under the project IP-2020-02-4344 entitled “Irradiated Polymer Nano-Coatings for Metal Protection” (RadMeNano).

Keywords: self-assembled molecular layers (SAMs), crosslinked aliphatic molecules, biomedical applications, surface modification

KONTROLIRANA ISPORUKA LIJEKOVA: DINAMIKA OTPUŠTANJA RADIJACIJSKI UMREŽENIH MONOSLOJEVA STEARINSKE KISELINE NA POROZNOM KALCIJEVOM KARBONATU

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Porozni kalcijev karbonat ($CaCO_3$) je obećavajući anorganski nosač za ciljanu isporuku lijekova zbog biokompatibilnosti, male veličine čestica i velike specifične površine. Lijekovi se mogu unijeti u pore $CaCO_3$ i zapečatiti biokompatibilnom prevlakom radi kontrolirane isporuke lijeka. Masne kiseline su prikladne za takve jer tvore aamoorganizirajuće molekulske slojeve (engl. *self-assembled monolayer*, SAM), koji se mogu stabilizirati ionizirajućim zračenjem, tvoreći polimernu nanoprevlaku (PNP).
U ovom radu istraženi su optimalni uvjeti za radijacijsko umrežavanje stearinske kiseline kako bi se formirala PNP na vateritu, specifično visokoporoznom polimorfu $CaCO_3$. Kako bi se ispitao potencijal ovog sustava u ispostavi lijekova, fluorescentno bojilo, kalcein, je korišteno kao modalni lijek. Oslobađanje lijeka praćeno je tijekom vremena u simuliranoj tjelesnoj tekućini (Hanksova otopina).
Vaterit je pokazao stabilnost prilikom zračenja u odsutnosti kisika, čak do 100 kGy. Umrežavanje stearinske kiseline na vateritu uspješno je postignuto spontanom samo-organizacijom, uz primjenu zračenja za optimiziranje stabilnosti prevlake. Otpuštanje kalceina iz čestica vaterita je odgođeno kada je vaterit obložen PNP-om.
Preciznim podešavanjem uvjeta zračenja omogućena je kontrola profila oslobađanja, što predstavlja značajan napredak u razvoju sustava za isporuku lijekova temeljenih na mikro- i nanomedicini.

Ključne riječi: porozni kalcijev karbonat, stearinska kiselina, radijacijsko umrežavanje, polimerna nanoprevlaka, isporuka lijekova

Zahvaljujemo Hrvatskoj zakladi za znanost (HRZZ IP-2020-02-4344) na potpori za istraživanja.

CONTROLLED DRUG DELIVERY: RELEASE DYNAMICS OF RADIATION CROSSLINKED STEARIC ACID MONOLAYERS ON POROUS CALCIUM CARBONATE

Helena Bach-Rojecky[1], Marija Mirosavljević[1], Damir Kralj[1], Katarina Marušić[1]

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Porous calcium carbonate ($CaCO_3$) is a promising inorganic carrier for targeted drug delivery due to its biocompatibility, small particle size, and large surface area. Drug molecules can be loaded into the pores of $CaCO_3$ and sealed with a biocompatible coating in order to achieve controlled drug delivery. Fatty acids are suitable for for this purpose as they form self-assembled monolayers (SAMs), which can be stabilized by ionizing radiation, resulting in a polymer nanocoating (PNC).
In this study, the optimal conditions for the radiation crosslinking of stearic acid were investigated to form a PNP on vaterite, a highly porous polymorph of $CaCO_3$. To examine the potential of this system for drug delivery, the fluorescent dye calcein was used as a model drug. Drug release was monitored over time in simulated body fluid (Hank's solution).
Vaterite demonstrated stability during irradiation in the absence of oxygen, even up to 100 kGy. The crosslinking of stearic acid on vaterite was successfully achieved through spontaneous self-assembly, with radiation applied to optimize coating stability. The release of calcein from vaterite particles was delayed when vaterite was coated with PNC.
By fine-tuning the irradiation conditions, precise control over the release profile was achieved, marking a significant breakthrough in the development of micro- and nanomedicine-based delivery systems.

Keywords: porous calcium carbonate, stearic acid, radiation crosslinking, polymer nanocoating, drug delivery

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ZABLUDE OPĆEG STANOVNIŠTVA I MEDICINSKOG OSOBLJA O ZRAČENJU

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Kao zaposlenici Zavoda za zaštitu od zračenja susrećemo se sa raznim upitima zabrinutih i loše informiranih građana, vezanih uz široko područje zračenja i radioaktivnosti. Iz nedostatnog razumijevanja fizike i iz dezinformacija često proizlazi iracionalan strah od svakodnevnih pojava i uređaja, tipa televizijskih antena i Wi-Fi *router*a.
Medicinsko osoblje koje radi na radiološkim odjelima i rukuje rendgenskim uređajima obvezno je proći odgovarajuću edukaciju, uključujući i pozadinsku fiziku ionizirajućeg zračenja. Unatoč visokoj obrazovanosti i obaveznoj obnovi znanja svakih 5 godina, redovito se susrećemo sa sličnim upitima i iracionalnim strahovima koje iznose liječnici, zubara, zrakoplovnih tehničara i drugih.
Druga je krajnost opasan nedostatak shvaćanja ozbiljnosti izloženosti ionizirajućem zračenju koji se također, iako rjeđe, pojavljuje u pretežito starijoj populaciji radnika s dugogodišnjih stažem rukovanja izvorima ionizirajućeg zračenja.
U ovom radu izlažemo neke od čestih zabluda i neosnovanih strahova općeg stanovništva ali i radnika obučenih za rukovanje izvorima ionizirajućeg zračenja te ukratko izlažemo osnovne činjenice i fiziku zračenja koje daju temelj za razumijevanje potencijalne opasnosti od rendgenskih uređaja u medicini i za provjeru prtljage, kao i od raznih drugih izvora neionizirajućeg zračenja koji se nalaze oko nas.

Ključne riječi: ionizirajuće zračenje, neionizirajuće zračenje, misinformacije, strah, fizika zračenja

PUBLIC AND MEDICAL PERSONEL MISCONCEPTIONS ABOUT RADIATION

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As employees of the Institute at the Radiation Protection Department, we encounter various inquiries from concerned and ill-informed citizens, related to the wide area of radiation and radioactivity. An irrational fear of everyday phenomena and devices, such as television antennas and Wi-Fi routers, often arises from misinformation and an insufficient understanding of physics.

Medical personnel working in radiology departments and handling X-ray machines are obliged to undergo related education, including the background physics of ionizing radiation. Despite the high education and mandatory renewal of knowledge every 5 years, we regularly encounter similar inquiries and irrational fears when dealing with doctors, dentists, airport technicians and others.

Another end of the extreme is the dangerous lack of understanding of the seriousness of exposure to ionizing radiation, which also, although less often, appears in the predominantly older population of professionals with many years of experience handling sources of ionizing radiation.

In this paper, we present some of the frequent misconceptions and unfounded fears of the general population, as well as professionals trained in handling sources of ionizing radiation, and we briefly present the basic facts and physics of radiation that provide a base for understanding the potential danger of X-ray devices in medicine and for checking luggage, as well as various other sources of non-ionizing radiation that surround us in our daily lives.

Keywords: ionizing radiation, non-ionizing radiation, misinformation, fear, radiation physics

IZAZOVI U GOSPODARENJU RADIOAKTIVNIM OTPADOM

CHALLENGES IN RADIOACTIVE WASTE MANAGEMENT

ZNANJE, INFORMIRANJE I OBRAZOVANJE U GOSPODARENJU RADIOAKTIVNIM OTPADOM I ISTROŠENIM NUKLEARNIM GORIVOM

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Sažetak

Iako su inženjerski izazovi odabira lokacije, projektiranja, izgradnje i dokazivanja koncepta (procjene sigurnosti) za odlagališta radioaktivnog otpada (RAO) ili istrošenog nuklearnog goriva (ING) izuzetno složeni, primarni problem koji se tiče potvrde lokacije i tehnologije leži u prihvaćanju RAO/ING programa i društvenih čimbenika. Budući da su svi restartani ili zaustavljeni programi gospodarenja/zbrinjavanja RAO-a i ING-a prošli tako radi društvenih/sociooloških problema, rješavanje ovog pitanja je od velike važnosti.

Postoji mnogo dionika s različitim interesima, gledištima i stajalištima u vezi gospodarenja i zbrinjavanja RAO-a i ING-a. Neki dionici su intenzivno zainteresirani, dok su drugi ravnodušni; neki mogu i hoće utjecati na Program, dok drugi neće. Odnos između razine interesa dionika za Program i njihove sposobnosti da utječu na njega, diktira pristup uključivanju dionika – kako ih uključiti u Program i raditi s njima u smislu osiguranja uspjeha Programa.

Tijekom ovih aktivnosti nužno je uzeti u obzir nekoliko bitnih stvari: znanje dionika o pitanjima upravljanja RAO-om i ING-om često je oskudno i netočno; dionici općenito djeluju u vlastitom interesu; najvažniji pokretači vjerojatno će biti emocionalni i ekonomski; dionici mogu prihvatiti da budu informirani, ali se opiru „potrebi da ih se obrazuje“; mogu zanemariti točne informacije ako su u sukobu s njihovim mišljenjima ili osobnim interesima. Istraživanja u ovom području pokazuju kako bi se mnogi problemi mogli spriječiti ako bi unutarnji dionici (implementator i regulator) bili dobro vođeni te ako se dovoljno vremena i resursa dodijeli programima uključivanja vanjskih dionika.

Može se ustvrditi kako je nužno temeljito razraditi program uključivanja dionika. Zainteresirane strane treba pažljivo istražiti i razumjeti, a angažman treba započeti prije odabira lokacije i nastaviti kroz cijeli program gospodarenja/odlaganja RAO-a i ING-a. Troškovi uključivanja dionika moraju se pažljivo predvidjeti i planirati sa značajnom marginom za prilagodbu. Osobito je važno da proces treba započeti s implementatorom i regulatorom. Dugoročno, ovaj će se pristup pokazati učinkovitim, štedeći i resurse i vrijeme.

Ključne riječi: Dionici, uključivanje, znanje, informiranje, obrazovanje

KNOWLEDGE, INFORMATION AND EDUCATION IN RADIOACTIVE WASTE AND SPENT NUCLEAR FUEL MANAGEMENT

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Abstract

Although the engineering challenges of site selection, design, construction, and proof of concept (safety assessment) for repositories intended for radioactive waste (RW) or spent nuclear fuel (SNF) are overwhelmingly complex, the primary issue concerning site and technology approval lies in RW/SNF program acceptance and societal concerns. Since all RW and SNF management/disposal programs that failed did so due to societal issues, addressing this problem is of paramount importance.

There are many stakeholders with differing interests, perspectives, and positions regarding RW and SNF management and disposal. Some stakeholders are highly invested in the issue, while others are indifferent; some can and will influence the program, while others will not. The relationship between a stakeholder's level of interest in the program and their ability to influence it dictates the approach to stakeholder engagement—how to involve them in the program and work with them to ensure its success.

Several points must be considered during these processes: stakeholders' knowledge about RW and SNF management issues is often sparse and inaccurate; stakeholders generally act in their own self-interest; the most significant drivers are likely to be emotional and economic; stakeholders may accept being informed but resist being educated; and they may disregard accurate information if it conflicts with their opinions or self-interest. Research in this field indicates that many problems could be prevented if internal stakeholders (implementers and regulators) are properly managed and if adequate time and resources are allocated for external stakeholder engagement programs.

It can be argued that a stakeholder engagement program must be thoroughly developed. Stakeholders should be carefully researched and understood, and engagement should begin before site selection and continue throughout the entire RW and SNF management/disposal program. Costs associated with stakeholder engagement must be carefully forecasted and planned with a significant margin for adjustment. Importantly, the process should begin with the implementer and regulator. In the long run, this approach will prove effective, saving both resources and time.

Keywords: Stakeholders, engagement, knowledge, information, education.

NATURAL ANALOGUES (NA) OF THE ENGINERED BARRIER SYSTEM (EBS)

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Abstract
In Croatia, as a decision on a repository site is some time away, it makes sense to focus current efforts on the repository engineered barrier system (EBS). The EBS is considered 'robust' in most safety cases (SC) but, to justify this view, it must be demonstrated that all conceivable processes which could degrade EBS performance have been assessed**.** For most engineered systems (e.g. bridges), this would include a range of laboratory experiments supported by simulation modelling and expert judgement based on experience of the same or similar systems. But repository design deviates from standard engineering practice as repositories are only now being constructed, so testing their compliance to design limits (and thus building confidence that they will isolate waste for thousands of years) will be a little difficult.
However, although no examples of 'aged' repositories exist, it is possible to identify natural systems which involve processes which are similar (or analogous) to those expected in a repository and which can be utilised to provide examples of future repository performance to a wide range of stakeholders. So, what is a 'natural analogue (NA)'? The most robust definition is "…an occurrence of materials or processes which resemble those expected in a proposed geological radioactive waste repository." (Come & Chapman, 1986). Basically, a NA should

- provide a method of testing our understanding of long-term (repository-relevant) processes
- provide methods for the extrapolation of (unrealistic) laboratory/rock laboratory/modelling results to the reality of the repository system
- provide support to extrapolations from simple laboratory to complex repository systems and from short-term, small-scale experimental systems to the geological temporal and spatial scales required in a SC

Here, examples of existing NA studies will be presented to highlight how NA data can be used to support repository SC:

- natural glasses - as NA of vitrified radioactive waste
- natural and archaeological iron, steel and copper – as NA of the metal containers for the radioactive waste
- natural bentonite clays – as NA of the clay which will seal the containers off from the rock which is hosting the repository
- natural and archaeological concretes which not only support deep tunnels, but are also used to contain and seal off radioactive waste

The strengths and weaknesses of the various approaches will be examined and a large body of information will be provided for later digestion and assessment.

Reference

Côme B & Chapman NA (1986). CEC Nucl. Sci. & Tech. Report EUR 10315, CEC, Luxembourg.

Keywords: radioactive waste repository, natural analogues, safety case support

RAZVOJ KRITERIJA ZA ODABIR LOKACIJE ODLAGALIŠTA ISKORIŠTENOG NUKLEARNOG GORIVA ZA POJEDINU ZEMLJU

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SAŽETAK

Kriteriji za odabir lokacije dubokog geološkog odlagališta (DGO) za iskorišteno nuklearno gorivo (ING) moraju uključivati niz čimbenika, tehničkih i sociooloških, prema kojima se pojedina područja odbacuju ili kvalitativno uspoređuju. Tehnički kriteriji, među kojima su najvažniji geološki, moraju osigurati odabir lokacije DGO-a koja neće proći nikakve promjene tijekom traženih 100.000 godina, koje bi mogle smanjiti sigurnost odlagališta i skratiti vrijeme migracije radionuklida prema bioti. Premda su neki kriteriji općeprihvaćeni (tektonika, propusnost matične stijene, udaljenost od rasjeda i seizmički aktivnih zona, itd.), drugi su specifični za svaku zemlju (udaljenost od aktivnih vulkana, dijapirizam, područje očekivane glacijacije, mogućnost tsunamija, sl.). Uz tehničke kriterije, poseban problem predstavljaju sociološki, koji se moraju prilagoditi nizu specifičnosti vezanih uz stanovništvo zemlje u kojoj se planira DGO. Prepreke odabiru lokacije DGO-a u sociološkom smislu su povjerenje u implementatora, regulatorna tijela, znanstvenike i stručnjake, te konačno u zakonodavnu i izvršnu vlast. Sekundarne sociološke prepreke uključuju stavove i mentalitet (način razmišljanja, vrednote, navike, reagiranja, opća obilježja temperamenta) naroda i društvenih grupa. Tehnički čimbenici i kriteriji, čak i u slučajevima kada ukazuju na smanjen broj potencijalno prihvatljivih područja, ne moraju biti presudni za odabir lokacije, jer se sigurno mjesto za DGO može pronaći kroz inženjerska rješenja – prilagodbom koncepata i tehnologija odlaganja. Sociološki faktori su, s druge strane, bili ključni za odgađanje početka Programa odabira lokacije DGO-a u nekim zemljama ili za ponovo pokretanje Programa u drugim zemljama, zbog čega je, nakon 80 godina postojanja ING-a, samo Finska započela izgradnju DGO-a. Ispravan način rješavanja problema vezanih uz sociološke faktore je sustavno uključivanje dionika u Program odabira lokacije, uz kontinuiran i intenzivan Program informiranja i obrazovanja. Kao što se obrazovanje povezano s Programom mora prilagoditi i obuhvatiti specifične društvene grupe s različitim intenzitetima, informiranje mora biti kontinuirano i sveobuhvatno, jasno i transparentno, uz korištenje svih dostupnih metoda komunikacije s dionicima, posebno medijima i društvenim mrežama. Hrvatsko-slovenski Program je specifičan jer uključuje odabir jedne lokacije u jednoj od dviju zemalja odgovornih za gospodarenje ING-om iz Nuklearne elektrane Krško. Osim tehničkih problema odabira lokacije u relativno malim zemljama s kompleksnom geologijom, uključivanje dionika znači komunikaciju i suradnju s dvama narodima uzimajući u obzir njihove sociološke specifičnosti.

Ključne riječi: iskorišteno nuklearno gorivo, odlagalište, odabir lokacije, tehnički kriteriji, sociološki kriteriji

DEVELOPMENT OF COUNTRY-SPECIFIC SITE SELECTION CRITERIA FOR SPENT NUCLEAR FUEL REPOSITORY

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ABSTRACT

Site selection criteria for spent nuclear fuel (SNF) deep geological repository (DGR) must include several technical and sociological factors, by which certain areas are rejected or qualitatively compared. The technical criteria, of which the geological ones are the most important, must ensure the selection of a DGR location that will not undergo any changes during the requested 100,000 years, that can reduce the repository's safety and shorten the radionuclides migration time towards biota. Although some criteria are generally accepted (tectonics, host rock permeability, distance from faults and seismically active zones, etc.), others are country-specific (distance from active volcanoes, diapirism, area of expected glaciation, possibility of a tsunami, etc.). In addition to the technical criteria, sociological ones represent a separate problem, which must be adapted to a series of specificities related to the population of the country where the DGR is planned. Sociological obstacles are: trust in the implementer, regulatory agency, scientists and experts, and finally in the legislative and executive authorities. Secondary sociological obstacles include attitudes and mentality (way of thinking, values, habits, reactions, general characteristics of temperament) of people and social groups. Technical factors and criteria, even in cases where they indicate a reduced number of potentially acceptable areas, do not have to be decisive for site selection, because a safe location for DGR can be found through engineering solutions - adapting concepts and disposal technologies. Conversely, sociological factors were crucial for postponing the start of the DGR site selection program in some countries or restarting the program in other countries, which is why, after 80 years of SNF's existence, only Finland has started the construction of DGR. The correct way to solve problems related to sociological factors is to systematically engage stakeholders in a site selection program, with a continuous and intensive information and education program. Just as education related to the Program must be adapted and encompass specific social groups in varying intensities, information must be continuous and comprehensive, clear and transparent, using all available methods of communication with stakeholders, especially media and social networks. The Croatian-Slovenian Program is specific because it includes the selection of a location in one of the two countries responsible for managing the SNF from the Krško nuclear power plant. In addition to the technical problems of site selection in relatively small countries with complex geology, stakeholder involvement means communicating and collaborating with the two peoples while considering their sociological specificities.

Keywords: spent nuclear fuel, repository, site selection, technical criteria, sociological criteria.

PROMJENE NA BENTONITNIM INŽENJERSKIM BARIJERAMA U ODLAGALIŠTIMA ISKORIŠTENOGA NUKLEARNOG GORIVA I NJIHOV UTJECAJ NA SIGURNOST ODLAGALIŠTA

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Sažetak
Korištenje Na-bentonita kao inženjerske barijere u dubokim geološkim odlagalištima (DGO) iskorištenoga nuklearnog goriva (ING) i visokoradioaktivnog otpada (VRAO) u kristaliničnim i sedimentnim stijenama koje se sastoje od ili sadrže gline, predstavlja jedan od glavnih mehanizama za usporavanje migracije radionuklida prema bioti. Trajnost inženjerske barijere u smislu zadržavanja traženih svojstava: niski koeficijent propusnosti, zadržavanje radionuklida, niski koeficijent difuzije, niska toplinska vodljivost i dr., dio je cjelovitog sustava koji osigurava sigurnost odlagališta u periodu do 100 000 godina. Obzirom na čimbenike koji utječu na bentonitnu barijeru: toplina oslobođena iz spremnika s ING-om ili VRAO-m, geokemijski uvjeti u matičnoj stijeni i podzemnoj vodi, utjecaj korozijskih produkata materijala od kojih je izrađen spremnik za odlaganje i sl. očekuje se kako će glinena barijera vremenom degradirati gubeći tražena svojstva. Početna istraživanja provedena na Sveučilištu u Zagrebu Rudarsko-geološko-naftnom fakultetu u LAGEMA laboratoriju ukazuju na brze promjene u mineraloškom sastavu bentonitne gline već kod malo povećanih temperatura (oko 40 °C) što indicira kako će promjene na temperaturama očekivanim u DGR-u (90 °C ili više) značajno utjecati na bentonitnu barijeru i njenu funkcionalnost. Bentonit sadrži značajni udio smektita, minerala glina koji kroz svoje sposobnosti bubrenja i izmjene kationa s okolinom treba usporavati migraciju radionuklida. No uslijed zagrijavanja smektit dehidrira, dolazi do kolapsa međuslojnog prostora čime se gubi značajan dio mjesta za izmjenu kationa i time i funkcionalnost barijere. Nastavak istraživanja predviđa određivanje promjena na bentonitu kod duže izloženosti povišenim temperaturama te promjene koje će se događati na kontaktu bentonit-bakar, na oba materijala u uvjetima koji se očekuju u DGR-u. Paralelno s navedenim istraživanjima provode se i dugotrajna in-situ istraživanja na grijaćem tijelu s košuljicom od bakra ugrađenim u stijenu s jednakim bentonitom kao inženjerskom barijerom između modela spremnika i stijene.

Ključne riječi: bentonit, iskorišteno nuklearno gorivo, inženjerska barijera, sigurnost odlagališta

CHANGES TO BENTONITE ENGINEERING BARRIERS IN SPENT NUCLEAR FUEL REPOSITORIES AND THEIR EFFECT ON REPOSITORY SAFETY

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Abstract

The use of Na-bentonite as an engineered barrier in deep geological repositories (DGRs) for spent nuclear fuel (SNF) and high-level radioactive waste (HLW) in crystalline and argillaceous rocks is one of the primary mechanisms for slowing down the migration of radionuclides toward biota. The durability of the engineered barrier, in terms of maintaining essential properties such as a low permeability coefficient, radionuclide retention, low diffusion coefficient, and low thermal conductivity, is a critical component of a comprehensive system designed to ensure repository safety for up to 100,000 years.

Given the factors affecting the bentonite barrier—heat released from the SNF or HLW container, geochemical conditions in the host rock and groundwater, and the influence of corrosion products from the disposal container materials—it is expected that the clay barrier will degrade over time, losing its required properties. Initial research conducted at the University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, in the LAGEMA laboratory, indicates rapid changes in the mineralogical composition of bentonite clay even at slightly elevated temperatures (40 °C). This suggests that changes at the temperatures expected in the DGR (90 °C or higher) will significantly impact the bentonite barrier and its functionality. Bentonite contains significant amounth of smectite, a clay mineral which, through its swealling and cation exchnage, should slow down the migration of radionuclides. But, in the process of heating, the smectite dehydrates, the collapse of interlayer space occures, and significant number of cation-exchange sites is lost what influences the functionality of the barrier.

Further research is planned to investigate the changes in bentonite during prolonged exposure to elevated temperatures and the interactions occurring at the bentonite-copper interface, including effects on both materials under conditions anticipated in the DGR. Concurrently, long-term in-situ studies are being conducted using a copper-jacketed heater embedded in rock, with the same bentonite serving as an engineered barrier between the container model and the surrounding rock .

Keywords: bentonite, spent nuclear fuel, engineering barrier, repository safety

LESSONS LEARNED FROM THE WORKSHOP AND INTERCOMPARISON MEASUREMENTS ON RADIOACTIVE WASTE CLEARANCE

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Abstract

The recent amendment to Hungary's radiation protection regulation introduced significant changes to radioactive waste clearance procedures. In response, an intercomparison measurement and workshop were organized on 2 February 2024 to assess its impact on practice. During this event, seven measurement teams evaluated two waste packages following a comprehensive methodology, including dose rate- and surface contamination measurements, isotope identification, activity and activity concentration estimation, and smear tests.

A dedicated webpage-based platform facilitated real-time data sharing among the participants. In addition to technical assessments, experts exchanged insights on waste clearance challenges and process optimization. The findings were further discussed in a roundtable session at the annual meeting of the Hungarian Radiation Protection Association. This presentation will provide key insights from the event, highlight methodological advancements, and share recommendations for enhancing radioactive waste management practices. Additionally, this presentation will include details on the latest activities of the Hungarian Radiation Protection Association.

Keywords: IRPA, radioactive waste clearance, radiation measurement, intercomparison

DEVELOPMENT OF SEPARATION PROTOCOL FOR DETERMINATION OF PALLADIUM-107 IN RADIOACTIVE WASTE

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Abstract
Pd-107 is, after I-129, the second longest-lived fission product with a half-life of 6.5E+6 years. As such, it is of concern for safe disposal of radioactive waste. Accurate estimate of its inventory should be thus made for spent nuclear fuel and high-level radioactive waste. Pd-107 is a pure beta emitter with 34.1 keV maximum beta energy and no gamma emission. Consequently, its detection is limited to radiometric detection of beta particles or mass spectrometric detection. Due to relatively long half-life, mass spectrometric detection will give lower detection limits and consequently lower sample masses will be required for achieving desired detection limit. However, isobaric interference of stable Ag-107 needs to be removed before mass spectrometric determination. For this purpose, we have investigated different extraction chromatography resin for the separation of Pd-107 from Ag-107. Ni Resin, TK 200 resin, LN resin and TBP resin were characterized in terms of distribution coefficients for Pd and Ag in different HNO_3 and HCl molarities in batch experiments. This was followed by testing and optimizing separation protocol for column separation. The results showed that all resin, except for TBP resin, could be utilized to some extent to separate Pd from Ag, whereas Ni Resin proved to be the best.

Key words: Pd-107, extraction chromatography, mass spectrometry

Acknowledgements:
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KONCEPT ODLAGALIŠTA NISKO I SREDNJE RADIOAKTIVNOG OTPADA S VISOKOM PASIVNOM SIGURNOŠĆU

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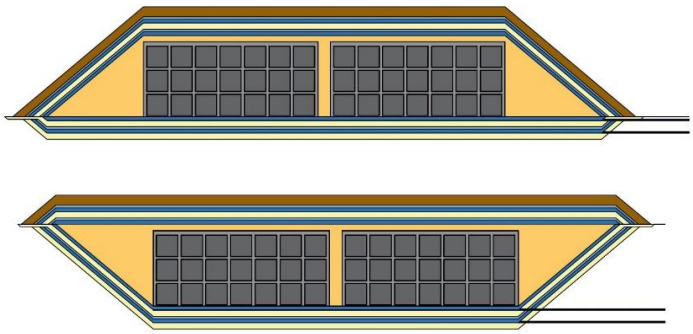
Sažetak
Do sada predloženi ili primijenjeni koncepti odlagališta nisko i srednje radioaktivnog otpada (NSRAO) zasnivaju se na korištenju betona kao primarne zaštitne barijere i u većini slučajeva sustav zaštitnih slojeva iznad odlagališta. Dno odlagališta je obično betonska podloga/temelj s pojačanim drenažnim sustavom koji služi za detekciju i evakuaciju procjedne tekućine u slučaju procjeđivanja. Novi, predloženi koncept (slika 1), predviđa gornji i donji kompleksni zaštitni sustav slojeva koji onemogućuje istjecanje procjedne tekućine osim uklanjanja pod kontroliranim uvjetima i samo tijekom ranog perioda nakon zatvaranja odlagališta. Na taj način je premošten problem kontinuirane kontrole i obrade procjedne tekućine u slučaju njene pojave nakon prestanka industrijskog nadzora (aktivni institucijski nadzor) ili u slučaju njegovog prekida uslijed administrativnih i sličnih razloga. Ostali koncepti u periodu (pasivnog) institucijskog nadzora i onako ne predviđaju kontinuiranu kontrolu procjeđivanja, a ako je i predviđaju, realna mogućnost njenog provođenja je mala. Problem je tim veći u slučaju kad su na odlagalištu zbrinuti materijali s dugoživućim radionuklidima. Institucijski nadzor obično traje oko 300 god ≈10 poluživota ^{137}Cs ili ^{90}Sr, dok je u slučaju ^{226}Ra s vremenom poluživota od 1 600 god. nužno uključiti ili specifičan način odlaganja ili posebne dugoživuće spremnike. Novi koncept odlagališta prema prvim istraživanjima daje duži period pasivne sigurnosti i manju mogućnost korozije betona i metalnih spremnika. Geometrija odlagališta je prethodno provjerena po pitanju stabilnosti kosina, a nastavak istraživanja će pokriti ostale karakteristike nužne za izradu studije sigurnosti.



Slika 1: Predloženi koncept nadzemnog pripovršinskog odlagališta (gornji) i ukopanog pripovršinskog odlagališta NSRAO (donji).

Ključne riječi: koncept odlagališta, nisko i srednje radioaktivni otpad, pasivna sigurnost

CONCEPT OF A LOW AND INTERMEDIATE LEVEL RADIOACTIVE WASTE REPOSITORY WITH A HIGH PASSIVE SAFETY

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Abstract

Concepts for low- and intermediate-level radioactive waste (LILW) disposal facilities proposed or implemented so far rely primarily on concrete as the main protective barrier. Most concepts also incorporate a system of protective layers on top of the disposal facility. The base of the disposal facility typically consists of a concrete foundation with an intensive drainage system designed to detect and evacuate leachate in case of percolation.

The newly proposed concept (Fig. 1) introduces a complex system of upper and lower protective layers to prevent leachate from escaping. Leachate removal is conducted only under controlled conditions and solely during the early post-closure period of the disposal site. This approach addresses the challenge of continuous monitoring and treatment of leachate, which may occur after the cessation of active institutional supervision or in cases where monitoring is interrupted due to administrative or other reasons.

Existing concepts during the period of passive institutional supervision typically do not include continuous leachate monitoring. Even when monitoring is envisioned, practical implementation is often limited. This issue is particularly significant for repositories containing materials with long-lived radionuclides. For example, institutional monitoring usually spans approximately 300 years, corresponding to about ten half-lives of Cs-137 or Sr-90. However, in cases involving Ra-226, which has a half-life of 1,600 years, either a specialized disposal method or long-lasting containers must be employed.

Initial research indicates that the new disposal concept offers a longer period of passive safety and reduces the likelihood of corrosion in concrete and metal containers. Repository's geometry has been evaluated for slope stability, and future studies will address additional characteristics required for a comprehensive safety analysis.

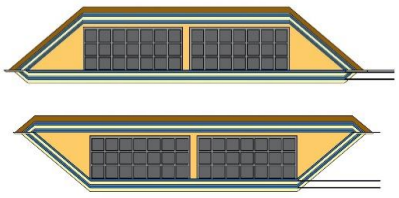

Figure 1: Suggested surface (upper), or a near surface (lower) concept for the LILW disposal facility

Keywords: disposal concept, low and intermediate level radioactive waste, passive safety

MODELIRANJE POLJA NEUTRONSKOG I GAMA ZRAČENJA OKO SUHO SKLADIŠTENIH SPREMNIKA ISTROŠENOG NUKLEARNOG GORIVA

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Sažetak
Nuklearna elektrana Krško (NEK) projektirana je za rad u trajanju od 40 godina te je 2023. godine obilježen kraj tog perioda. U međuvremenu je NEK programom nadogradnje sigurnosti postigao produljenje vijeka trajanja za još 10 godina i već sada započete su pripreme za još jedno produljenje od 10 godina. Rezultat rada elektrane je visokoradioaktivni otpad u formi istrošenih gorivnih elemenata koji su prvotno skladišteni u bazenu za istrošeno gorivo do popunjenja njegovih kapaciteta. U svrhu nastavka stabilnog rada elektrane, izgrađeno je suho skladište istrošenog goriva te je u 2023. godini provedena prva kampanja unutar koje je u skladištu pohranjeno 16 višenamjenskih suhih spremnika unutar kojih su pohranjena 592 istrošena gorivna elementa. Po provedenoj kampanji, izvedena su mjerenja doza zračenja na više dodirnih točaka na samim spremnicima te je utvrđeno da su izmjerene doze unutar propisanih normi. Cilj ovog rada bio je izrada teorijskog modela koji na poluempirijski način opisuje polja neutronskog i gama zračenja u prostoru oko suhih spremnika. Uz to, razmotreni su termodinamički aspekti ovakvog načina skladištenja te sigurnosni zahtjevi koje spremnici i samo skladište moraju ispunjavati.

Ključne riječi: suho skladište, istrošeno nuklearno gorivo, model polja zračenja

MODELING OF NEUTRON AND GAMMA RADIATION FIELDS AROUND DRY STORED SPENT NUCLEAR FUEL CONTAINERS

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Abstract
The Krško Nuclear Power Plant (NEK) was designed to operate for 40 years, and 2023 marked the end of that period. In the meantime, NEK achieved an extension of its service life by another 10 years through the safety upgrade program, and preparations for another 10-year extension have already begun. The result of the plant's operation is highly radioactive waste in the form of spent fuel elements, which were initially stored in the spent fuel pool until its capacity was filled. In order to continue the stable operation of the plant, a dry spent fuel storage facility was built, and in 2023 the first campaign was carried out, during which 16 multipurpose dry containers were transferred in the facility, inside which 592 spent fuel elements were stored. After the campaign, radiation dose measurements were carried out at several contact points on the containers themselves, and it was determined that the measured doses were within the prescribed standards. The aim of this paper was to develop a theoretical model that describes the neutron and gamma radiation fields in the space around dry containers in a semi-empirical manner. In addition, the thermodynamic aspects of this storage method and the safety requirements that the containers and the storage facility must meet were considered.

Keywords: dry storage, spent nuclear fuel, radiation field model

PRIMJENA GIS TEHNOLOGIJE ZA SANACIJU *BROWNFIELD* LOKACIJA KOJE SADRŽE REZIDUE

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Sažetak
Brownfield lokacije su napuštena, zapuštena, neiskorištena ili onečišćena/zagađena zemljišta, napušteni, zapušteni ili neiskorišteni industrijski i trgovački objekti ili infrastruktura, odnosno zemljišta, objekti, infrastruktura koji zahtijevaju kakvu intervenciju kako bi se ponovno vratili u uporabu. *Brownfield* lokacije predstavljaju prostorni i razvojni resurs, ali zahtijevaju sanaciju koja najčešće uključuje dekontaminaciju ili čišćenje tla, čišćenje ili rušenje objekata i slične zahvate. GIS tehnologija omogućuje vođenje dobre evidencije o svim takvim lokacijama unutar države, ali olakšava i upravljanje pojedinim lokacijama, budući da se svi podaci o lokacijama mogu kvantitativno i kvalitativno prikazati korištenjem GIS tehnologije i time olakšati gospodarenje njima. Specifičan problem predstavljaju lokacije na kojima se nalaze rezidui, budući da osim prirodnih radionuklida materijali na tom tipu *brownfield* područja moguće očekivati i druga onečišćenja poput kemijski aktivnih tvari, teških metala i sl. Lokacija bivše tvornice plastike i kemijskih proizvoda, Jugovinil, Grad Kaštela, Hrvatska, jedna je od takvih lokacija, obzirom da su na njoj pronađeni prirodno radioaktivni materijali, teški metali i druga zagađivala. Dio zagađenja posljedica je odlaganja pepela i šljake nastalih spaljivanjem ugljena u termoelektrani bivše tvornice, a ostatak je vezan uz industrijske aktivnosti provođene nakon rušenja tvornice (mala brodogradilišta). GIS tehnologija omogućuje prikaz kako površinske tako i dubinske raspodjele zagađivala, odnos lokacije s ostalim topografskim značajkama, kao i geološkim, hidrogeološkim i ostalim karakteristikama područja. Time je olakšano sagledavanje stanja na lokaciji, planiranje i izvođenje sanacije.

Ključne riječi: *brownfield*, rezidui, sanacija, GIS

APPLICATION OF GIS TECHNOLOGY FOR REMEDIATION OF BROWNFIELD SITES CONTAINING NORM RESIDUES

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Abstract

Brownfield sites are abandoned, neglected, unused or contaminated/polluted terrains, abandoned, neglected or unused industrial and commercial facilities or infrastructure, or land, facilities, infrastructure that require some kind of intervention in order to be put back into use. Brownfield sites represent a spatial and development resource but require remediation that most often includes decontamination or soil cleaning, cleaning or demolition of constructions/buildings and similar interventions. GIS technology enables proper records to be kept of all such sites within the country, but also facilitates the management of individual sites, since all data on sites can be quantitatively and qualitatively displayed using GIS technology, thus facilitating their management. A specific problem is represented by sites where NORM residues are found, since in addition to natural radionuclides, other contaminants such as chemically active substances, heavy metals, etc. can be expected in materials on this type of brownfield sites. The location of the former plastics and chemical products factory, Jugovinil, City of Kaštela, Croatia, is one such site, since naturally radioactive materials, heavy metals and other pollutants were found on the location. Part of the pollution is a consequence of the disposal of ash and slag created by burning coal in the thermal power plant of the former factory, and the rest is related to industrial activities carried out after the demolition of the factory (small shipyards). GIS technology enables the display of both surface and distribution of pollutants by depth, the relationship of the location with other topographical features, as well as geological, hydrogeological and other characteristics of the area. This makes it easier to assess the situation at the location, plan and carry out remediation.

Keywords: brownfield, NORM residues, remediation, GIS

MOGUĆE POVIŠENE RAZINE PRIRODNE RADIOAKTIVNOSTI PORIJEKLOM IZ PRM ZA VRIJEME REKONSTRUKCIJSKIH GRAĐEVINSKIH RADOVA NA LOKACIJI GRADNJE NOVE KUPOLE SKLADIŠTA UGLJENA U TERMOELEKTRANI

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Sažetak
Ovaj rad se bavi očitim tehnološkim potrebama prikupljanja svih dostupnih podataka (mala meta-analiza) o do sada provedenom praćenju lokacije TPP-a i njezinih otpada, podzemnih voda i biote u vezi s ostatcima PRM rezidua i njihovim mogućim utjecajem na radnike koji izvode rekonstrukciju postrojenja gradnju novog zatvorenog spremnika za ugljen. Svi ostali okolišni stresori prisutni na novom gradilištu, a koji potječu od redovitog rada TPP-a (uključujući regulirani otpad) nisu uključeni u dozimetrijska mjerenja ili/i laboratorijsku gama spektrometrijsku analizu uzoraka tla i vode. To je bila osnova za terenski rad. Odlučeno je provesti mjerenja brzine prostorne ekvivalentne doze zračenja u okolišu metodom tragova (koji potječu od PRM-a) i utvrditi lokalno pozadinsko ionizirajuće zračenje cijelog područja (LBG). Uzeti su kvalificirani uzorci za laboratorijsku gama spektrometrijsku analizu poštujući specifične protokole uzorkovanja ovisno o dubini iskopa uzoraka. Dodatno, izrađena je magnetometarska konturna karta (matrica vrijednosti izmjerenog magnetskog polja (nT/m) širom budućeg gradilišta za zatvoreno skladište ugljena. Izvršena su dubinska radarska mjerenja sadržaja u dubini tla kako bi podržali tvrdnje da u tlu nije zakopan nikakav otpad iz proizvodnje električne energije.

Ključne riječi: brownfield, PRM residui, sanacija, GIS, magnetometerska kontura

POSSIBLE ENHANCED LEVELS OF NATURAL RADIOACTIVITY ORIGINATING FROM NORM WHILE PERFORMING THE CONSTRUCTION WORKS AT THE SITE OF NEW COAL STORAGE DOME OF THE THERMAL POWER PLANT

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Abstract

This paper deals with the obvious technological need to gather all possible data (small meta-analysis) of the, till today, performed monitoring of the TPP site and it´s wastes, underground waters and biota regarding NORM residua and possible occupational impact to workers performing construction of a new coal Storage Dome.

All other environmental stressors present at the new construction site and originating from regular TPP operation (including regulated waste) are not in the scope of the dosimetric measurements and/or laboratory gamma spectrometric analysis collected soil and water samples. This was the basis for the field work. The decision was to perform dosimetry of ambient equivalent dose rate trace measurements of ionizing radiation (originating from NORM) and to establish the local background radiation of the whole site (LBG). Samples for laboratory gamma spectrometric analysis were contracted to be delivered by client after they were sampled at the site obeying the specific basic depth depending sampling protocol given by IMROH. Additionally, the magnetometer contour map (matrix of magnetic field values (nT/m) across the future coal storage dome construction site and radar depth of soil measurements were done to support the statements that there in the soil no production waste was buried.

Keywords: brownfield, NORM residues, remediation, GIS, magnetometer contour

GOSPODARENJE RADIOAKTIVNIM OTPADAOM NA EUROPSKOM SPALACIJSKOM IZVORU NEUTRONA U LUNDU

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Sažetak
Europski spalacijski izvor (ESS) zajednički je znanstvenoistraživački projekt 13 europskih država, uključujući zemlje domaćine Švedsku i Dansku. Cilj projekta je izgradnja naprednog izvora neutrona velike snage. U ovom radu dan je kratak pregled i opisano trenutno stanje projekta; test i puštanje u pogon cijelog linearnog akceleratora (protonski snop snage 12,5 kW i energije 870 MeV) planirani su za proljeće 2025., prvi neutroni očekuju se krajem 2025. (protonski snop na volframsku metu, snaga protonskog snopa 2 MW, energija protona 870 MeV). Kratko je predstavljen i švedski kontekst upravljanja nuklearnim i nenuklearnim radioaktivnim otpadom.
U radu su predstavljeni neki od problema i planirana rješenja u gospodarenju radioaktivnim otpadom koje je ESS susreo u fazi planiranja i dizajna, planirane količine i vrste otpada te opis metoda obrade za svaku pojedinu klasu otpada. Opisuje se trenutni status izgradnje i testnog puštanja u rad postrojenja (RWTF) za gospodarenje niskoradioaktivnim otpadom (metalni otpad i otpadne vode) i postrojenja (ACF) za obradu i skladištenje srednje radioaktivnog otpada (metalni otpad koji potječe iz monolita i same spalacijske mete).
Posebna pažnja posvećena je planovima za transport i izazovima u pronalaženju rješenja za odlaganje nenuklearnog radioaktivnog otpada, kao i inovativnim metodama obrade (npr. inDRUM proces za obradu iskorištene mase za ionsku izmjenu).

Ključne riječi: radioaktivni otpad, spalacijski izvor enutrona, linearni akcelerator

RADIOACTIVE WASTE MANAGEMENT AT EUROPEAN SPALLATION SOURCE

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Abstract
European Spallation Source (ESS) is a pan-European project with 13 European nations as members, including the host nations Sweden and Denmark, with the aim of constructing an advanced, high-power neutron spallation source. A short description of the project is given with the focus on the current status; the commissioning of the whole accelerator (proton beam to the dump, 12.5 kW, 870 MeV) beeing planned for the spring 2025 and first neutron are expected in the fall 2025 (proton beam to the target, 2 MW, 870 MeV).
As introduction, an overview of the Swedish system for the radioactive waste management is provided.
This work presents plans for radioactive waste management at ESS, and provides foreseen amounts and types of waste, as well as a description of the handling methods. It includes the handling on-site, and transport to external waste treatment facilites and interim storage sites. Radioactive Waste Treatment Facility (RWTF) for management of low-level wastes (metallic wastes and radioactive water treatment) and Active Cell Facillity (ACF) for intermediate-level radioactive waste (metallic waste originating from target monolith) are described.
A special attention is given to clearance of radioactive waste and to innovative tretment methods (e.g. inDRUM process for treatment of spent ion exchange resin).

Keywords: radioactive waste, non-nuclear radioactive waste, accelerator, spallation source

DOZIMETRIJA ZRAČENJA

RADIATION DOSIMETRY

ENERGIJSKA I KUTNA OVISNOST ODZIVA RPL STAKLENOG DOZIMETRA TIPA GD-352M

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Sažetak

Radiofotoluminiscentni (RPL) stakleni dozimetri su zbog svojih izvrsnih dozimetrijskih svojstava sve češće u upotrebi u dijagnostičkoj radiologiji i radioterapiji. RPL dozimetri (serija GD-300) sastoje se od štapićastog detektora od fosfatnog stakla dopiranog s Ag koji se nalazi u plastičnom držaču sa (GD-352M) ili bez (GD-302M) filtera. Filter od kositra i olova služi za kompenziranje energijske ovisnosti odziva RPL stakla na nižim energijama (<100 keV) što čini GD-352M pogodnim za korištenje u dijagnostičkoj radiologiji ili mjerenju doza u područjima gdje se očekuje i prisutnost nižih energija kao npr izvan ciljnog volumen u radioterapiji. U ovim primjenama zračenje može doći iz širokog raspona kuteva i energija koji nam nisu uvijek unaprijed poznati. Stoga je od iznimne važnosti istražiti kutnu i energijsku ovisnost odziva RPL dozimetra GD-352M u keV-skom rasponu energija što je cilj ovog rada. U tu svrhu, u Sekundarnom standardnom dozimetrijskom laboratoriju (SSDL) Instituta Ruđer Bošković, RPL dozimetri GD-352M zračeni su u zraku na 1m udaljenosti kalibracijskim izvorom Cs-137 Hopwell Designes G10-2-2600-M (kružno polje Ø20 cm) te na rendgenskom uređaju Hopewell X82 (kružno polje Ø10 cm) koristeći kvalitete zračenja N-serije (ISO 4037). Za određivanje energijske ovisnosti, napravljena su zračenja kvalitetama od N-20 do N-150 (16,3 – 118 keV). Za utvrđivanje kutne ovisnosti, napravljena su zračenja korištenjem izvora Cs-137 te kvalitetama N-40 i N-60 za kuteve od -90^o do +90^o te za kvalitetu N-120 na kutevima od 0^o do +90^o . Preliminarni rezultati dosadašnjih zračenja za energijsku ovisnost ukazuju na dobro slaganje relativnog odziva GD-352M za kvalitete od N-60 do N-150 s obzirom na Cs-137. Za N-40 uočeno je povećanje odziva dok je za kvalitete N-20 do N-30 uočeno značajno smanjenje odziva sa smanjenjem srednje energije spektra X-zračenja. Za N-40, N-60 i N-120 preliminarni rezultati ukazuju na postojanje kutne ovisnost odziva dozimetra GD-352M za kuteve od ±45^o i veće. Za Cs-137 kutna ovisnost dozimetra je manje izražena. Ovi preliminarni rezultati ukazuju na potrebu za korekcijama u slučaju zračenja energijama manjim od 50 keV i/ili u slučajevima kada zračenje dolazi pod kutevima ±45^o i većim. Daljnji koraci u istraživanju uključivati će testiranje na RQR, RQT i RQM kvalitetama zračenja te zračenja u fantomima.

Literatura:

[1] HRN EN ISO 4037-1,2,3:2021 - Radiološka zaštita -- X i gama referentno zračenje za umjeravanje dozimetara i dozatora i za određivanje njihovog odziva kao funkcije energije fotona

Ključne riječi: RPL dozimetri, energijska ovisnost, kutna ovisnost

ENERGY AND ANGULAR DEPENDENCE OF RPL GLASS DOSIMETER RESPONSE, TYPE GD-352M

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Abstract
Due to their excellent dosimetric properties, radiophotoluminescent (RPL) glass dosimeters are being more frequently used in diagnostical radiology and radiotherapy. RPL dosimeters (GD-300 series) consist of a rod-shaped phosphate glass doped with Ag encased in a plastic holder with (GD-352M) or without (GD-302M) filter. The filter made out of tin and lead is used to compensate for the energy dependence of the RPL glass response at lower energies (<100 keV). This makes the GD-352M appropriate for use in diagnostic radiology and generally in dose measurements where it is expected to have lower energy X-ray contribution, such as in out-of-field region in radiotherapy. In these applications, the radiation can come from a wide range of angles and with energies that are not always known. Therefore, it is of great importance to study the angular and energy dependence of the GD-352M response in the keV energy range, which is the goal of this work. To accomplish this, at the Secondary Standard Dosimetry Laboratoy at Ruđer Bošković Institute, RPL dosimeters GD-352M were irradiated free in air at a distance of 1 m with a calibration source Cs-137 Hopwell Designes G10-2-2600-M (circular field Ø20 cm) as well as with the Hopewell X82 X-ray irradiator system (circular field Ø10cm filed) using the N- series qualities (ISO 4037). So far, to determine the energy dependence, irradiations have been done using the N-20 to N-150 (16.3 – 118 keV) radiation qualities. For the angular dependence, irradiations have been done using the Cs-137 and the N-40 and N-60 qualities for angles from - 90^o to + 90^o and the N-120 for angles from 0^o to + 90^o. The preliminary results of these irradiations show that, for the energy dependence, there is a good response of the GD-352M for N-60 to N-150 qualities relative to Cs-137. For the N-40 quality there is an overresponse while for the N-20 to N-30 qualities an under response with the decrease of the mean energy of the X-ray spectrum is observed. For the N-40, N-60, and N-120 qualities, the preliminary results indicate the existence of an angular dependence for angles of ±45^o or higher. For the Cs-137 the angular dependence is less pronounced. These preliminary results point out the need for corrections if dosimeters are used in conditions where radiation energy is below 50 keV and/or it is coming at angles of ±45^o or higher. The next steps of this research should include testing for RQR, RQT, and RQM radiation qualities as well as in phantom measurements.

References:
[1] HRN EN ISO 4037-1,2,3:2021 - Radiological protection -- X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy

Keywords: RPL dosimeters, energy dependence, angular dependence

USPOREDBA UMJERAVANJA IONIZACIJSKIH KOMORA U SNOPOVIMA KVALITETE CO-60 I FOTONSKIH SNOPOVA LINEARNIH AKCELERATORA

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Sažetak

Apsorbirana doza u vodi osnovna je veličina korištena u radioterapiji te radioterapijski centri koriste ionizacijske komorice kako bi je odredili. Kako bi osigurali točno određivanje apsorbirane doze, komorice je potrebno umjeravati s osiguranom sljedivošću do primarnog standarda. Ovaj korak najčešće osiguravaju Sekundarni Standardni Dozimetrijski Laboratoriji (SSDL) umjeravanjem u snopu izvora Co-60.

Co-60 je u prošlosti korišten kao glavni izvor za radioterapiju, no danas većina centara koristi linearne akceleratore. Akceleratori su skupi i nepraktični za većinu SSDL-a, tako da se danas i dalje većina ionizacijskih komorica umjerava u snopu kvalitete Co-60. Zbog razlike u kvalitetama, odnosno spektrima između laboratorijskih i bolničkih uvjeta postoji potreba za korekcijskim faktorom k_Q. Faktori k_Q određeni su mjerenjima s primarnim standardima i simulacijama za velik broj modela ionizacijskih komora te ovise o energiji snopa. Faktori su zatim objavljeni u međunarodnim protokolima poput IAEA TRS-398 (International Atomic Energy Agency) i AAPM TG-51 (American Association of Phsycists in Medicine).

SSDL Instituta Ruđer Bošković je, osim u standardnom snopu Co-60, umjerio sekundarni standard i u nizu fotonskih akceleratorskih snopova. Cilj ovog istraživanja bio je proučiti izvedivost umjeravanja komora direktno u snopovima akceleratora, bez uporabe faktora k_Q. U tu svrhu korišteno je 6 različitih kalibracijskih faktora sekundarnog standarda sljedivih do primarnog standarda međunarodne organizacije Bureau International des Poids et Mesures (BIPM-a) za različite $TPR_{20,10}$ vrijednosti (od 0,57 do 0,78). Kroz tih 6 točaka prilagođena je funkcija $k_Q(TPR_{20,10})$ iz protokola TRS-398, čime je određen kalibracijski faktor sekundarnog standarda za bolničke snopove ovisno o $TPR_{20,10}$-u.

Mjerenja su provedena na 3 linearna akceleratora Kliničkog bolničkog centra Zagreb (snopovi 6 MV i 18 MV) te za 4 različite ionizacijske komorice (tipa Farmer i Semiflex). Rezultati su uspoređeni s kalibracijskim faktorima dobivenim pomoću izvora Co-60 i faktora k_Q. Za komorice tipa Farmer, razlika dvije metode manja je od 0,5% dok ta razlika ide i do 1,5% kod komorica tipa Semiflex. Planiran je nastavak mjerenja na dodatnim akceleratorima uz veći broj različitih ionizacijskih komorica.

Ključne riječi: umjeravanje ionizacijskih komorica, Co-60, linearni akcelerator

COMPARISON OF IONIZATION CHAMBERS CALIBRATION IN CO-60 BEAM QUALITY AND LINEAR ACCELERATOR PHOTON BEAMS

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Abstract

Absorbed dose to water is the basic quantity used in radiotherapy, and radiotherapy centres use ionization chambers for its determination. To ensure accurate determination, the chambers need to be calibrated with traceability to the primary standard. This step is usually provided by Secondary Standard Dosimetry Laboratories (SSDL) through calibration in the Co-60 photon beam.

Co-60 was used as the main radiation source for radiotherapy in the past, but today most centres use linear accelerators. Accelerators are expensive and impractical for most SSDLs, so today, most ionization chambers are still calibrated in the Co-60 beam quality. Due to the difference in qualities, i.e. the spectra between the laboratory and hospital conditions, there is a need for a correction factor k_Q. The k_Q factors are determined using primary standard measurements and simulations for a large number of ionization chamber models and depend on the beam energy. These factors are then published in international protocols such as the IAEA TRS-398 (International Atomic Energy Agency) and AAPM TG-51 (American Association of Physicians in Medicine).

In addition to the standard Co-60 beam, SSDL of the Ruđer Bošković Institute calibrated the secondary standard in a series of photon accelerator beams. The aim of this research was to study the feasibility of chamber calibration directly in the accelerator beams, without using the k_Q factor. For this purpose, 6 different calibration factors of the secondary standard traceable to the primary standard of the international organisation Bureau International des Poids et Mesures (BIPM) were used for different $TPR_{20,10}$ values (from 0,57 to 0,78). Through those 6 points, a function $k_Q(TPR_{20,10})$ from the TRS-398 protocol was fitted, which determined the calibration factor of the secondary standard for hospital beams depending on the $TPR_{20,10}$.

Measurements were performed on 3 linear accelerators of the University Hospital Centre Zagreb (6 MV and 18 MV beams) and for 4 different ionization chambers (Farmer and Semiflex type). The results were compared with the calibration factors obtained via Co-60 and the k_Q factor. For the Farmer-type chambers, the difference between the two methods is less than 0,5%, while this difference goes up to 1,5% for the Semiflex-type chambers. The measurements on additional accelerators with a larger number of different ionization chambers are planned to continue.

Keywords: calibration of ionization chambers, Co-60, linear accelerator

ODREĐIVANJE DOZE IZVAN POLJA ZRAČENJA U ROBOTSKOJ RADIOKIRURGIJI

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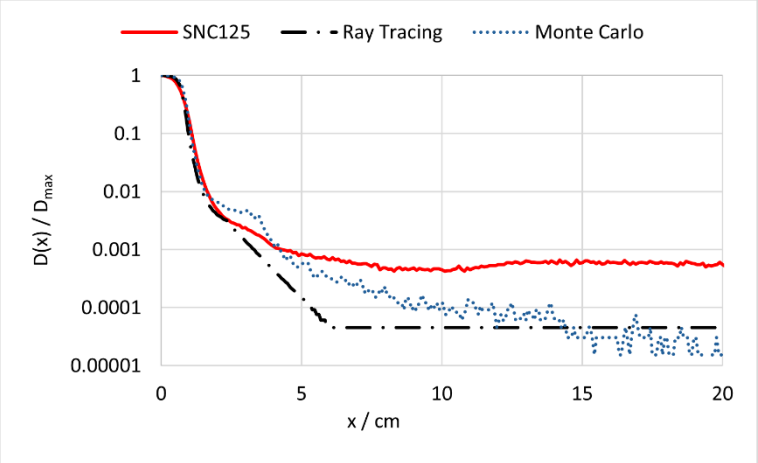
Sažetak

Robotska radiokirurgija uređajem CyberKnife (Accuray) raširena je metoda stereotaksijske radioterapije. Sustavi za optimizaciju i izračun apsorbirane doze u radioterapiji (engl. *treatment planning system*, TPS) vrlo su točni u području ciljnog volumena i okolnim organima, dok na udaljenostima od već desetak centimetara izvan polja zračenja pokazuju značajna odstupanja. Za određivanje udaljenih apsorbiranih doza stoga se koriste eksperimentalne metode ili računski, odnosno simulacijski modeli.

U ovom istraživanju mjerena je apsorbirana doza izvan polja zračenja za niz kružnih otvora



Slika 1: Usporedba rezultata mjerenja komorom SNC125 i dva algoritma TPSa za polje promjera 15 mm.

polja različitih promjera u skenirajućem vodenom fantomu (SunScan3D, SunNuclear) ionizacijskim komorama aktivnog volumena 0,125 cm^3 (SNC125, SunNuclear) i 0,6 cm^3 (Farmer, PTW). Obuhvaćeno je područje do više od 40 cm izvan ruba polja duž jedne osi. Usporedbom s profilima doze iz TPS-a za RayTracing (RT) algoritam izračuna doze, uočeno je odstupanje veće od reda veličine već na udaljenosti 6 cm od osi snopa (slika 1). Monte Carlo algoritam je pokazao nešto bolje slaganje s mjerenjima, uz razlike veće od reda veličine na udaljenosti od 15 cm. Rezultati potvrđuju da TPS značajno podcjenjuje apsorbirane doze izvan polja zračenja te se mogu iskoristiti za razvoj analitičkog modela doze izvan polja. U nastavku istraživanja mjerenja će se ponoviti u uvjetima sličnijim kliničkim, koristeći antropomorfni fantom i termoluminiscentne dozimetre.

Ključne riječi: CyberKnife, radiokirurgija, apsorbirana doza izvan polja zračenja

DETERMINATION OF OUT-OF-FIELD DOSES IN ROBOTIC RADIOSURGERY

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Abstract

Robotic radiosurgery using CyberKnife (Accuray) is a widespread stereotactic radiotherapy. Treatment planning systems (TPS) provide very accurate absorbed dose calculations in the planning target volume and surrounding organs, while they show significant deviations at distances of as little as ten centimeters outside the field. Either experimental or computational methods can more accurately determine absorbed doses outside the field.

This study aimed to experimentally determine the out-of-field dose for a series of circular field openings of varying diameter using a scanning water phantom (SunScan3D, SunNuclear) and ion chambers with an active volume of 0.125 cm^3 (SNC125, SunNuclear) and 0.6 cm^3 (Farmer, PTW). Scanning was done up to 40 cm along one axis. Comparing measurement results with the dose profiles from TPS for the RayTracing (RT) dose calculation algorithm, a deviation greater than an order of magnitude was observed already at a distance of 6 cm from the beam axis (Figure 1). The Monte Carlo algorithm showed somewhat better agreement with the measurements, with differences greater than an order of magnitude at a distance of 15 cm. Our results confirm that TPS significantly underestimates absorbed doses outside the radiation field and can be used to develop an analytical model for out-of-field dose estimation. In the future, measurements will be repeated under conditions more similar to patient treatment using an anthropomorphic phantom and thermoluminescent dosimeters.

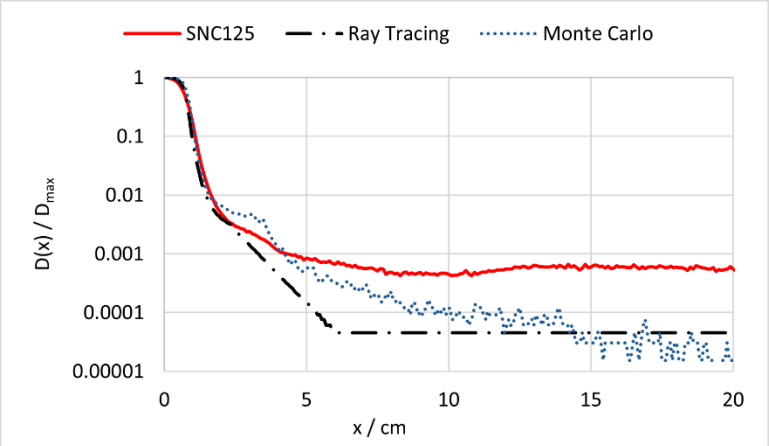

Figure 1: Comparison of SNC125 measurement and two calculation algorithms for a circular 15 mm field.

Keywords: CyberKnife, radiosurgery, out-of-field dose

SCINTILLATORS FOR IN VIVO REAL-TIME DOSIMETRY: CONVENTIONAL, FLASH AND PARTICLE THERAPY

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Abstract
Errors in radiotherapy are rare, but their consequences can be significant for the patient and may have a huge impact on public opinion due to misconceptions related to ionizing radiation. Radiotherapy processes continuously change in light of new research and emerging new technologies. Health and regulatory organizations typically recommend that in vivo dosimetry (IVD) should be routine in radiotherapy. Ideally, IVD systems should give real-time accurate and reliable multidimensional dose maps.
In SCK CEN, a prototype system has been developed based on a 2D real-time scintillation dosimeter. It minimally perturbs the treatment beam, while assessing the 2D dose rate and field shapes in real time. The system combines reusability, linear dose-rate response, and high spatial and time resolution in a single radiation detection technology that can be applied to patient-specific quality assurance (PSQA), surface dose estimation and machine QA. We present results in volumetric arc therapy (VMAT), stereotactic radiosurgery (SRS), electron ultra-high dose rate (eUHDR-FLASH Radiotherapy) and particle therapy. The pixels from the images acquired with the camera are transformed into a calibrated image space so that each pixel area corresponds to 0.1 mm x 0.1 mm and with time resolutions according to application: 20 ms (VMAT/Particle therapy), 0.6 µs (SRS) and 130 µs (UHDR). For each application, we tested: machine and PSQA in VMAT; small field dose profiles determination in SRS; and general dosimetry for pre-clinical studies in eUHDR. We used the treatment planning system (TPS) or EBT films for verification.

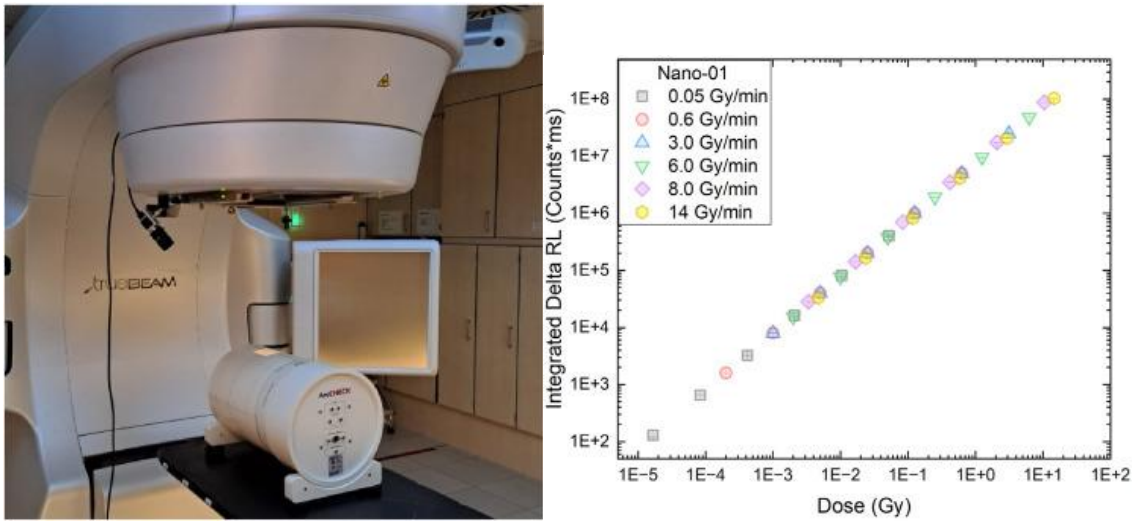

Figure 1: a) Camera placed at the head of the LINAC, facing the beam's isocentre; b) Dose response curves for integrated RL signals using different machine dose rates (from 0.05 to 14 Gy/min)

Key words: Scintillations, real time dosimetry, radiotherapy

OVISNOST RELATIVNE UČINKOVITOSTI STAKLENIH RADIOFOTOLUMINISCENTNIH DOZIMETARA O LINEARNOM PRIJENOSU ENERGIJE ZA RAZLIČITE IONSKE SNOPOVE

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Sažetak
Hadronska terapija postaje sve važnija i učinkovitija metoda liječenja onkoloških bolesnika. Pouzdana primjena radiofotoluminiscentnih (RPL) dozimetara u ionskim snopovima zahtijeva temeljito ispitivanje njihovih svojstava. Poznato je da učinkovitost luminiscentnih dozimetara ovisi o linearnom prijenosu energije (engl. Linear Energy Transfer, LET). No, za razliku od drugih vrsta luminiscentnih dozimetara, za RPL dozimetre u literaturi još uvijek nema dovoljno podataka. Prethodna istraživanja bila su usmjerena na ispitivanje ovisnosti relativne učinkovitosti RPL dozimetara o LET-u u snopovima protona [1]. Relativna učinkovitost dozimetra definira se kao omjer odziva i apsorbirane doze za danu vrstu zračenja prema istom omjeru za referentno zračenje. Cilj ovog rada bio je ispitati ovisnost relativne učinkovitosti za različite vrste iona i za što širi raspon LET-a.
Eksperimenti su provedeni u centru za ionsku radioterapiju (Heidelberg Ion Beam Therapy Center, HIT). RPL dozimetri (tip GD-302M) su zračeni u polimetil-metakrilatnom (PMMA) fantomu snopovima iona H-1, He-4, C-12, O-16. Da bi se ispitalo što više različitih vrijednosti LET-a, dozimetri su postavljani na različite dubine duž Braggove krivulje te su korištene različite početne energije snopova. Linearnost odziva na apsorbiranu dozu provjerena je za najmanju i najveću vrijednost LET-a svakog iona. Relativna učinkovitost RPL dozimetra određena je u odnosu na referentno gama zračenje izvora Co-60 u Sekundarnom standardnom dozimetrijskom laboratoriju na Institutu Ruđer Bošković. Koristeći Monte Carlo programske pakete Geant4 i PHITS, na položajima dozimetara računati su spektri LET-a i izračunate su vrijednosti LET-a usrednjavanjem po toku čestica (engl. Fluence) i dozi.
Preliminarni rezultati su pokazali linearnost doznog odziva za ispitani raspon doza i vrijednosti LET-a za sve vrste iona. Relativna učinkovitost opada s povećanjem LET-a i pokazuje ovisnost o vrsti iona. Ovo istraživanje pruža nove podatke o relativnoj učinkovitosti RPL dozimetara za ione H-1, He-4, C-12 i O-16. Posebno su značajni rezultati za He-4 i O-16 jer za njih u literaturi nema eksperimentalnih podataka.

Ključne riječi: RPL dozimetri, hadronska radioterapija, LET, metoda Monte Carlo

Reference:
[1] Majer, M. et al. Relative efficiency of radiophotoluminescent glass dosimeters in a scanning pencil proton beam. Radiat. Phys. Chem. 216 (2024), https://doi.org/10.1016/j.radphyschem.2023.111396

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DEPENDENCE OF THE RELATIVE EFFICIENCY OF RADIOPHOTOLUMINESCENT GLASS DOSIMETERS ON LINEAR ENERGY TRANSFER FOR DIFFERENT ION BEAMS

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Abstract

Hadron therapy is an increasingly important and effective method for treating cancer patients. The reliable application of radiophotoluminescent (RPL) dosimeters in ion beams requires a thorough evaluation of their properties. While it is known that the performance of luminescent dosimeters depends on linear energy transfer (LET), data on RPL dosimeters remain scarce compared to other types of luminescent dosimeters. Previous studies focused on examining the dependence of the relative efficiency of RPL dosimeters on LET in proton fields [1]. Relative efficiency is defined as the ratio of response to absorbed dose for a given type of radiation relative to the same ratio for the reference radiation. The aim of this work was to investigate the relative efficiency of RPL dosimeters for different ion types across a broader range of LET values. The experiments were conducted at the Heidelberg Ion Beam Therapy Center (HIT). RPL dosimeters (type GD-302M) were irradiated in a polymethyl methacrylate (PMMA) phantom with H-1, He-4, C-12, and O-16 ion beams. To explore a wide range of LET values, the dosimeters were placed at different depths along the Bragg curve, and the ion beams were delivered at varying initial energies. The linearity of the dose response was checked at the higest and lowest LET value for each ion. The relative efficiency of the RPL dosimeter was determined in comparison to reference Co-60 gamma radiation source at the Secondary Standard Dosimetry Laboratory of the Ruđer Bošković Institute. Using the Monte Carlo simulation packages Geant4 and PHITS, LET spectra were calculated at the dosimeter positions, and fluence- and dose-averaged LET values were derived.

Preliminary results demonstrated a linear dose response across the investigated dose range and LET values for all ion types. The relative efficiency of dosimeters decreased with increasing LET and showed a clear dependence on ion type. This study provides new data on the relative efficiency of RPL dosimeters for H-1, He-4, C-12, and O-16 ions. The results for He-4 and O-16 are particularly significant, as no experimental data for these ions are currently available in the literature.

Key words: RPL dosimeters, hadron radiotherapy, LET, Monte Carlo method

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SMANJENJE PROFESIONALNE IZLOŽENOSTI RADNIKA NA DOZIMETRIJSKOM NADZORU KOD INSTITUTA ZA MEDICINSKA ISTRAŽIVANJA I MEDICINU RADA U PERIODU OD 2020. DO 2025. GODINE

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Sažetak

U periodu od početka 2020. do kraja 2024. godine došlo je do općenitog smanjenja profesionalne izloženosti (doze veće od 0.08 mSv za Hp(10), doze veće od 4.2 mSv za Hp(0.7)) kod izloženih radnika. Povećanje profesionalne izloženosti vidljivo je kod vrhunca korona krize a nakon što je kriza prošla nastavlja se trend pada profesionalne izloženosti. Pretpostavkom da razdvojimo djelatnosti u četiri bitne kategorije (medicina, industrija, znanost, sigurnost) najveće smanjenje doza je u kategoriji sigurnosti gdje čak najveći dio radnika koji rade s uređajima koji proizvode ionizirajuće zračenje nije niti pod dozimetrijskim nadzorom zbog dugogodišnjih rezultata dozimetrijskog nadzora gdje su uvijek doze bile ispod bilo kakve profesionalne ozračenosti. Pod dozimetrijskim nadzorom u sigurnosti ostali su samo djelatnici MUP-RH. U znanosti također padaju zaprimljene doze. Industrija ima smanjene doze jer je djelatnost takva da je došlo do smanjenja obujma poslova pa isto tako nema zabilježenih doza, osim u izuzetno rijetkim situacijama. U medicini intervencijska radiologija, kardiologija, neuroradiologija su jedine kod kojih se još uvijek znaju zabilježiti bitne doze zbog naravi posla (izloženi radnici nalaze se u blizini snopa zračenja za vrijeme rada). U nuklearnoj medicini izloženi radnici rukuju s otvorenim izvorima te istovremeno se nalaze u blizini pacijenata koji su zaprimili otvoreni radioaktivni izvor. Ostala radna mjesta u medicini uspjela su smanjiti doze na minimum zbog adekvatne količine sredstava za zaštitu od zračenja i dobrog planiranja a još k tome tehnologija napreduje u dobrom smjeru.

Kroz rezultate, u zadnjih pet godina, vidi se trend smanjenja profesionalne izloženosti, što je rezultat dobre prakse prilikom korištenja izvora ionizirajućeg zračenja te dobrim planiranjem prostorija i zaštite od zračenja gdje se ti izvori nalaze.

Ključne riječi: Profesionalna izloženost, Smanjene zaprimljenih doza

DECLINE IN PROFESSIONAL EXPOSURE FOR WORKERS MONITORED BY INSTITUTE FOR MEDICAL RESEARCH AND OCCUPATIONAL HEALTH IN PERIOD OF FIVE YEARS FROM 2020. TO 2025.

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Abstract

In the period from the beginning of 2020 to the end of 2024, there was a general decrease in professional exposure (doses greater than 0.08 mSv for Hp(10) and doses greater than 4.2 mSv for Hp(0.07)) to workers. Assuming that we separate the activities into four important categories (medicine, industry, science, safety), the best results in dose reduction are definitely in the safety category, where even the largest part of workers who work with devices that produce ionizing radiation are not even being monitored due to the results of long-term dosimetric monitoring where doses have always been below any occupational exposure. Only employees of the MIA of the Republic of Croatia remained on dosimetric monitoring. In science, possible doses received are also decreasing rapidly. Industry also has reduced doses, because the volume of work has decreased, so there are also no doses except in extremely rare situations. In medicine, interventional radiology, cardiology, neuroradiology are the only departments where significant doses are still recorded due to the nature of the work (exposed workers are near primary x-ray beam). Nuclear medicine workers are handling open sources and also are in contact with patients who received open sources. Other medical workplaces have managed to keep doses to a minimum due to the large amount of radiation protection equipment and good planning and advances in technology.

The results, over the last five years, show a good trend in decline of received doses, which is the result of good practice in the use of ionizing radiation sources and good planning of rooms and radiation protection where these sources are located.

Key words: Professional exposure, Registered dose lowering

ISKUSTVA I IZAZOVI USPOSTAVE NOVOG DOZIMETRIJSKOG SUSTAVA ZA OPTIČKI STIMULIRANU LUMINISCENCIJU

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Tehnologija optički stimulirane luminiscencije (OSL) pokazala se kao dobar kandidat za unaprijeđenje dozimetrije i zamjenu tehnologije temeljene na termoluminiscenciji (TLD). OSL dozimetri sadrže materijale (kao što je aluminijev oksid ili slične spojeve) koji pohranjuju energiju kada su izloženi ionizirajućem zračenju. Kada je dozimetar stimuliran svjetlom (obično plavom ili zelenom svjetlošću), pohranjena energija se oslobađa u obliku luminiscencije, a intenzitet svjetlosti proporcionalan je dozi zračenja. OSL dozimetri bi trebali osigurati mogućnost višestrukog očitanja doze, bolji energijski odziv te brže vrijeme očitavanja, za razliku od TLD dozimetara koji se mogu očitati samo jednom.
Povodom modernizacije dozimetrijskih procesa na Institutu za medicinska istraživanja nabavljen je novi OSL dozimetrijski sustav, koji se trenutno osposobljava za potrebe stručno-tehničkog servisa. Sama uspostava OSL dozimetrijskog sustava pokazala se izazovnom, budući da su se izrada samog uređaja (poput mehaničkih komponenti i automatizacije) te sofverska rješenja pokazali neučinkovitim i manjkavim za dozimetrijske procese u kojima se koristi veliki broj (500 i više) dozimetara. Kako se sustav oslanja na nova tehnološka rješenja, za koje se pokazalo da nisu u potpunosti optimizirana, komunikacija s korisničkom podrškom je bila neizostavni dio procesa. Iz tih razloga je sama upotreba sustava u stručno-tehničkim procesima bila limitirana zbog sporosti rješavanja nastalih poteškoća.
Ova iskustva pokazuju kako je stariji, ali robusniji i optimizirani dozimetrijski sustav baziran na TLD tehnologiji i dalje prihvatljivija opcija za sustave s velikim brojem dozimetara, kakav je već u dugotrajnoj primjeni na Institutu.

Ključne riječi: OSL, TLD, Dozimetrijski sustav, Mehanika, Programska podrška

EXPERIENCES AND CHALLENGES WHEN ESTABLISHING A NEW DOSIMETRY SYSTEM FOR OPTICALLY STIMULATED LUMINESCENCE

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Optically stimulated luminescence (OSL) technology has emerged as a good candidate to replace and improve thermoluminescence (TLD) based dosimetry. OSL dosimeters contain materials (such as aluminum oxide or similar compounds) that store energy when exposed to ionizing radiation. When the dosimeter is stimulated by light (usually blue or green light), the stored energy is released in the form of luminescence, and the intensity of the light is proportional to the radiation dose. OSL dosimeters should provide the possibility of multiple dose readings, better energy response, and faster reading times, unlike TLD dosimeters that can only be read once.

In connection with the modernization of dosimetry processes at the Institute for Medical Research, a new OSL dosimetry system was purchased, which is currently being set up for the needs of technical service. The process of establishing the OSL dosimetry system itself proved to be challenging, since the design of the device itself (such as mechanical components and automation) and software solutions proved to be inefficient and deficient for dosimetry processes in which a large number (500 and more) of dosimeters are being used. As the system relies on new technological solutions, which have proven to be not fully optimized, communication with user support was an indispensable part of the process. For these reasons, the use of the system in professional and technical processes was limited due to the slowness of resolving the problems that arose.

These experiences show that older, but more robust and optimized dosimetry system based on TLD technology are still a more acceptable option for systems with a large number of dosimeters, as has already been in long-term use at the Institute.

Keywords: OSL, TLD, Dosimetry system, Mechanics, Software

BIOLOŠKI UČINCI ZRAČENJA

BIOLOGICAL EFFECTS OF RADIATION

EFFECTS OF X-RAY ON THE HEMATOLOGICAL PARAMETERS IN INTERVENTIONAL CARDIOLOGY

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Abstract

Interventional radiology procedures have experienced an increase in frequency in recent years. Coronary angiography is the most common angiographic procedure. However, workers involved in interventional procedures have high effective doses and extremity doses can reach the regulatory limits. The hematopoietic system is highly sensitive to radiation and peripheral blood count may serve as a good biological indicator to assess the biological damage.

The aim of this study was to identify the effect of X-ray occupational exposure on the hematological parameters in interventional cardiology.

The cross-section study included 64 male examinees classified into two groups: 33 interventional cardiologists and 31 examinees of the control group with a mean of age 41 years. The average annual effective dose to monitored cardiologists was 2.01 mSv (0.76 - 5.53mSv) and they were exposed to radiation for an average of 12 years. Hematological parameters were obtained by examining peripheral venous blood in a Beckman Counter HMX device.

The investigated groups do not differ between each other in the mean number of erythrocytes, platelets and leukocytes and these values are within the limits of the reference values. Although there was no significant difference in the average platelet count, lower values were noted in interventional cardiologists ($F= 0.739$; $p= 0.39$). The difference was not found in the absolute, as well as in the relative number of neutrophils, eosinophils and monocytes. Although the difference in the absolute number of lymphocytes is not significant among the groups, there is a significant difference in the relative number of lymphocytes ($F= 1.216$; $p= 0.04$). Among interventional cardiologists, a significant negative correlation was found between the annual effective dose and the absolute number of lymphocytes ($r= -0.377$; $p=0.031$). This was similar to what was reported by other authors. Many researchers did not compare atypical lymphocyte percentages between the two groups. All studied workers had only complete blood counts but no cell morphology examination.

The obtained results require periodical hematopoetic examination in interventional cardiologists. The further examination should be included morphological and functional examination of leucocytes and platelets.

Keywords: interventional cardiology, ionizing radiation, occupational exposure, hematological parameters

MOLEKULARNE PROMJENE UZROKOVANE GAMA ZRAČENJEM NA KRATKIM FRAGMENTIMA DNA: UVIDI IZ MULTIVARIJATNE ANALIZE I ULOGA MAGNEZIJEVIH IONA

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Sažetak

Ova studija istražuje molekularne promjene uzrokovane gama ionizirajućim zračenjem na uzorcima fragmenata kratke (15 – 50 parova baza) deoksiribonukleinske kiseline (DNA) u prisutnosti magnezijevih iona, za koje je poznato da stabiliziraju strukturu DNA. Izlaganje gama zračenju izaziva promjene u molekularnoj strukturi DNA, osobito u funkcionalnim skupinama poput karbonila (C=O), imina (C=N) i fosfatnih (PO_2) skupina, koje su ključne za stabilnost i funkciju DNA.

Infracrvena spektroskopija s Fourierovom transformacijom (engl. FTIR - *Fourier transform infrared spectroscopy)* korištena je za analizu uzoraka DNA ozračenih različitim dozama gama zračenja. Napredne multivarijatne tehnike, uključujući analizu glavnih komponenti (engl. PCA - *Principal component analysis*) i parcijalna projekcija najmanjih kvadrata (engl. PLS - *Partial least squares*), korištene su za identifikaciju spektralnih promjena ovisnih o dozi i kvantificiranje odnosa između doze zračenja i molekularnih promjena. Diskriminacijska analiza pomoću potpornih vektora (engl. SVMDA - *support vector machine discriminant analysis*) primijenjena je za klasifikaciju spektralnih podataka, razlikujući ozračene i neozračene uzorke te ističući diferencijalne učinke magnezijevih iona.

Uzorci s različitim koncentracijama magnezijevih kationa pripremljeni su i ozračeni na uređaju Gamma Knife Icon apsorbiranim dozama u rasponu od 0,3 Gy do 100 Gy koristeći gama zrake Co-60. Za potrebe ozračivanja, otopina DNA bila je smještena u prilagođeni 3D ispisani umetak, izrađen od tkivu ekvivalentne plastike, korišten s Polymethyl Methacrylate (PMMA) fantomom koji je postavljen u izocentar uređaja. Neozračeni uzorci korišteni su kao referenca, a testirano je nekoliko koncentracija magnezijevih iona kako bi se procijenio njihov utjecaj na molekularne promjene DNA uzrokovane gama zračenjem.

Integralni intenziteti izračunati su za svaku dozu, otkrivajući nelinearne trendove koji ukazuju na strukturne modifikacije. PCA je korištena za smanjenje dimenzionalnosti spektralnih podataka, uspješno izolirajući varijacije povezane s dozom i identificirajući ključne spektralne regije koje pridonose promatranim promjenama. PLS regresija korištena je za povezivanje spektralnih značajki s dozom zračenja, dok su klasifikacijske metode poput SVMDA pokazale visoku prediktivnu točnost, omogućujući kvantifikaciju učinaka zračenja na molekularnoj razini.

Ključne riječi: Gama zračenje, DNA, magnezijevi ioni, FTIR spektroskopija, PCA, PLS regresija, SVMDA, multivarijatna analiza, molekularne promjene, oštećenje zračenjem.

MOLECULAR CHANGES INDUCED BY GAMMA RADIATION ON SHORT-CHAIN DEOXYRIBONUCLEIC ACID: INSIGHTS FROM MULTIVARIATE ANALYSIS AND THE ROLE OF MAGNESIUM IONS

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Abstract

This study investigates the molecular changes induced by gamma ionizing radiation on short-chain (15–50 base pairs) deoxyribonucleic acid (DNA) samples in the presence of magnesium ions, which are known to stabilize DNA structures. Gamma radiation exposure induces alterations in DNA's molecular structure, particularly in functional groups such as carbonyl (C=O), imine (C=N), and phosphate (PO_2) groups, which are critical to DNA stability and function.

Fourier Transform Infrared (FTIR) spectroscopy was employed to analyze DNA samples irradiated with varying doses of gamma radiation. Advanced multivariate techniques, including Principal Component Analysis (PCA) and Partial Least Squares (PLS) regression, were used to identify dose-dependent spectral changes and quantify the relationship between radiation dose and molecular alterations. Support Vector Machine Discriminant Analysis (SVMDA) was applied to classify spectral data, distinguishing irradiated from non-irradiated samples and highlighting the differential effects of magnesium ions.

Samples with varying concentrations of magnesium cations were prepared and irradiated with doses ranging from 0.3 Gy to 100 Gy using Co-60 beams delivered by the Gamma Knife Icon built on the Perfexion platform, a device used in brain radiosurgery. For irradiation purposes, the DNA solution was placed at the custom 3D printed insert, made of tissue-equivalent plastics, employed with the Polymethyl Methacrylate (PMMA) phantom and positioned at the device's isocentre. Non-irradiated samples were used as a reference, and several concentrations of magnesium ions were tested to evaluate their influence on gamma radiation-induced molecular changes.

Integral intensities were computed for each dose, revealing nonlinear trends indicative of structural modifications. PCA was employed to reduce the dimensionality of the spectral data, successfully isolating dose-related variations and identifying key spectral regions contributing to the observed changes. PLS regression was used to correlate spectral features with radiation dose, while classification methods such as SVMDA demonstrated high predictive accuracy, enabling the quantification of radiation effects at the molecular level.

Keywords: Gamma radiation, DNA, magnesium ions, FTIR spectroscopy, PCA, PLS regression, SVMDA, multivariate analysis, molecular changes, radiation damage

UČINAK NISKIH DOZA IONIZIRAJUĆEG ZRAČENJA NA STANIČNI CIKLUS I OKSIDACIJSKI STRES KOD MEZENHIMSKIH MATIČNIH STANICA ŠTAKORA

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Sažetak
Izloženost ljudi niskim dozama ionizirajućeg zračenja u stalnom je porastu, što je osobito izraženo u području medicine sve većom primjenom različitih dijagnostičko-terapijskih postupaka. Sam mehanizam djelovanja kao i potencijalni rizici za ljudsko zdravlje pri tome su još uvijek nedovoljno poznati. Cilj ovog *in vitro* istraživanja bio je utvrditi biološki učinak zračenja 100 mGy na mezenhimske matične stanice (MMS) praćenjem promjena staničnog ciklusa te pojavu oksidacijskog stresa. Rezultati istraživanja provedenih 24 h nakon ozračivanja stanica ukazuju na povećanu proliferaciju, značajnu aktivnost antioksidacijskih enzima katalaze (engl. CAT - catalase) i glutation peroksidaze (engl. GPx) te povećani udio jednolančanih DNA lomova. Dobiveni rezultati pridonose boljem razumijevanju promjena koje nastaju uslijed izloženosti niskim dozama zračenja te imaju potencijal za unaprjeđenje korištenja MMS u medicinske svrhe.

Ključne riječi: *in vitro*; proliferacija; antioksidacijska obrana; DNA oštećenja

EFFECT OF LOW DOSES OF IONIZING RADIATION ON CELL CYCLE AND OXIDATIVE STRESS IN RAT MESENCHYMAL STEM CELLS

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Abstract

Human exposure to low doses of ionizing radiation is constantly increasing, which is particularly evident in the field of medicine with the increasing use of various diagnostic and therapeutic procedures. The exact mechanism of action itself as well as the potential risks to human health are still insufficiently known. The aim of this *in vitro* study was to determine the biological effect of 100 mGy radiation exposure on mesenchymal stem cells (MSCs) by monitoring cell cycle changes and the occurrence of oxidative stress. Research results conducted 24 hours after irradiation indicate increased cell proliferation, significant activity of the antioxidant enzymes catalase (CAT) and glutathione peroxidase (GPx), and an increased proportion of single-stranded DNA breaks. The obtained results contribute to a better understanding of the changes that occur due to exposure to low doses of radiation and have the potential to improve the use of MSCs for medical purposes.

Keywords: *in vitro*; proliferation; antioxidant defence; DNA damage

IZOLACIJA, DIFERENCIJACIJA I KARAKTERIZACIJA MEZENHIMSKIH MATIČNIH STANICA ŠTAKORA KAO NOVI MODEL MJERENJA BIOLOŠKIH UČINAKA IONIZIRAJUĆEG ZRAČENJA NISKE DOZE

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Sažetak

Mezenhimalne matične stanice (MMS), također poznate kao mezenhimalne stromalne stanice, vrsta su multipotentnih stanica koje se nalaze u koštanoj srži s jedinstvenom važnom ulogom u homeostazi. Njihova primarna uloga je održavanje i popravak koštanog tkiva, što se postiže diferencijacijom u hondrocite, osteocite i adipocite. Također se mogu diferencirati u druge stanice mezodermalne loze. MMS lokalizirane su blizu krvnih žila *in vivo*, no također su izolirane i iz raznih drugih tkiva – masnog tkiva, koštane srži, mišića, korijena zuba i pupkovine. Razvijene su različite tehnike izolacije stanica, kao što je razvrstavanje stanica putem antitijela obilježenih fluorescentnim bojama ili magnetskim zrncima. Izvorna metoda izolacije MMS prianjanjem na plastične površine još uvijek je najbolji postupak izolacije stanica. MMS su izolirane iz odraslih muških Wistar štakora starih 4 mjeseca. Bedrene kosti su isprane u izopropanolu i sterilnoj fiziološkoj otopini, te su izolirane stanice koštane srži. Stanice su resuspendirane u DMEM mediju, nasađene i uzgajane 2 tjedna u tikvici stanične kulture na 37°C i 5% CO_2. Nakon uzgoja MMS su inkubirane u mediju za diferencijaciju u adipocite i osteocite kako bi se utvrdio njihov potencijal diferencijacije i potvrdila pluripotentnost ekstrahiranih stanica. Nakon 21-dnevne inkubacije s odgovarajućim medijem, stanice su obojane radi vizualizacije i kvantifikacije diferenciranih stanica.

Ključne riječi: mezenhimalne matične stanice, imunocitokemija, CD29, CD90

ISOLATION, DIFFERENTIATION AND CHARACTERIZATION OF RAT MESENCHYMAL STEM CELLS AS A NEW MODEL OF BIOLOGICAL EFFECTS OF IONIZING LOW-DOSE RADIATION

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Abstract
Mesenchymal stem cells (MSCs), also known as mesenchymal stromal cells, are a type of multipotent cells residing in bone marrow with uniquely important roles in homeostasis. Their primary role is maintenance and repair of skeletal tissue, which is achieved by differentiation into chondrocytes, osteocytes and adipocytes, also they are able to differentiate into other cells of mesodermal lineage and hematopoietic stem cells. MSCs were shown to localize close to blood vessels in vivo, however, they were also isolated from various other tissues – adipose, bone marrow, muscle, tooth root and umbilical cord. Although different techniques for cell isolation have been developed since their initial discovery, such as cell sorting via antibodies labelled with fluorescent dyes or magnetic beads, the original method of MSC selection by adherence to plastic surfaces is still an often used, cost-effective procedure. MSCs were extracted from adult 4-month-old male Wistar rats rat femurs. Femurs were extracted from hind limbs and cleaned from remaining muscle and tissue. Cleaned femurs were rinsed in isopropanol and sterile phosphate-buffered saline and bone marrow cells were isolated from the femur. Cells were re-suspended in DMEM medium, seeded and cultured for 2 weeks in a cell culture flask at 37° C and 5% CO2. After Cultured MSC were incubated with media for adipocyte and osteocyte differentiation to ascertain their differentiation potential and confirm the pluripotency of extracted cells. After 21-day incubation with appropriate media, cells were stained for visualization and quantification of differentiated cells.

Keywords: mesenchymal stem cells, immunocytochemistry, CD29, CD90

IZLOŽENOST STANOVNIŠTVA ZRAČENJU

PUBLIC EXPOSURE

HOW THE ANNUAL DOSE OF NATURAL BACKGROUND IN SLOVENIA INCREASED FROM 2.4 mSv TO 6.0 mSv

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Abstract

The value of 2.4 mSv was used in Slovenia for almost 35 years (from 1989) as the annual dose of natural background of ionising radiation. Since that time many parameters that contribute to the dose of the natural background changed. First of all there are comprehensive measurement data on natural radioactivity from radioactivity monitoring in Republic of Slovenia and Off-site radiological monitoring of the Krško Nuclear Power Plant. From 2006 Ministry of Health begun program of radon measurement in schools and kindergardens which was in 2018 extended with measurements in private buildings. The International Commission on Radiological Protection in its Publication 115 (ICRP Publication 115) increased the dose conversion factor for radon by almost factor 2 also. Due to this new and comprehensive data we proposed Ministry of Health to finance the project on new calculation of natural background in Slovenia. The project was carried out in 2023. Taking into account all the contributions (natural radioactivity in air, food and water, cosmic radiation, radon concentration in air, external radiation, population density) the average annual dose of natural background in Slovenia was estimated to 6.0 mSv with the maximum annual dose in most exposed municipality Mirna Peč of 17.8 mSv and minimum annual dose of 2.0 mSv in Piran. The contributions to annual dose due to natural background in Slovenia are shown in Figure 1.

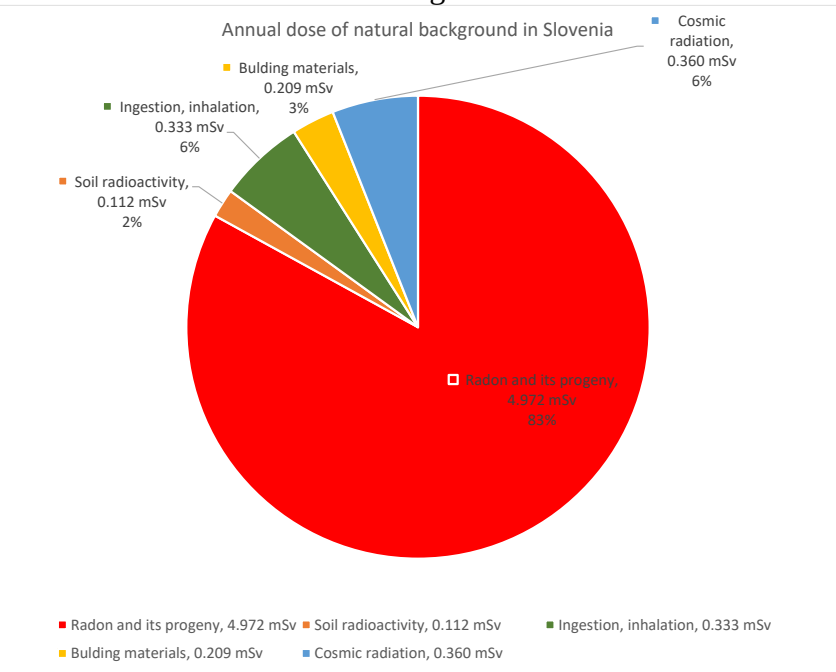

Figure 2: Contributions to average annual natural bckground dose in Slovenia

Key words: natural background, radioactivity, radon, dose

PRAĆENJE ^{90}Sr U STOČNOJ HRANI U PERIODU OD DESET GODINA (2013-2023)

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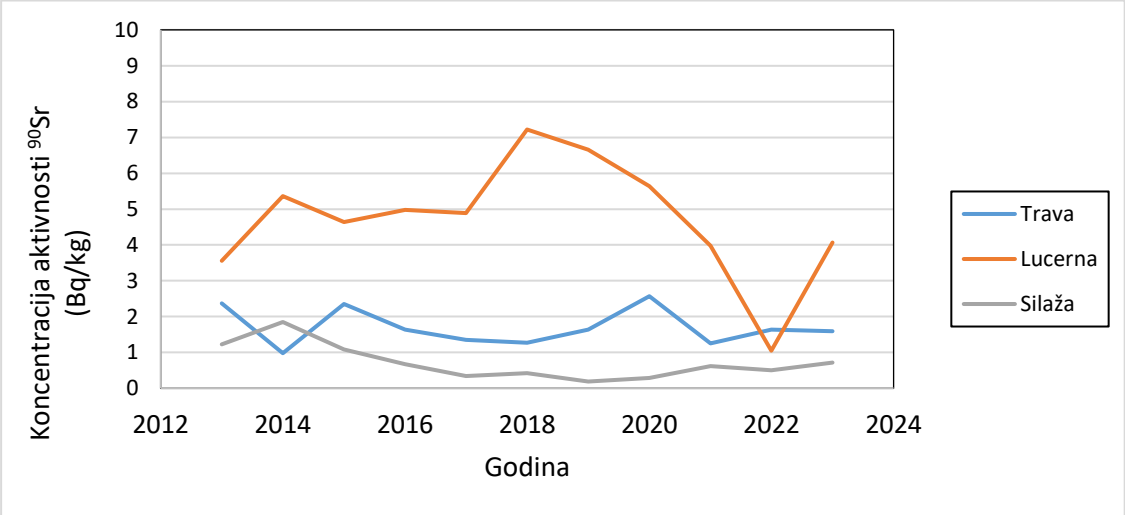
Sažetak
Prisutnost radionuklida u stočnoj hrani predstavlja potencijalni rizik za zdravlje životinja i ljudi zbog njihove bioakumulacije u hranidbenom lancu. Radionuklid stroncija ^{90}Sr je nusproizvod nuklearnih nesreća i eksplozija i nekih industrijskih procesa, a posebno je važan zbog svog relativno dugog vremena poluraspada te svoje kemijske i metaboličke sličnosti s kalcijem zbog čega se taloži u kostima i mlijeku. Cilj ovog rada je prikazati rezultate mjerenja stroncija u uzorcima stočne hrane (trava, lucerna i silaža) skupljenih u desetogodišnjem periodu (2013. – 2023.) u Slavoniji.
Za analizu ^{90}Sr uzorak se suši na 105 ºC, a zatim spaljuje na 650 ºC. Alikvot pepela otopi se u dušičnoj kiselini, te se standardnom metodom ekstrakcije TBP-om uz dodatak itrijevog nosača određuje koncentracija aktivnosti ^{90}Sr. Određivanje se temelji na radioaktivnoj ravnoteži ^{90}Sr i ^{90}Y. Nakon provedene kemijske analize, dobiveni uzorak ^{90}Y se mjeri u antikoincidentnom beta brojaču niskog osnovnog zračenja (modeli RISØ GM-25-5 i RISØ GM-25-5A). Vrijeme mjerenja uzorka je minimalno 84000 sekundi.
Koncentracija ^{90}Sr u stočnoj hrani tijekom desetogodišnjeg perioda praćenja prikazana je na Slici 1. Koncentracije aktivnosti ^{90}Sr kretale su se od 0,19 Bq/kg u silaži do 7,2 Bq/kg u lucerni.



Slika 3: Koncentracije aktivnosti ^{90}Sr u travi, lucerni i silaži u Slavoniji.

Iako su izmjerene razine niske, rezultati pokazuju da se koncentracija aktivnosti ne smanjuje vremenom kao što je to vidljivo u drugim uzorcima iz okoliša, Ipak, kontinuirano praćenje radioaktivnosti u okolišu je potrebno kako bismo bili sigurni da razine radioaktivnosti ostaju niske i u prihvatljivim vrijednostima za ljude, životinje i biljke.

Ključne riječi: radioaktivnost, praćenje, stočna hrana, stroncij

TEN YEAR MONITORING (2013-2023) OF ^{90}Sr IN FEED IN CROATIA

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Abstract
The presence of radionuclides in agricultural feed poses potential risks to both animal and human health through bioaccumulation in the food chain. Strontium radionuclide ^{90}Sr is a by-product of nuclear fallout and industrial processes and is of particular concern due to its long half-life and chemical similarity to calcium, leading to its incorporation into bones and milk. This study focuses on the systematic measurement and analysis of ^{90}Sr in feed samples (grass, clover, and silage) collected over a ten-year period (2013–2023) at Slavonija region of Croatia. For ^{90}Sr analysis, the samples were dried at 105 °C, milled and ashed at 650 °C. An aliquot of ash is dissolved in nitric acid, and ^{90}Sr is determined by the standard TBP extraction method with the addition of yttrium carrier based on radioactive balance with ^{90}Y, which is measured in an low background anti-coincidence beta counter (models RISØ GM-25-5 and RISØ GM-25-5A). The sample measurement time is at least 84000 seconds.
The results provide insight into 10-year levels of radioactivity levels in feed and are shown in Figure 1. The activity concentrations of ^{90}Sr were in the range 0.19 Bq/kg in silage samples to 7.2 Bq/kg in clover samples.

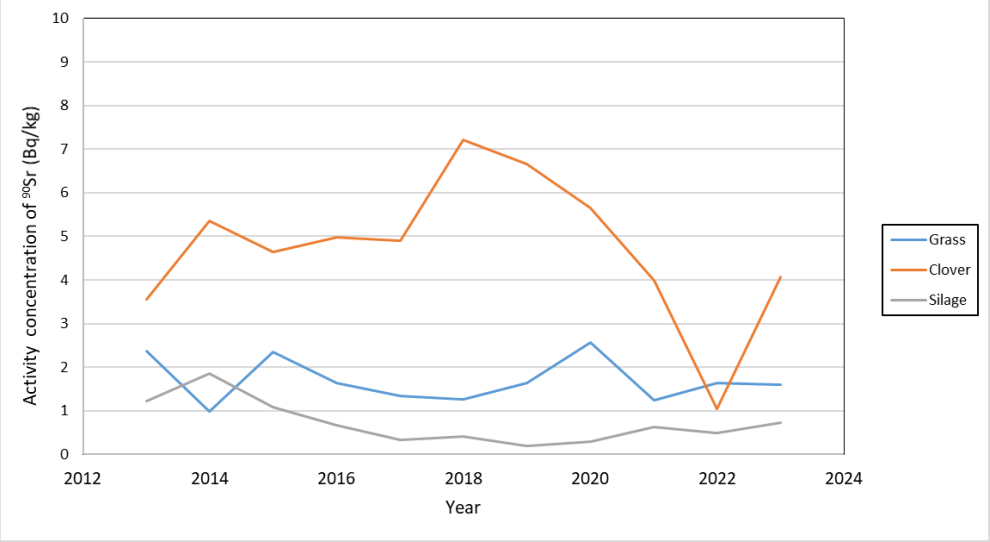

Figure 4: Activity concentrations of ^{90}Sr in grass, clover and silage from Slavonija region.

Although the levels are low, the monitoring results show that the activity concentration is not decreasing as seen usually in other environmental samples. Continuous monitoring of radioactivity in environment is necessary to ensure that radiation levels stay low and within safety limits for humans, animals and plants.

Key words: radioactivity, monitoring, feed, strontium

ZAŠTITA OD ZRAČENJA U MEDICINI

RADIATION PROTECTION IN MEDICINE

RADIOTERAPIJA IONSKIM SNOPOVIMA – TRENUTNO STANJE

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Sažetak

Počeci radioterapije vezani su za fotonske snopove. Tek krajem 80tih godina 20tog stoljeća počela je izgradnja protonskih centara, a krajem stoljeća krenulo se i s drugim ionskim snopovima (1). Trenutno se u redovitoj kliničkoj praksi koriste snopovi protona te iona ugljika, ali postoji još kandidata koji su već primijenjeni za liječenje pacijenata ili se to očekuje u budućnosti.
Velika prednost ionskih snopova u odnosu na fotone i elektrone za primjenu u radioterapiji je njihova specifična raspodjela apsorbirane doze po dubini te radiobiološka učinkovitost. S druge strane, sekundarne čestice nastale u nuklearnim reakcijama upadnih iona s materijom predstavljaju veću opasnost za zdravo tkivo izvan ciljnog volumena od sekundarnih fotona koji dominiraju u klasičnoj fotonskoj radioterapiji. Stoga je prije primjene važno kvantificirati i optimizirati dobrobit i rizik. Posebno osjetljiva skupina pacijenata za koju je to važno su djeca i trudnice. Metode koje se koriste za procjenu doza sekundarnog zračenja su računalne simulacije te mjerenja i svaka predstavlja poseban izazov.
U prvom dijelu predavanja dat će se opći uvod u terapiju ionskim snopovima, a u drugom pregled znanstvenih aktivnosti dozimetrijske grupe Laboratorija za radijacijsku kemiju i dozimetriju na Institutu Ruđer Bošković koje su vezane za karakterizaciju radiofotoluminiscentnih dozimetara (2) te dozimetrijska mjerenja u polju sekundarnog zračenja u ionskoj radioterapiji (3).

Ključne riječi: radioterapija; ionski snopovi; dubinska dozna raspodjela; radiobiološka učinkovitost; sekundarno zračenje; radiofotoluminiscentna dozimetrija

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ION BEAM THERAPY – CURRENT STATE

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Abstract

The beginnings of radiotherapy are associated with photon beams. Only in the late 1980s did the construction of proton centers begin, and by the end of the century, work had also started with other ion beams (1). Currently, proton beams and carbon ions are used in routine clinical practice, but other candidates have already been applied in the treatment of patients or are expected to be in the future.
A significant advantage of ion beams over photons and electrons for application in radiotherapy is their specific depth dose distribution and radiobiological effectiveness. On the other hand, secondary particles generated in nuclear reactions of incident ions with matter pose a greater risk to healthy tissue outside the target volume than the secondary photons that dominate in classical photon radiotherapy. Therefore, it is crucial to quantify and optimize the benefits and risks before application. A particularly sensitive group of patients for whom this is important includes children and pregnant women. The methods used to assess doses of secondary radiation are computational simulations and measurements, each presenting unique challenges. The first part of the lecture will provide a general introduction to ion beam therapy, while the second part will review the scientific activities of the dosimetry group at the Laboratory for Radiation Chemistry and Dosimetry at the Ruđer Bošković Institute, related to the characterization of radiophotoluminescent dosimeters (2) and dosimetric measurements in the field of secondary radiation in ion radiotherapy (3).

Key words: radiotherapy; ion beams; depth dose distribution; relative biological effectiveness; secondary radiation; radiophotoluminescent dosimetry

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NEOPRAVDANA RADIOGRAFSKA SNIMANJA ILI KAKO KORISTITI E-GUIDE SMJERNICE U KLINIČKOJ PRAKSI

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Sažetak

Ovaj rad istražuje ulogu „e-guide“ smjernica u prepoznavanju i smanjenju neprimjerenih indikacija za radiografske snimke, s ciljem optimizacije dijagnostičkog procesa i smanjenja nepotrebne izloženosti pacijenata zračenju. Neprimjerene indikacije predstavljaju značajan izazov u radiološkoj praksi, jer mogu dovesti do nepotrebnih snimanja, povećanja troškova i potencijalne štete za pacijente.

Razvijanje e-guide smjernica omogućuje automatsko prepoznavanje takvih indikacija kroz digitalne platforme koje integriraju kliničke smjernice, preporuke temeljenje na najboljim praksama i relevantne kriterije za procjenu nužnosti radiografskih snimki. Ovaj rad analizira kako e-guide smjernice mogu podržati zdravstvene radnike u donošenju informiranih odluka, smanjujući broj snimanja koja nisu medicinski opravdana i poboljšavajući učinkovitost zdravstvene skrbi. U radu će se prikazati primjeri iz kliničke prakse.

Kroz analizu postojećih smjernica i njihovih nedostataka u prepoznavanju neprimjerenih indikacija, razmatrani su potencijali integracije e-guide sustava u svakodnevnu praksu. Osim toga, razmatrani su izazovi u implementaciji tih smjernica, uključujući potrebe za obukom zdravstvenih radnika, prilagodbu digitalne infrastrukture i osiguranje kvalitete podataka.

Rad će prikazati kako korištenje smjernica može značajno unaprijediti sigurnost pacijenata i smanjiti rizike povezane s nepotrebnim radiološkim pretragama.

Ključne riječi: e-guide, smjernice, neprimjerene indikacije, radiografske snimke, dijagnostika, zračenje, zdravstvena skrb.

NON-JUSTIFIED RADIOGRAPHIC IMAGING OR HOW TO USE E-GUIDE IN CLINICAL PRACTICE

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Abstract This work explores the role of e-guide guidelines in identifying and reducing inappropriate indications for radiographic imaging, to optimize the diagnostic process and minimize unnecessary patient radiation exposure. Inappropriate indications represent a significant challenge in radiological practice, as they can lead to unnecessary imaging, increased costs, and potential harm to patients. The development of e-guide guidelines enables the automatic identification of such indications through digital platforms that integrate clinical guidelines, best practice recommendations, and relevant criteria for assessing the necessity of radiographic exams. This paper examines how e-guide guidelines can assist healthcare professionals in making informed decisions, thereby reducing the number of medically unjustified imaging procedures and improving healthcare efficiency. This paper will present the examples from clinical practice. Through the analysis of existing guidelines and their shortcomings in recognizing inappropriate indications, the potential for integrating e-guide systems into daily practice is discussed. Additionally, the challenges in implementing these guidelines are considered, including the need for healthcare worker training, adaptation of digital infrastructure, and ensuring data quality. This work provides valuable insights into the development of tools that can significantly enhance patient safety and reduce the risks associated with unnecessary radiological procedures.

Keywords: e-guide, guidelines, inappropriate indications, radiographic imaging, diagnostics, radiation, healthcare.

OPRAVDANOST RADIOLOŠKIH PRETRAGA: REZULTATI PROJEKTA EU-JUST-CT (EUROPEAN CO-ORDINATED ACTION ON IMPROVING JUSTIFICATION OF CT)

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Sažetak
Projekt Europske komisije EU-JUST-CT provođen je od 2021-2024.godine u sedam zemalja članice Europske unije. Cilj projekta je poboljšati proceduru procjene opravdanosti (justification) CT pretraga u EU kroz koordiniranu akciju. U projektu su sakupljene informacije o stanju na polju procjene opravdanosti CT pretraga u EU. Razvijena je metodologija za procjenu opravdanosti (audit) upućivanja pacijenata na CT pretrage. Izvršene je koordinirani retrogradni audit temeljem sakupljanja dokumentacije o upućivanju pacijenata na CT pretrage u sedam EU zemalja, korištenjem clinical decision support sustava i-guide kao standarda, koji je razvilo Europsko društvo radiologa u suradnji s American College of Radiology. Rezultati su pokazali iznimnu varijabilnost u sedam zemalja i bit će prikazani na predavanju. Rezultati projekta su publicirani u publikaciji Europske komisije RP 205 krajem 2024.godine.

Ključne riječi: opravdanost, CT, audit, i-guide, primjerenost

EUROPEAN CO-ORDINATED ACTION ON IMPROVING JUSTIFICATION OF CT- RESULTS OF THE EU-JUST-CT PROJECT

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Abstract
European Commission EU-JUST-CT project is a 36-month project that aimed to improve justification of computed tomography in Europe through coordinated action. It was performed from 2021-2024 in seven EU member states; Finland, Denmark, Belgium, Estonia, Hungary, Slovenia and Greece. The project has met following specific objectives: (a) Collect up-to-date information about justification of CT examinations in Europe; (b) develop a common methodology for auditing justification of CT examinations; (c) Carry out co-ordinated pilot audits of justification of CT examinations; (e) Discuss the status of justification of CT examinations with the Member States and identify opportunities for further action. The imaging referral guidelines of the ESR, embedded in the ESR iGuide, were used as a standard for the audits. The guidelines are based on the American College of Radiology Appropriateness Criteria and additional ACR Select content. The results have demonstrated huge variability in seven member states and will be presented in the lecture. The results have been published in European Commission radiation protection publication RP 205, published in October 2024.

Keywords: justification, CT, audit, i-guide, appropriateness

RAZVOJ I UNAPREĐENJE METODE ZRAČENJA CIJELOG TIJELA U KLINIČKOM BOLNIČKOM CENTRU ZAGREB

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Sažetak

Zračenje cijelog tijela (eng. Total Body Irradiation – TBI) specijalna je metoda u radioterapiji gdje se visokoenergijsko fotonsko zračenje isporučuje cijelom tijelu. U našoj ustanovi TBI je dio pripreme za alogenu (donorsku) transplantaciju koštane srži kod pacijenata oboljelih od leukemije. Provodi se u svrhu uništavanja ili potiskivanja pacijentovog imunog sustava čime se prevenira odbacivanje transplantirane koštane srži. Ujedno se tim postupkom uništavaju rezidualne stanice raka i pacijentova vlastita koštana srž, stvarajući prostor za transplantat.

Klinički bolnički centar Zagreb ima preko 40 godina iskustva uspješnog provođenja zračenja cijelog tijela, od zračenja gama snopom ^{60}Co do suvremenog zračenja uporabom linearnog akceleratora. Ovaj kompleksan i dugotrajan postupak zahtijeva predanost multidisciplinarnog tima sastavljenog od liječničkog konzilija, medicinskih fizičara i radioloških tehnologa. Isporučena doza od 12 Gy uzrokuju ireverzibilno oštećenje koštane srži koje se može poništiti samo transplantacijom te cijeli niz kratkoročnih i dugoročnih nuspojava. Stoga je vrlo bitan precizan izračun i praćenje doze te detaljno razrađen postupak.

U radu će se prikazati problematika koju je bilo neophodno riješiti za sigurno uspostavljanje postupka: pozicioniranje bolesnika, dozimetrija, kalibracija detektora, in-vivo praćenje apsorbirane doze u tijelu bolesnika, uniformnost doze, zaštitu pluća, utjecaj brzine doze itd. Također, uvođenjem novog sustava za oslikavanje osigurava se kontinuirano praćenje položaja bloka za zaštitu pluća u odnosu na pacijenta, čime se osigurava isporuka doze na cijelo tijelo uz ograničavanje doze na pluća ispod klinički prihvatljive razine.

Ključne riječi: zračenje cijelog tijela, transplantacija koštane srži, linearni akcelerator, apsorbirana doza, brzina doze

DEVELOPMENT AND IMPROVEMENT OF TOTAL BODY IRRADIATION METHOD AT UNIVERSITY HOSPITAL CENTRE ZAGREB

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Abstract

Total body irradiation (TBI) is a specialized method in radiotherapy in which high-energy photon radiation is delivered to the entire body. In our institution, TBI is a part of the preparation for allogeneic (donor) bone marrow transplantation in patients with leukemia. This treatment is carried out to destroy or suppress the patient's immune system, thereby preventing the rejection of the transplanted bone marrow. At the same time, this procedure destroys residual cancer cells and the patient's own bone marrow, creating space for the transplant.

University Hospital Centre Zagreb has over 40 years of experience in the successful implementation of total body irradiation, from radiation with a ^{60}Co gamma beam to modern radiation using a linear accelerator. This complex and time-consuming procedure requires the commitment of a multidisciplinary team composed of a medical council, medical physicists, and radiation therapists. The delivered dose of 12 Gy causes irreversible damage to the bone marrow, which can only be reversed by transplantation, along with a wide range of short-term and long-term side effects. Therefore, it is crucial to precisely calculate and monitor the dose, as well as to have a detailed and elaborated procedure in place.

This work will present the challenges that needed to be addressed for the safe establishment of the procedure: patient positioning, dosimetry, detector calibration, in-vivo monitoring of the absorbed dose in the patient's body, dose uniformity, lung shielding, the influence of the dose rate, etc. Additionally, the introduction of a new imaging system ensures continuous monitoring of the position of the lung shielding block relative to the patient, ensuring that the dose is delivered to the entire body, while keeping the dose to the lungs below the clinically acceptable level.

Key words: total body irradiation, bone marrow transplatation, linear accelerator, absorbed dose, dose rate

SIGURNI, OPTIMIZIRANI I PERSONALIZIRANI RADIOLOŠKI I RADIOTERAPIJSKI POSTUPCI ZA TRUDNICE (PROJEKT SONORA)

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Sažetak

Poznato je da je fetus posebno osjetljiv na ionizirajuće zračenje, zbog čega je potrebno pažljivo razmotriti opravdanost i optimizaciju radioloških i radioterapijskih postupaka kod trudnica. Nedostatak znanja u kombinaciji sa strahom pacijenata može rezultirati nepotrebnim prekidima trudnoće, naglašavajući važnost točne procjene i optimizacije doza koje prima fetus. Međutim, nedostatak usklađenosti kliničke prakse dovodi do značajnih odstupanja u procjenama doza na fetus.

Projekt Sonora ima za cilj povećati točnost procjene fetalne doze u dijagnostičkoj i intervencijskoj radiologiji (DIR), kao i u postupcima radioterapije (RT).

Glavni ciljevi projekta su: 1. Razvoj fantoma koji predstavljaju različite stadije trudnoće; 2. Istraživanje doza koje prima fetus i dozimetrijske metode za različite DIR postupke, RT tehnike i anatomije pacijenata; 3. Identifikacija čimbenika koji utječu na procjenu doze za metode koje se trenutno koriste u kliničkoj praksi; 4. Razvoj i testiranje metode u kliničkoj praksi za procjenu doze na fetus u protonskoj RTprilagođenoj prema individualnoj anatomiji trudnice i parametrima kliničkog plana.

Sonora projekt čini konzorcij od 17 institucija (12 europskih zemalja), a projekt je podijeljen u 5 radnih paketa. Projekt će rezultirati smjernicama dobre prakse za procjenu doze na fetus kod trudnica ili potencijalno trudnih pacijentica koje su podvrgnute dijagnostičkim i intervencijskim radiološkim i radioterapijskim postupcima. Podaci o dozi i povezanim rizicima razmatrat će se i raspravljati iz etičke perspektive kako bi se poboljšala kvaliteta komunikacije s pacijentima o rizicima i dobrobiti.

Ključne riječi: Sonora projekt, trudnice, doze na fetus

Reference:

[1] https://pianoforte-partnership.eu/sonora/

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TOWARDS SAFE, OPTIMIZED AND PERSONALIZED RADIOLOGY AND RADIOTHERAPY PROCEDURES FOR PREGNANT PATIENTS (SONORA PROJECT)

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Abstract

It is well known that the foetus is particularly sensitive to ionising radiation, necessitating careful consideration of the justification and optimization of radiological and radiotherapy procedures involving pregnant patients.

A lack of knowledge coupled with patients' fears can result in unnecessary pregnancy terminations, underscoring the importance of accurately assessing and optimizing foetal doses. However, the lack of harmonization of clinical practice leads to significant discrepancies in foetal dose estimations.

The Sonora project (EU Pianoforte) aims to enhance the accuracy of foetal dose estimation in diagnostic and interventional radiology (DIR) as well as in radiotherapy (RT) procedures.

The main objectives of the project are: 1. To develop phantoms of different pregnancy stages; 2. To investigate foetal doses and dosimetry methods for different DIR procedures, RT techniques and patient anatomies; 3. To identify the factors influencing foetal dose estimation for the methods used in clinical practice; 4. To develop and test a clinical tool for estimating foetal dose in proton RT according to individual pregnant patient anatomy and clinical plan parameters. A consortium of 17 institutions (12 European countries) has been established and 5 Work Packages have been formed to achieve the project's objectives.

The project will result in good practice guidelines for fetal dose assessment in pregnant or potentially pregnant patients undergoing diagnostic and interventional radiology and radiotherapy procedures. The fetal dose and associated risk data will be considered and discussed from an ethical perspective to improve the quality of risk-benefit communication with patients.

Keywords: Sonora project, pregnant patients, fetal doses

References:

[1] https://pianoforte-partnership.eu/sonora/

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UMJETNA INTELIGENCIJA U KLINIČKOJ RADIOLOGIJI – ZNANJE, ISKUSTVO I MIŠLJENJE OSOBLJA ODJELA KLINIČKE RADIOLOGIJE TE STUDENATA MEDICINE I RADIOLOŠKE TEHNOLOGIJE

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Sažetak

Cilj: Primjena umjetne inteligencije (UI) ima dalekosežne posljedice u zdravstvu, posebice u svakodnevnom radu u kliničkoj radiologiji i u zaštiti od zračenja. Cilj ovoga istraživanja bio je stjecanje uvida u poznavanje pojmova i korištenja UI-a u kliničkoj radiologiji od strane osoblja odjela kliničke radiologije (liječnika specijalista i specijalizanata kliničke radiologije, radioloških tehnologa i medicinskih fizičara) te studenata čija je buduća struka vezana za kliničku radiologiju (studenata medicine i studenata radiološke tehnologije), kao i njihovi stavovi vezani za navedeno.

Rezultati: Ispitivanje je provedeno putem online upitnika o poznavanju UI-a, kao i obrazovanju te predviđanjima i povjerenju vezanim za UI u kliničkoj radiologiji. U ispitivanju je sudjelovalo 117 zaposlenika odjela kliničke radiologije te 136 studenata čija je buduća struka vezana za kliničku radiologiju. Obje ispitivane skupine smatraju da im treba više edukacije iz ovog područja (zaposlenici odjela kliničke radiologije 82 % i studenti 71 %). Većina osoblja odjela kliničke radiologije (68 %) i studenata (63 %) nije se na svom radnom mjestu (tj. fakultetu za studente) koristila programima UI-a namijenjenima kliničkoj radiologiji. Ispitanici smatraju da će na njihovu struku znatno utjecati razvoj UI-a u bližoj budućnosti (zaposlenici odjela kliničke radiologije 43 % i studenti 26 %), a više od polovine ispitanika smatra da će budući programi UI-a bitno utjecati na smanjenje ozračenja pacijenta tijekom radiološkog oslikavanja.

Zaključak: Rezultati ovog ispitivanja ukazuju na potrebu edukacije iz područja UI-a, kako osoblja odjela kliničke radiologije tako i studenata čija je buduća struka vezana za kliničku radiologiju. Većina ispitanika smatra da će primjena UI-a u njihovom poslu donijeti promjene na koje žele biti spremni.

Ključne riječi: umjetna inteligencija, radiologija

ARTIFICIAL INTELLIGENCE IN CLINICAL RADIOLOGY - KNOWLEDGE, EXPERIENCE AND OPINION OF THE STAFF OF THE CLINICAL RADIOLOGY DEPARTMENT AND STUDENTS OF MEDICINE AND RADIOLOGICAL TECHNOLOGY

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Abstract

Aim: The application of artificial intelligence (AI) has wide consequences in healthcare, especially in clinical radiology routine and in radiation protection. The aim of this research was to gain insight into the knowledge of the concepts and use of AI in clinical radiology by the staff of the clinical radiology department (radiologist and radiology residents, radiographers and medical physicists) and by healthcare students whose education is related to radiology (future radiographers and future medical doctors), as well as in their opinions related to the above.

Results: The survey was conducted through an online questionnaire about knowledge on AI, as well as education, predictions and confidence related to AI in clinical radiology. The survey was answered by 117 healthcare professionals and 136 students whose future profession is related to clinical radiology. Both surveyed groups believe that they need more education in this field (employees of the clinical radiology department 82% and students 71%). The majority of clinical radiology department staff (68%) and students (63%) did not use AI programs intended for clinical radiology at their workplace (i.e. student faculty). Respondents believe that their profession will be significantly affected by the development of AI in the near future (clinical radiology department employees 43% and students 26%), and more than half of the respondents believe that future AI programs will significantly influence the reduction of patient exposure during radiological imaging.

Conclusion: The results of this study indicate the need for education in the field of AI, both for the staff of the clinical radiology department and for students whose future profession is related to clinical radiology. Most of the respondents believe that the application of AI in their work will bring changes that they want to be ready for.

Keywords: artificial intelligence, radiology

PrISMA - PRIPREMNE AKTIVNOSTI ZA PODRŠKU PROVEDBI KVALITETNE I SIGURNE PRIMJENE IONIZIRAJUĆEG ZRAČENJA U MEDICINI

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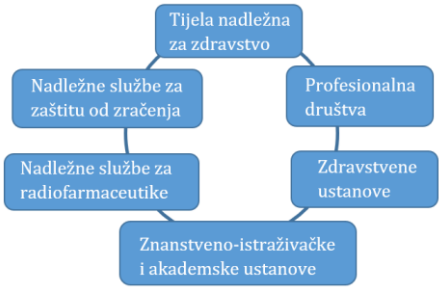
Sažetak

Različite tehnologije i metode u medicini koriste ionizirajuće zračenje koje ima važnu ulogu u dijagnostici i radioterapiji. Međutim, zbog štetnih učinaka koje zračenje može izazvati, veća uporaba i povećana izloženost zračenju među europskim stanovništvom izaziva zabrinutost.
PrISMA (Pripremne aktivnosti za podršku provedbi kvalitetne i sigurne primjene ionizirajućeg zračenja u medicini) europski je projekt koji proizlazi iz akcijskog plana Europske unije (EU) SAMIRA (Strategic Agenda for Medical Ionizing Radiation Applications), podupirući sigurnu, visokokvalitetnu i pouzdanu uporabu radiološke i nuklearne tehnologije u zdravstvu. Europska komisija usvojila je SAMIRA-u, kao akcijski plan, u veljači 2021., kako bi doprinijela Europskom planu za borbu protiv raka. PrISMA ima za cilj utrti put budućem zajedničkom djelovanju, putem kojeg bi se podržala i održala postignuća u razvoju kvalitetne i sigurne medicinske primjene ionizirajućeg zračenja u svim državama članicama EU. U tu svrhu formiran je i multidisciplinarni konzorcij PrISMA-e, koji se sastoji od 18 organizacija iz 11 država članica EU i Norveške. Većinu zemalja prvenstveno predstavljaju vladine agencije, ministarstva, stručna društva, zavodi za (javno) zdravstvo ili zaštitu od zračenja.
PrISMA ima dva ključna cilja:
1. Mapirati relevantne aktere u području zaštite od zračenja (Slika 1) u vezi s medicinskom primjenom ionizirajućeg zračenja i uključiti ih u buduće zajedničko djelovanje.
2. Izraditi nacrt teksta prijedloga budućeg zajedničkog djelovanja, s detaljnom definicijom ciljeva, opsega i aktivnosti.



Slika 1: Relevantni akteri u području zaštite od zračenja.

Uspješna provedba PrISMA-e i budućeg zajedničkog djelovanja trebala bi za europsko stanovništvo pridonijeti održivoj, visokokvalitetnoj i sigurnoj uporabi ionizirajućeg zračenja u medicini.

Ključne riječi: PrISMA, akcijski plan SAMIRA, zajedničko djelovanje, zaštita od zračenja.

Co-funded by the European Union

PrISMA projekt je sufinanciran sredstvima Europske Komisije, unutar programa EU4Health 2021-2027, prema ugovoru o dodjeli bespovratnih sredstava broj 101162826.

PrISMA - PREPARATORY ACTIVITIES TO SUPPORT IMPLEMENTATION OF QUALITY AND SAFETY OF MEDICAL IONISING RADIATION APPLICATIONS

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Abstract

In medicine, various technologies and methods use ionising radiation, playing an important role in all aspects of diagnostics and therapy. However, due to the potentially harmful effects of radiation, the increasing use and consequent rise in radiation exposure among the European population have raised concerns.

PrISMA (Preparatory activities to support Implementation of quality and Safety of Medical ionising radiation Applications) is a European project that comes from the European Union SAMIRA action plan (Strategic Agenda for Medical Ionising Radiation Applications), supporting the safe, high-quality, and reliable use of radiological and nuclear technology in healthcare. SAMIRA was adopted in February 2021 by the European Commission to contribute to Europe's Beating Cancer Plan. PrISMA joint action aims to pave the way for future Joint Action to support and sustain the implementation of developments in quality and safety issues concerning medical applications of ionising radiation across all EU Member States. For that purpose, the multidisciplinary consortium of PrISMA was formed, representing 18 organisations from 11 Member States (MS) and Norway. Most countries are represented primarily by government agencies, ministries, professional societies, departments of (public) health, or radiation protection.

The PrISMA has two key objectives:

1. To map the relevant actors in the field of radiation protection (Figure 1) regarding the medical use of ionising radiation, and get them involved in the future Joint Action.
2. To draft a proposed text for the future Joint Action, with detailed definition of the objectives, scope, and activities.

Figure 1: Relevant actors in the field of radiation protection.

The successful implementation of PrISMA and future Joint Action should contribute to a sustainable, high-quality, and safe use of medical ionising radiation for European citizens.

Key words: PrISMA, SAMIRA action plan, Joint Action, radiation protection.

Co-funded by the European Union

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TOMOGRAFIJOM U HITNOJ SLUŽBI KLINIČKOG BOLNIČKOG CENTRA ZAGREB

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Uvod: Politrauma je hitno stanje koje se najčešće događa mladim, radno sposobnim osobama u reproduktivnoj dobi, koje imaju dug očekivani životni vijek. Takvi pacijenti obično zahtijevaju više radioloških pregleda tijekom života, čime se povećava kumulativna izloženost ionizirajućem zračenju. Stoga je smanjenje doze zračenja ključno za zaštitu zdravlja pacijenata, posebice u hitnim situacijama kada je važno i brzo donošenje odluka. Primjena naprednih tehnologija, kao što je dvoenergijska kompjutorizirana tomografija (eng. *dual-energy computed tomography*, DECT), omogućuje istovremeno smanjenje doze zračenja i očuvanje potrebne kvalitete dijagnostičkih informacija.
Cilj: Procjena smanjenja tipičnih vrijednosti DLP-a (doznog indeksa, koji označava umnožak doze i duljine skeniranja) kod politraumatiziranih pacijenata primjenom novih DECT protokola snimanja, uz zadržavanje potrebne kvalitete dijagnostičkih informacija.
Materijali i metode: Ova studija obuhvatila je 84 tipična pacijenta (raspon mase 70±10 kg) koji su podvrgnuti CT snimanjima tijekom četveromjesečnog razdoblja. Ispitanici su podijeljeni u dvije skupine: prva skupina, koja je obuhvatila 38 pacijenata, podvrgnuta je standardnom protokolu snimanja s pomoću jednoenergijskog CT uređaja, dok je druga skupina (46 pacijenata) snimljena koristeći novi DECT protokol. Jednoenergijski CT protokol uključivao je jednu nativnu i dvije postkontrastne snimke, dok je DECT protokol učinjen kroz dvije postkontrastne snimke uz stvaranje virtualne nativne snimke iz učinjene postkontrastne snimke tehnikama naknadne obrade. Uspoređen je medijan vrijednosti DLP-a između starog i novog protokola. Za procjenu statističke značajnosti korišten je t-test.
Rezultati: Rezultati su pokazali značajnu razliku između starog i novog protokola snimanja. Medijan vrijednosti DLP-a za DECT protokol bio je 3027,55 mGycm, dok je za standardni CT protokol iznosio 5126,52 mGycm, što ukazuje na iznimnu učinkovitost novog protokola u smanjenju izloženosti pacijenata ionizirajućem zračenju za 40,95 % ($p < 0,001$), bez ugrožavanja prijašnje kvalitete dijagnostičkih informacija.
Zaključak: Rezultati ove studije ukazuju na to da optimizirani DECT protokol može značajno smanjiti izloženost ionizirajućem zračenju tijekom hitne radiološke obrade politraumatiziranih pacijenata uz istovremeno održavanje potrebne kvalitete dijagnostičkih slika. Ova tehnologija predstavlja važan korak prema unaprjeđenju sigurnosti pacijenata, posebice mladih osoba koje se suočavaju s dugoročnom potrebom za radiološkim pregledima.

Ključne riječi: dvoenergijska kompjutorizirana tomografija (DECT), hitno radiološko zbrinjavanje, politrauma, optimizacija protokola snimanja, doza zračenja

OPTIMIZATION OF THE COMPUTERIZED TOMOGRAPHY IMAGING PROTOCOL OF POLYTRAUMATIZED PATIENTS IN THE EMERGENCY DEPARTMENT OF UNIVERSITY HOSPITAL CENTER ZAGREB

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Introduction: Polytrauma is an emergency condition that most often occurs in young people of working and reproductive age with a long life expectancy. Such patients usually require multiple radiological examinations during their lifetime, thus increasing the cumulative exposure to ionizing radiation. Therefore, reducing the radiation dose is essential for protecting patients' health, especially in emergencies when quick decision-making is essential. The application of advanced technologies, such as dual-energy computed tomography (dual-energy CT, DECT), enables simultaneous reduction of the radiation dose and preservation of the necessary quality of diagnostic information.
Objective: Evaluation of the typical DLP values reduction (dose index, which indicates the product of dose and scan length) in polytraumatized patients using new DECT imaging protocols while maintaining the required quality of diagnostic information.
Materials and methods: This study included 84 typical patients (body weight range 70±10 kg) who underwent CT scans over a four-month period. The subjects were divided into two groups. The first group, consisting of 38 patients, underwent a standard imaging protocol with a single-energy CT device, while the second group (46 patients) was scanned with the new DECT protocol. The single-energy CT protocol included one non-contrast and two post-contrast images. In contrast, the DECT protocol involved two post-contrast images, with a virtual non-contrast image generated using post-processing techniques based on the post-contrast images. The median value of DLP between the old and the new protocol was compared. A t-test was used to assess statistical significance.
Results: The results showed a significant difference between the old and the new imaging protocol. The median DLP value for the DECT protocol was 3027.55 mGycm, while the median DLP value for the standard CT protocol was 5126.52 mGycm. This indicates the exceptional efficiency of the new protocol in reducing patient exposure to ionizing radiation by 40.95% ($p < 0.001$) without compromising the existing quality of diagnostic information.
Conclusion: This research shows that the optimized DECT protocol can significantly reduce exposure to ionizing radiation during emergency radiological treatment of polytraumatized patients while maintaining the required quality of diagnostic images at the same time. This technology represents an important step towards improving the safety of patients, especially young people who face a long-term need for radiological examinations.

Keywords: dual-energy computed tomography (DECT), emergency radiological treatment, polytrauma, imaging protocol optimization, radiation dose

IMPLEMENTACIJA ALADA PRINCIPA KOD RADIOLOŠKIH TEHNOLOGA KLINIČKOG ZAVODA ZA DIJAGNOSTIČKU I INTERVENCIJSKU RADIOLOGIJU KLINIČKOG BOLNIČKOG CENTRA ZAGREB U SVRHU ZAŠTITE PACIJENTA OD PREKOMJERNOG ZRAČENJA

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Cilj: Anketno istražiti koliko su radiološki tehnolozi upoznati i kako implementiraju *As low as diagnostically acceptable* (ALADA) principe pri zaštiti pacijenata od prekomjernog zračenja vodeći pri tome računa o kvaliteti radiološke slike.
Materijali i metode: Istraživanje je provedeno u obliku ankete, a upitnik je podijeljen na sekcije: demografski podaci, znanje o ALADA principu, implementacija, prepreke i stavovi.
Rezultati: Anketirano je 38 radioloških tehnologa, od kojih je 57 % bilo ženskog spola, prosječnog su raspona godina između 26-35 (50 %) .
Ukupno je 89 % anketiranih izjavilo da su upoznati sa ALADA principom, a prvi put su čuli za njega tijekom formalnog obrazovanja (82 %). Pri tome ih 52 % misli da uvijek primjenjuje ALADA princip, 29 % misli da ga primjenjuje često, 11 % misli da ga primjenjuje povremeno, a 8 % je izjavilo da misli da ga nikad ne primjenjuje.
Od propisanih koraka za zaštitu pacijenta od zračenja, najveći broj anketiranih izjavilo je da primjenjuju korištenje zaštitne opreme (95 %), prilagodbu tehničkih parametara uređaja (95 %), optimizaciju protokola snimanja (95 %) dok se u manjoj mjeri primjenjuje obuka pacijenta o položaju tijekom snimanja (73 %) te redovito održavanje uređaja (58 %).
Samo 16 % anketiranih tehnologa izjavilo je da redovito provodi kontrolu kvalitete radi usklađenosti s ALADA principom, 42 % ih povremeno provodi, a ostalih 42 % ih uopće ne provodi.
Od prepreka pri provođenju ALADA principa najveći broj navodi pritisak za povećanjem broja pregleda (84 %), zatim vremenska ograničenja (82 %), nedostatak opreme (71 %) te nedovoljnu edukaciju (58 %).
52 % ispitanih smatra da je ALADA princip vrlo važan za sigurnost pacijenta, dok se nitko nije izjasnio da uopće nije važan. 81 % ispitanih radioloških tehnologa vidi potrebu za svojom dodatnom edukacijom u tom području.
Velik broj nema nešto posebno za predložiti kako bi se poboljšala implementacija ALADA principa u našoj ustanovi (71 %), dok ostali predlažu uvođenje dodatne edukacije kao i pridržavanje vremenskih normativa pri pregledu pacijenta.
Zaključak: Rezultati pokazuju visoku razinu svijesti o ALADA principima među ispitanicima. Međutim ključni izazovi uključuju pritisak zbog broja pregleda i vremenska ograničenja, što otežava optimalnu implementaciju. Nadalje, čak 95 % ispitanih izjavilo je da još uvijek primjenjuje zaštitna sredstva, što nije u skladu s najnovijim smjernicama. Poboljšanje edukacije i ulaganje u resurse moglo bi pomoći u prevladavanju ovih prepreka.

Ključne riječi: Zaštita od zračenja, ALADA principi, obuka radioloških tehnologa

IMPLEMENTATION OF ALADA PRINCIPLE AMONG RADIOGRAPHERS AT THE DEPARTMENT OF RADIOLOGY, UNIVERSITY HOSPITAL CENTRE ZAGREB, TO PROTECT PATIENTS FROM EXCESSIVE RADIATION

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Objective: To conduct a survey on the awareness and implementation of the *As Low As Diagnostically Acceptable* (ALADA) principle by radiographers to protect patients from excessive radiation exposure while maintaining the quality of radiologic images.
Materials and Methods: The research was conducted through a survey, with the questionnaire divided into sections: demographic data, knowledge of the ALADA principle, implementation, obstacles, and attitudes.
Results: The survey included 38 radiographers, 57% of whom were female, with an average age range of 26–35 years (50%).
A total of 89% of respondents stated they were familiar with the ALADA principle, having first learned about it during formal education (82%). Of these, 52% believe they always apply the ALADA principle, 29% believe they apply it often, 11% believe they apply it occasionally, and 8% reported they believe they never apply it.
Among the prescribed steps for radiation protection, the majority of respondents reported using protective equipment (95%), adjusting technical parameters of the device (95%), and optimizing imaging protocols (95%). Less commonly implemented were patient education on positioning during imaging (73%) and regular maintenance of devices (58%). Only 16% of radiographers reported regularly conducting quality control for compliance with the ALADA principle, 42% conducted them occasionally, and 42% did not conduct them at all.
The most frequently cited obstacles to implementing the ALADA principle were the pressure to increase the number of examinations (84%), time constraints (82%), lack of equipment (71%), and insufficient education (58%).
A total of 52% of respondents considered the ALADA principle very important for patient safety, while none deemed it unimportant.
Additionally, 81% of respondents saw a need for further education in this area. A significant portion had no specific suggestions for improving the implementation of the ALADA principle at their institution (71%), while others proposed additional education and adherence to time standards during patient examinations.
Conclusion: The results indicate a high level of awareness of the ALADA principle among respondents. However, key challenges include pressure due to the volume of examinations and time constraints, which hinder optimal implementation. Furthermore, 95% of respondents still use protective shielding, which is inconsistent with the latest guidelines. Improving education and investing in resources could help overcome these obstacles.

Keywords: Radiation protection, ALADA principles, training of radiographers

IMPLEMENTACIJA CT SIMULATORA U RADIOTERAPIJSKI SUSTAV KBC-A ZAGREB

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Sažetak

CT simulator (engl. *Computed Tomography Simulator*) ima važnu ulogu u radioterapiji. CT simulacijom započinje radioterapijski proces, pri čemu se u prvom koraku dobivaju volumetrijske informacije o anatomiji od interesa. Dobiveni podaci koriste se za izradu radioterapijskog plana zračenja, koji ima za cilj predaju visokih doza zračenja na ciljni volumen (tumor), prilikom čega je potrebno poštedjeti zdravo okolno tkivo. Medicinski fizičari osiguravaju da planirani izračun apsorbirane doze odgovara predanoj dozi pacijentu. Izračun apsorbirane doze zračenja provodi se računalnim algoritmima sustava za planiranje radioterapije (engl. *Treatment Planning System, TPS*) koji koriste informacije o elektronskoj gustoći tkiva. Različite gustoće u tkivu skeniranog volumena opisane su CT brojevima, odnosno Hounsfieldovim jedinicama. Kako bi se skenirani podaci mogli koristiti za izradu radioterapijskog plana zračenja, potrebno je odrediti krivulju pretvorbe CT brojeva u elektronske gustoće.

U ovom radu prezentiran je proces implementacije CT simulatora (Siemens go.Open Pro) u Odjelu za radioterapiju Klinike za onkologiju KBC-a Zagreb. Provedena su standardna prihvatna mjerenja koja uključuju mehaničke i geometrijske provjere CT simulatora, kao i različite testove za provjeru kvalitete slike i točnosti doznih parametara. Također, provedena su mjerenja za određivanje krivulje pretvorbe Hounsfieldovih jedinica u elektronske gustoće, koja će se koristiti za izračun apsorbirane doze u Eclipse sustavu za planiranje radioterapije. Mjerenja su izvedena na CIRS fantomu koji sadrži različite umetke poznatih elektronskih gustoća. Jedan od ciljeva bio je utvrditi utjecaj novih CT značajki, odnosno rekonstrukcijskih parametara, na CT brojeve. U radu su prikazani rezultati ispitivanja utjecaja jačine parametra SAFIRE (engl. *Sinogram Affirmed Iterative Reconstruction*) te prisutnosti iMAR (engl. *Iterative Metal Artifact Reduction*) i iBHC (engl. *Iterative Beam Hardening Correction*) parametara na Hounsfieldove jedinice. Također, provedena su skeniranja na različitim kvalitetama kako bi se ustanovio utjecaj CT brojeva na izračun doze. Naposljetku je simuliran cijeli pacijentov put kroz postupak radioterapije (engl. *End-to-end test*) s novim CT simulatorima. Tako se u konačnici potvrdilo da su implementirani CT simulatori i cjelokupan radioterapijski proces precizni i sigurni za korištenje u kliničkoj praksi.

Ključne riječi: CT simulator, elektronska gustoća, CT brojevi (Hounsfieldove jedinice)

IMPLEMENTATION OF A CT SIMULATOR IN THE RADIOTHERAPY SYSTEM AT KBC ZAGREB

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Abstract

The CT simulator (Computed Tomography Simulator) is crucial in radiotherapy. CT simulation initiates the radiotherapy process, during which volumetric information about the anatomy of interest is obtained. The data acquired in this way are used to create a radiation therapy plan to deliver high doses of radiation to the target area, while sparing the surrounding healthy tissue. Medical physicists ensure that the planned absorbed dose calculation corresponds to the dose delivered to the patient. The radiation dose is computed using computer algorithms in the Treatment Planning System (TPS), which utilizes information about the electron density of the tissue. Different tissue densities within the scanned volume are described by CT numbers, i.e., Hounsfield units. To use the CT scanned data for creating a radiotherapy treatment plan, a conversion curve from CT numbers to electron densities must be created.

This work presents the process of implementing new CT simulators (Siemens go.Open Pro) at the Department of Radiotherapy, Clinic for Oncology of KBC Zagreb. Standard acceptance measurements were performed on the CT simulators, including mechanical and geometric checks, as well as various tests for image quality and the accuracy of dose parameters. These measurements were essential for creating the conversion curve of Hounsfield units to electron densities, which will be used to calculate the absorbed dose in the Eclipse radiotherapy planning system. Measurements were conducted on a CIRS phantom containing various inserts with known electronic densities. One of the goals was to assess the impact of the new CT features, i.e., reconstruction parameters, on CT numbers. This study presents the results of testing the influence of the strength of the SAFIRE parameter (Sinogram Affirmed Iterative Reconstruction), as well as the presence of iMAR (Iterative Metal Artifact Reduction) and iBHC (Iterative Beam Hardening Correction) parameters on Hounsfield units. Furthermore, scans were performed at different beam qualities to establish the influence of CT numbers on the dose calculation. Finally, the entire patient's pathway through the radiotherapy procedure was simulated (End-to-end test) using the new CT simulators. Ultimately, it was confirmed that the implemented CT simulators and the entire radiotherapy process are accurate and safe for clinical practice.

Keywords: CT simulator, electron density, CT numbers (Hounsfield units)

RADIOEKOLOGIJA

RADIOECOLOGY

CONCENTRATIONS OF TOTAL BETA ACTIVITY AND ^{90}Sr ACTIVITY IN SEDIMENT, FISH, AND ALGAE FROM THE DANUBE IN THE PERIOD 2021–2024

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Abstract

A potential polluter of the Danube is the Paks nuclear power plant, located 85 km from the Serbian-Hungarian border. The two countries monitored the radioactivity of the Danube from 1988 to 1991, after which the cooperation was interrupted. It resumed in 1997 and continues to this day. At the border profiles Bezdan (Serbia) and Mohács (Hungary), water, sediment, fish (both whitefish and predatory species), and algae samples are collected six times a year. The aim of this study is to monitor total beta activity and ^{90}Sr activity in sediment, fish, and algae from the Danube during the period 2021–2024. Measurements were performed using a proportional gas αβ counter (PIC-WPC-9550) with a beta radiation efficiency of 42%. Results published by the "Ruđer Bošković" Institute in Zagreb (Determination of Radioactivity in the Danube River for 1988, 1989) were used as the "baseline" reference.

Table 1. Concentrations of total beta activity and ^{90}Sr activity in sediment, fish, and algae from the Danube – "Baseline State"

Activity concentration	Sediment (dry 105 ^{0}C)	Fish (dry 105 ^{0}C)	Algae
Total beta aktivity (Bq/kg)	801 ± 44	76 ± 16	988 ± 173
^{90}Sr (Bq/kg)	7,1 ± 6,8	0,62 ± 0,57	-

Table 2. Minimum and maximum concentrations of total beta activity and ^{90}Sr activity in sediment, fish, and algae from the Danube during the period 2021–2024

Year of testing	Sediment (Bq/kg, dry 105^{0}C)	Fish (Bq/kg, dry 300 ^{0}C/fresh)		Algae (Bq/kg, dry 105^{0}C)
	^{90}Sr	Ukupna-β	^{90}Sr	Ukupna-β
2021	0,10 - 0,40	46,9 – 70,4	0,03 – 0,24	346 - 942
2022	0,13 - 0,38	43,4 – 65,0	0,02 – 0,20	301 – 391
2023	0,10 – 0,35	38,3 – 80,0	0,02 – 0,36	257 – 738
2024	0,10 – 0,34	40,4 – 98,9	0,02 – 0,14	308 - 441

Based on the results presented in Table 2, we observe that the concentration levels of total beta activity and ^{90}Sr activity in sediment, fish, and algae samples from the Danube during the period 2021–2024 are at the same levels as they were before the Paks nuclear power plant became operational (Table 1). Monitoring of the Danube ecosystem's radioactivity continues to ensure environmental protection and public health, with ongoing annual interlaboratory comparisons of results between the two countries.

Keywords: radioactivity, Danube ecosystem, activity concentration

SEZONSKO PRAĆENJE RADIONUKLIDA U DAGNJE *Mytilus galloprovincialis* UZ HRVATSKU OBALU JADRANA (2008.-2023.)

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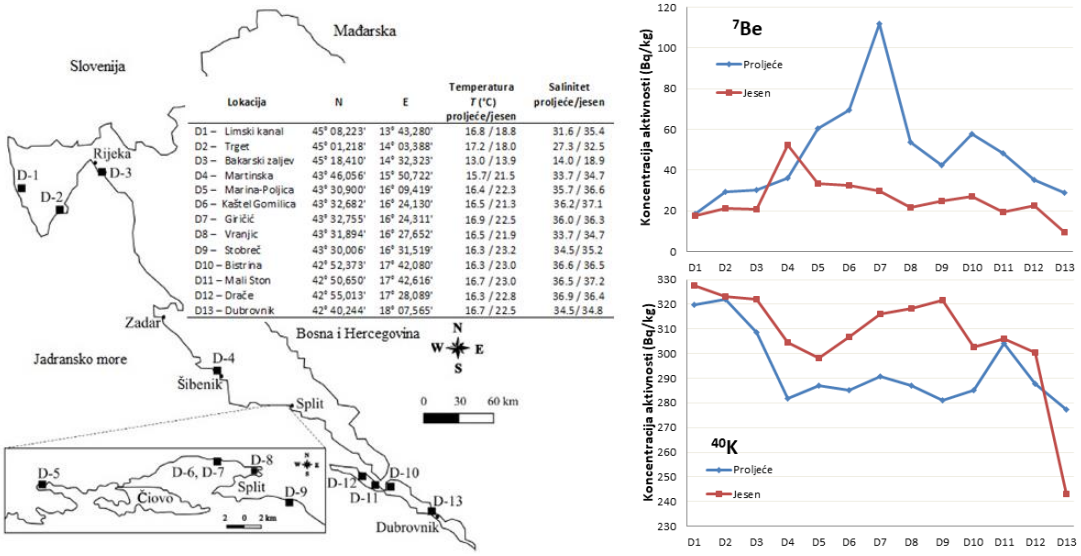
Sažetak

Mjerenjem radioaktivnosti u dagnje *Mytilus galloprovincialis* procijenjeno je radioekološko stanje Jadranskog mora uz hrvatsku obalu Jadrana u razdoblju od 15 godina (2008. – 2023.). Koncentracije aktivnosti ^{7}Be, ^{40}K, ^{232}Th, ^{226}Ra, ^{238}U i ^{137}Cs određene su gama-spektrometrijski u suhom tkivu dagnji. Predstavljeni rezultati su razmatrani i uspoređeni s obzirom na lokaciju i sezonu uzorkovanja, donosa slatke vode te parametre temperature i saliniteta morske vode. Koncentracije aktivnosti ^{137}Cs u dagnjama bile su uglavnom ispod granice detekcije. Tek su u nekoliko navrata detektirane niske koncentracije aktivnosti (do 1,05 Bq/kg), neovisno o sezoni uzorkovanja i lokaciji. Koncentracije aktivnosti ^{7}Be u dagnjama bile su najviše u proljeće (do 335 Bq/kg) za sve lokacije, što se može pripisati utjecaju kiše i dotoku slatke vode. Prosječna vrijednost koncentracije aktivnosti ^{40}K iznosila je 302 Bq/kg, bez značajnih razlika s obzirom na sezonu i lokaciju uzorkovanja, što se može pripisati njegovoj visokoj i ujednačenoj koncentraciji u moru. Koncentracije aktivnosti ^{232}Th, ^{238}U i ^{226}Ra općenito su bile ispod granica detekcije. Rezultati mjerenja radiaktivnosti u dagnji kao indikatora morskog onečišćenja upućuju na to da je radioekološko stanje Jadranskog mora uz hrvatsku obalu zadovoljavajuće.



Slika 1: a) Lokacije uzorkovanja dagnje *M. galloprovincialis* sa sezonskom prosječnom temperaturom i salinitetom morske vode; b) Prosječne koncentracije aktivnosti ^{7}Be i ^{40}K (Bq/kg suhe težine) u tkivu dagnji uzorkovanim u proljeće i jesen duž hrvatske obale Jadrana u razdoblju od 2008. do 2023. godine.

Ključne riječi: Jadransko more, dagnja *Mytilus galloprovincialis*, gama-spektrometrija, radioekološko stanje Jadrana

SEASONAL MONITORING OF RADIONUCLIDES IN MUSSEL *Mytilus galloprovincialis* ALONG THE CROATIAN ADRIATIC COAST (2008-2023)

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Abstract

The radioecological condition of Adriatic Sea along the Croatian coast has been assessed by measuring radioactivity in mussel *Mytilus galloprovincialis* over a 15-year period (2008-2023). Activity concentrations of ^{7}Be, ^{40}K, ^{232}Th, ^{226}Ra, ^{238}U and ^{137}Cs were determined by gamma-spectrometry in dry tissue of mussels. The presented results were discussed and compared regarding the sample location, sampling season, freshwater input, seawater temperature and salinity. Activity concentrations of ^{137}Cs in mussels were mostly below the detection limit. Low activity concentrations (max. 1.05 Bq/kg) were detected only in a few samples, regardless of the sampling season and location. Activity concentrations of ^{7}Be in mussels were the highest in spring periods (max. 335 Bq/kg) for all locations, which can be attributed to the impact of rain and freshwater inflow. The average value of the activity concentration of ^{40}K was 302 Bq/kg, without significant differences regarding the season and sampling location. It can be attributed to its high and uniform concentration in the sea. Activity concentrations of ^{232}Th, ^{238}U and ^{226}Ra were generally below the detection limits. The results obtained by measuring radioactivity in mussels as an indicator organism of marine pollution indicate that the radioecological condition of the Adriatic Sea along the Croatian coast is satisfactory.

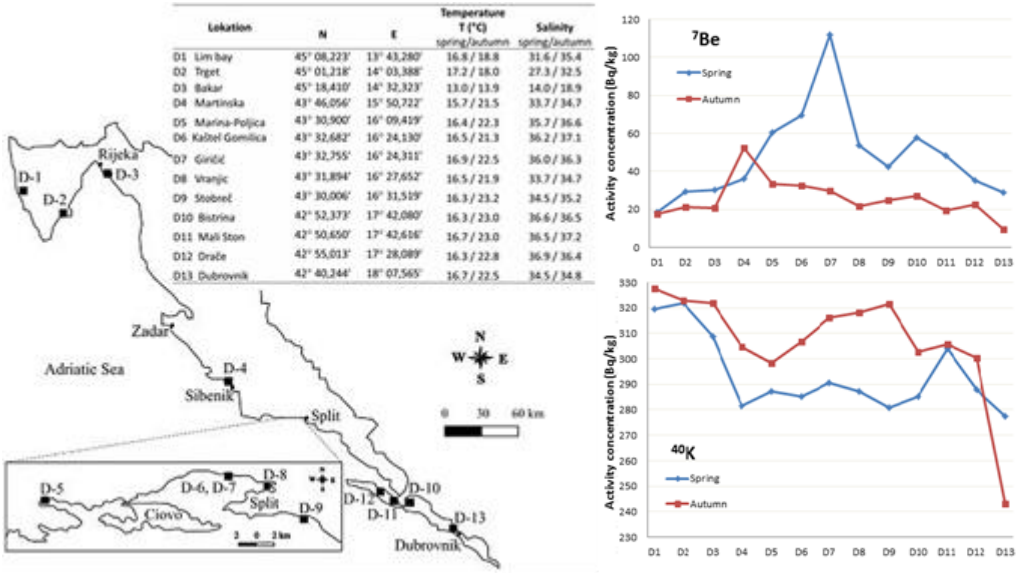

Figure 1: a) Sampling locations of mussel *M. galloprovincialis* with seasonal average temperature and salinity of seawater; b) Average activity concentrations of ^{7}Be and ^{40}K (Bq/kg d.w.) in mussel tissues sampled in spring and autumn along the Croatian Adriatic coast in the period from 2008 to 2023.

Key words: Adriatic Sea, mussel *Mytilus galloprovincialis*, gamma-spectrometry, Adriatic radioecological condition

EVALUATION OF PT SCHEME RESULTS FOR BUILDING MATERIALS: SIGNIFICANCE OF MEASUREMENT UNCERTAINTY AND CORRECTIVE ACTIONS

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Abstract

Proficiency Testing (PT) schemes play a critical role in assessing the validity of test results, identifying errors, and implementing corrective actions. This paper presents a specific case requiring correction. During participation in the "**REM 2020 Proficiency Test on Naturally Occurring Radionuclides in Building Materials"**, the activities of natural radionuclides (^{40}K, ^{226}Ra, ^{228}Ra, ^{228}Th, ^{232}Th, and ^{238}U) were analyzed in samples of cement (NORM 1), expanded clay (NORM 2) and powdered clay (NORM 3). The analysis was conducted using gamma spectrometry with an HPGe detector (Ortec, FWHM 1.85 keV at 1332 keV, relative efficiency 40 %). Samples were measured for 60,000 seconds in 0.5 L Marinelli beakers. Energy and efficiency calibrations of the detector were performed using certified reference materials, and measurement uncertainty was assessed according to ISO GUM guidelines, considering all relevant factors influencing the results.

The PT report indicated satisfactory accuracy but inconsistent precision (NORM 1: for all radionuclides except ^{40}K, NORM 2; for ^{226}Ra and NORM 3: for ^{226}Ra and ^{238}U). This inconsistency was caused by an incorrect coverage factor (k=2 instead of k=1), which led to unrealistically low uncertainty estimates and poor precision ratings. After correcting the coverage factor, the reanalysis confirmed that the results met both accuracy and precision criteria. Both reported and corrected results were visualized using **PomPlot graphs** for all three sample types.

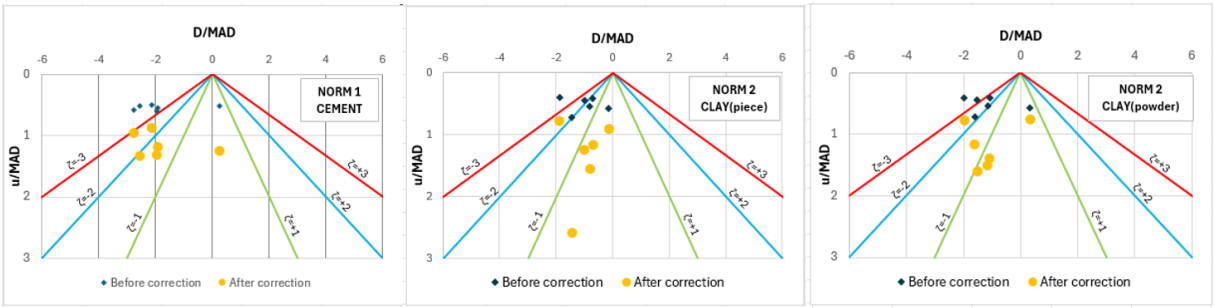

Figure 1: Laboratory performance evaluation in the PT scheme with reported and corrected results.

This error significantly influenced the evaluation of the laboratory's performance in the PT scheme, although no analytical errors were identified that could affect accuracy. As a corrective measure, a mandatory internal review by two analysts was introduced before submitting results, minimizing the risk of similar errors in the future. This study emphasizes the importance of accurate measurement uncertainty assessment and its impact on interpreting results.

Keywords: PT scheme, gamma spectrometry, building materials, measurement uncertainty, PomPlot

RADIOLOGICAL CHARACTERIZATION OF PHOSPHATE-CONTAINING MATERIALS

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Abstract
The FIC-Fighters project (Fair, Inclusive, Circular, and Healthy cities: Valorisation of phosphogypsum wastes into commercial products through sustainable and circular processes) is a 48-month initiative funded by the European Commission, that started on 1 June 2024.FIC-Fighters aims to demonstrate a circular and systemic solution for regenerating phosphogypsum (PG) stacks in Europe. By fostering interdisciplinary collaboration across six European sites, the project is dedicated to transforming PG waste into valuable resources that support sustainable urban regions and reduce environmental impacts.
As a part of FIC-Fighters project, the research was conducted on few selected samples. This paper will focus on the analysis of materials that contain phosphates, regardless of their chemical form. Four different samples have been analyzed in total, which vary in composition as well as in physical (geometrical) shape. The samples went through detailed chemical investigation and than measured on gamma spectrometry. Special attention has been given to the gammaspectrometric analysis of two samples which were small in dimensions and irregular in form. Using efficiency transfer method, the aforementioned samples were carefully modelled in the respect of their matrix (composition) and geometry.
The obtained results show the importance of the detailed and careful analysis in order to make appropriate radiological and hazard characterization.

Keywords: Gamma spectrometry, efficiency transfer, phosphate-containing samples

BIOAKUMULACIJA ^{137}Cs U VRETENCIMA (*ODONATA*) U VIROVITIČKO-PODRAVSKOJ ŽUPANIJI

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Sažetak

Vretenca (*Odonata*) smatraju se dobrim indikatorima prisutnosti teških metala u vodenim staništima. Međutim, rijetko se koriste za analizu prisutnosti radionuklida u vodi. Cilj ovog istraživanja bio je ocijeniti potencijal vretenaca kao bioindikatora prisutnosti radionuklida mjerenjem aktivnosti ^{137}Cs u uzorcima životinja, kao i u pripadajućem vodenom staništu. Vretenca su uzorkovana na 11 različitih lokacija unutar Rezervata biosfere Mura-Drava-Dunav u Virovitičko-podravskoj županiji od svibnja do kolovoza 2022. Odrasle jedinke sakupljene su entomološkom mrežicom, a ličinke su sakupljene iz vodenog staništa „kick-sweep“ metodom. Na svakoj je lokaciji uzorkovano i 20 L vode, koja je zatim uparena do 1 L te je koncentracija aktivnosti ^{137}Cs izmjerena u Marinelli posudama volumena jedne litre. U prikupljenim uzorcima metodom gama spektrometrije visoke razlučivosti određene su aktivnosti ^{137}Cs. Rezultati su pokazali aktivnost ^{137}Cs u riječnoj vodi u rasponu od 4 do 13 Bq/m^3, dok je aktivnost ^{137}Cs u uzorcima vretenaca bila značajno veća, od 1,7 do 3 Bq/kg. Ovim rezultatima dokazana je sposobnost vretenaca da akumuliraju ^{137}Cs te da se mogu koristiti kao potencijalni bioindikator prisutnosti ^{137}Cs u vodenim staništima.

Ključne riječi: vretenca, bioindikatori, ^{137}Cs, gama spektrometrija

BIOACCUMULATION OF ^{137}Cs IN DRAGONFLIES (ODONATA) IN VIROVITICA-PODRAVINA COUNTY

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Abstract

Dragonflies (Odonata) are considered to be good indicators of heavy metal presence in aquatic habitats, however they are rarely used as bioindicators of radionuclides in water. The aim of this study was to evaluate dragonflies as potential bioindicators of radionuclides by measuring ^{137}Cs activity concentrations in dragonfly samples, as well as in river water samples. Dragonflies were sampled from 11 different locations inside the Mura-Drava-Danube Biosphere Reserve, in the area of Virovitica-Podravina County, from May to August 2022. Adult specimens were caught with an entomological net, whereas larvae were collected from their aquatic habitat using the "kick-sweep" method. A total of 20 liters of water were sampled in each location and evaporated to 1 L, after which activity concentration of ^{137}Cs was measured in 1-liter Marinelli beakers. The activity concentrations of ^{137}Cs in collected animal samples were determined by gamma spectrometry method. The results show that the activity concentrations of ^{137}Cs in the river water were in the range from 4 to 13 Bq/m^3, whereas activity concentrations of ^{137}Cs in dragonflies were significantly higher, ranging from 1.7 to 3 Bq/kg. These results have shown dragonfly ability to accumulate ^{137}Cs, and that dragonflies could be used as a potential bioindicators of ^{137}Cs in aquatic habitats.

Keywords: dragonfly, bioindicators, ^{137}Cs, gamma-ray spectrometry

PRELIMINARNI REZULTATI MJERENJA U SKLOPU PROJEKTA RAINSTORM

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Sažetak
Projekt RAINSTORM - Razvoj i implementacija hibridnih gama spektrometrijskih metoda za povećanje kapaciteta radiološkog nadzora okoliša nuklearnih elektrana je usmjeren na inovativnu uporabu radiološkog kartiranja kao alata za brzu *in-situ* gama spektrometrijsku karakterizaciju okoliša te povećanje njenih kapaciteta. Radiološko kartiranje je ključni korak u procesu novorazvijene in-situ gama spektrometrijske metode, jer omogućuje brzo i efikasno prepoznavanje interesnih točaka unutar velikih područja. Tradicionalne metode gama spektrometrijskih mjerenja zahtijevaju dugotrajno pokrivanje svakog segmenta područja, gdje mjerenje na jednoj točki može trajati i do 120 min. Ovo predstavlja značajnu prepreku u situacijama kada je potrebno brzo reagirati, kao što su incidenti u okolišu. S druge strane, radiološko kartiranje omogućuje brzu identifikaciju područja s povišenom radioaktivnošću – žarišnih točaka, što značajno skraćuje vrijeme potrebno za detaljna *in-situ* mjerenja, istovremeno omogućuje provedbu *ad hoc* analize rizika i povećava efikasnost cjelokupnog procesa monitoringa.

Provedena su terenska istraživanja radiološkog kartiranja na lokaciji JUPP Kopački rit, koristeći uređaj za mjerenje ambijentalnog doznog ekvivalenta tvrtke Thermo Fisher Scientific, model FH 40G. Radiološko kartiranje obuhvatilo je interesno područje dimenzija 28 x 28 metara, koje je podijeljeno u matricu od 7x7 polja, pri čemu svako polje pokriva površinu od 4x4 metra. U središtu svakog polja izvršeno je mjerenja na visini od 1 metra, u trajanju od 5 minuta, kako bi se dobila srednja vrijednost ambijentalnog doznog ekvivalenta. Zabilježene su minimalne i maksimalne vrijednosti od 95 nSv/h (točka 12) i 136 nSv/h (točka 21). U točki maksimalne vrijednosti je potom izvršeno gama spektrometrijsko mjerenje koje omogućuje dublju analizu prisutnosti radionuklida u tlu.

Uz istraživanja u JUPP Kopački rit, planirano je istraživanje i na istraživačkom poligonu Instituta za medicinska istraživanja i medicinu rada “Šumbar”, gdje će se stečena iskustva i razvijeni algoritmi dodatno validirati i optimizirati za široku primjenu u radiološkom nadzoru.

Ključne riječi: radiološko kartiranje, in-situ gama spektrometrija, nuklearne elektrane, radionuklidi, hibridne metode, ambijentalni dozni ekvivalent, radiološki nadzor okoliša, detekcija žarišnih točaka, radiološka sigurnost

PRELIMINARY RESULTS FOR RAINSTORM PROJECT

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Abstract
Project RAINSTORM is focused on innovative use of radiological mapping as tool for fast in-situ gamma-ray spectrometry characterization of the environment and increase of its capabilities. Radiological mapping is key step in process of new-developed *in-situ* gamma-ray spectrometry method, because it enables fast and efficient detection of points of interest inside large areas. Traditional gamma-ray spectrometry methods demand long term coverage of every field segment, where measurement at one point can last up to 120 minutes. This represents significant drawback in situations when fast response is of great importance, such as radiological incident in environment. On the other hand, radiological mapping enables fast identification of area with increased radioactivity – focal points, which significantly reduces time needed for detailed *in-situ* measurements, simultaneously enabling instant implementation of *ad hoc* risk analysis and increases total monitoring process efficiency.

Radiological mapping field research was performed at location JUPP Kopački rit, using ambient dose equivalent rate detector Thermo Fisher Scientific FH 40G. Radiological mapping included field of interest with dimensions 28 x 28 meter, which is divided in 7x7 meter matrix, in which every field covers area of 4x4 meters. In the middle of every field, measurement was performed 1 meter above ground, in 5 minutes interval, in which mean value of ambient dose equivalent rate was obtained. Minimum and maximum values of ambient dose equivalent rate measurements showed 95 nSv/h (point 12) and 136 nSv/h (point 21). At focal point with maximum value in-situ gamma-ray spectrometry measurement was performed, which provided better assessment of radionuclide presence in the soil.

Along with research in JUPP Kopački rit, another research is planned, at research facility "Šumbar", which will validate obtained measurements and experience along with developed algorithms, and optimize it for wide use in radiological monitoring.

Key words: radiological mapping, in-situ gamma-ray spectrometry, nuclear power plant, radionuclides, hybrid methods, ambient dose equivalent, radiological monitoring of environment, focal-point detection, radiation safety

PROCJENA RADIOAKTIVNOSTI I SIGURNOSNOG STANJA PLINSKOG POLJA MOLVE: REZULTATI I PREPORUKE ZA 2024. GODINU

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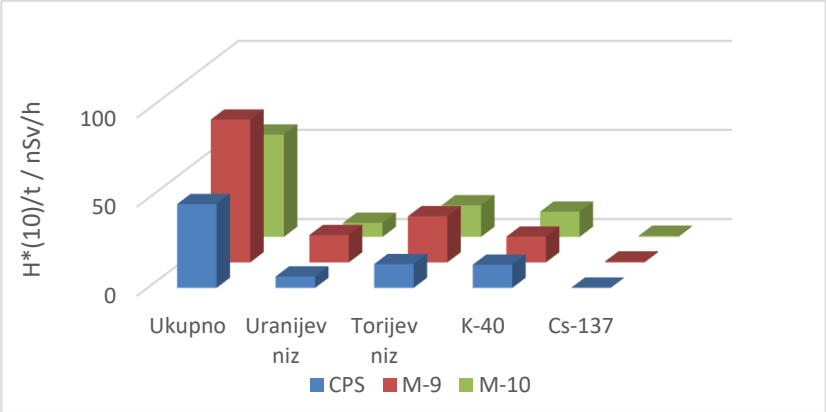
Sažetak
Institut za medicinska istraživanja i medicinu rada (IMI) provodi praćenje stanja okoliša objekta plinskog polja Molve.
Mjerenja su provedena na tri lokacije: aktivna plinska bušotina M-9, zatvorena bušotina M-10 i centralna plinska stanica M-CPS. Korišteni su uređaji za mjerenje brzine ambijentalnog doznog ekvivalenta (H*(10)/t) (Thermo Eberline ESM) i elektronički dozimetri ALARA za neprekidno mjerenje brzine ambijentalnog doznog ekvivalenta. Također, napravljena je i gama-spektrometrijska analiza uzoraka tla.
Prosječne vrijednosti (H*(10)/t) iznosile su 97 ± 6 nSvh^{-1} na lokaciji M-9, 72,3 ± 0,8 nSvh^{-1} na M-10 i 75 ± 1 nSvh^{-1} na lokaciji M-CPS. Posebno su analizirani doprinosi prirodnih radionuklida (^{238}U, ^{235}U, ^{232}Th i ^{40}K) te ^{137}Cs. Koncentracije aktivnosti ^{137}Cs u tlu iznosile su 0,14 ± 0,06 Bqkg^{-1}na M-CPS, 0,45 ± 0,01 Bqkg^{-1}na M-9 i 0,5 ± 0,1 Bqkg^{-1} na lokaciji M-10. Koncentracije ^{40}K u tlu iznosile su 447 ± 2 Bqkg^{-1}na lokaciji M-CPS, 496 ± 3 Bqkg^{-1}na lokaciji M-9 te 485 ± 4 Bqkg^{-1}na lokaciji M-10.



Slika 1. Doprinosi H(10)/t članova uranovijevog i torijevog prirodnog radioaktivnog niza, ^{40}K i fisijskog ^{137}Cs izračunati iz gama-spektrometrijskih mjerenja uzoraka tla uzorkovanih na poznatim lokacijama*

S obzirom da se u tlu u okolici plinskog polja koncentracije aktivnosti za ^{40}K iznose 100 – 600 Bqkg^{-1}, a ^{137}Cs 0 – 95 Bqkg^{-1} [1], izmjerene koncentracije aktivnosti ^{40}K i ^{137}Cs nisu posljedica rada plinskih bušotina plinskog polja Molve. Rad plinskih bušotina ne utječe na radioaktivnost u okolišu plinskog polja Molve.

1. Šoštarić, M., Petrinec, B., Avdić, M., Petroci, L., Kovačić, M., Zgorelec, Ž., Skoko, B., Bituh, T., Senčar, J., Branica, G., Franić, Z., Franulović, I., Rašeta, D., Bešlić, I., Babić, D. (2021.) a. Radioactivity of soil in Croatia II: 137Cs, 40K, and absorbed dose rate, Arhiv Higijene Rada i Toksikologije 72(1):15–22.

Ključne riječi: brzina ambijentalnog doznog ekvivalenta, ^{137}Cs, gamaspektrometrija, tlo

ESTIMATION OF RADIOACTIVITY AND SAFETY CONCERNS OF MOLVE GAS FIELD: RESULTS AND RECCOMENDATIONS FOR YEAR 2024.

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Abstract

Institute for Medical Research and Occupational Health (IMI) conducts environmental monitoring of the Molve gas field site.

Measurements were conducted at three locations: active gas well M-9, decommissioned gas well M-10, and central gas station M-CPS. Measurements were conducted with dose rate monitors (H*(10)/t) (Thermo Eberline ESM) and ALARA electronic dosimeters for continuous monitoring of the ambient dose equivalent rates. Additionally, gamma spectrometric analysis of soil samples was performed. Average (H*(10)/t) values were 97 ± 6 $nSvh^{-1}$ at M-9 location, 72.3 ± 0.8 $nSvh^{-1}$ at M-10, and 75 ± 1 $nSvh^{-1}$ at M-CPS. Contributions of natural radionuclides (^{238}U, ^{232}Th and ^{40}K), and ^{137}Cs were specifically analyzed. Activity concentrations of ^{137}Cs in the soil samples were 0.14 ± 0.06 $Bqkg^{-1}$at M-CPS, 0.45 ± 0.01 $Bqkg^{-1}$ at M-9, and 0.5 ± 0.1 Bq/kg at M-10. Concentrations of ^{40}K in the soil amounted to 447 ± 2 $Bqkg^{-1}$at M-CPS location, 496 ± 3 $Bqkg^{-1}$at M-9, and 485 ± 4 $Bqkg^{-1}$at location M-10.

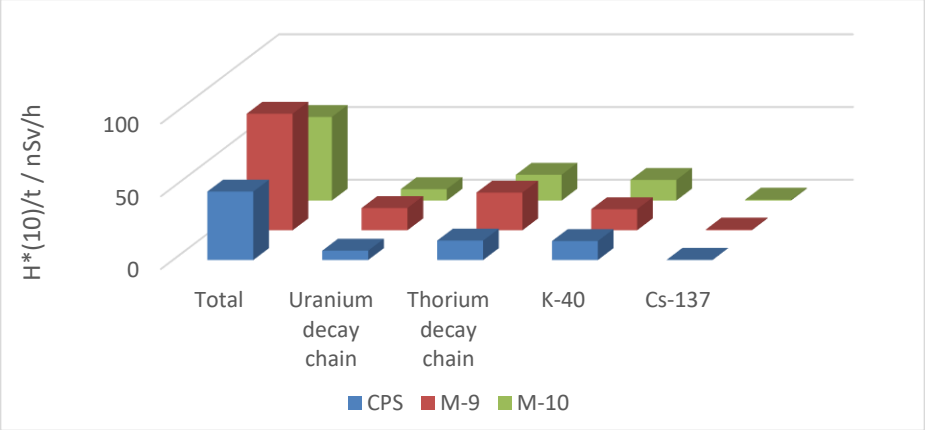

Figure 1. Contributions of H(10)/t members of the uranium and thorium natural radioactive decay series, ^{40}K, and fission-derived ^{137}Cs, determined from gamma spectrometric analysis of soil samples from well-known locations*

Considering that activity concentrations of soil in the vicinity of the gas field are 100 – 600 $Bqkg^{-1}$ for ^{40}K [1], and 0 – 95 $Bqkg^{-1}$ for ^{137}Cs, measured ^{40}K and ^{137}Cs activity concentrations are not the result of the operations of the Molve gas field.

1. Šoštarić, M., Petrinec, B., Avdić, M., Petroci, L., Kovačić, M., Zgorelec, Ž., Skoko, B., Bituh, T., Senčar, J., Branica, G., Franić, Z., Franulović, I., Rašeta, D., Bešlić, I., Babić, D. (2021.) a. Radioactivity of soil in Croatia II: 137Cs, 40K, and absorbed dose rate, Arhiv Higijene Rada i Toksikologije 72(1):15–22.

Keywords: ambient dose rate equivalent, cesium-137, gamma-ray spectrometry, soil

USPOREDBA METODA SAMODEPOZICIJE PO NA UZORCIMA DAGNJI KAO BIOINDIKATORIMA MORSKOG OKOLIŠA

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Sažetak
Najveći udio doze zračenja koji ljudi prime od prirodne radioaktivnosti potječe od tzv. NORM (*naturally occurring radionuclide material*) radionuklida kao što su izotopi U, Th, Ra, Rn, Pb i Po. Aktivnosti ovih radionuklida mogu rasti i mijenjati se raznim geološkim procesima ili ljudskim intervencijama u okolišu kao što su rudarenje ili industrijska aktivnost [1,2]. Stoga je točno određivanje njihove aktivnosti od izuzetnog značaja, posebice uzme li se u obzir utjecaj radionuklida na čovjeka i njegovo zdravlje. Uz vanjsko zračenje kojem su ljudi neprekidno izloženi, dio ukupne godišnje doze koju osoba primi potjecat će i od radionuklida koji se unesu u organizam hranom. Iako je put od okoliša do hrane vrlo kompleksan i ovisi o nizu faktora, vrlo je važno pronaći način kojim bi se precizno mogla pratiti procjena stanja i trendova unutar proučavanog ekosustava. U tu svrhu koriste se bioindikatori. Jedan od bioindikatora čijom se analizom može dobiti reprezentativna slika radionuklida u morskom okolišu su dagnje. Za njih je poznato da filtriraju i više od 80 litara vode dnevno pri čemu, između ostaloga, akumuliraju i teške metale i radionuklide iz morske vode zbog čega odlično odražavaju stanje u morskom okolišu te se stoga vrlo često i koriste kao bioindikatori za procjenu onečišćenja morskog okoliša [3]. Iako se one već dugi niz godina koriste u tu svrhu, u ovom radu ispitana je mogućnost određivanja Po-210 metodom prema referenci [3] koja se sastoji od samodepozicije Po na pločicu srebra u trajanju od četiri sata, pri 90 °C. Elektrolit koji se pritom koristi je 0,1 mol dm^{-3} klorovodična kiselina uz dodatak 0,5 g askorbinske kiseline.
Koncentracija aktivnosti polonija također je određena i primjenom istog elektrolita, ali uz vrijeme trajanja samodepozicije od približno 19 sati (preko noći), pri sobnoj temperaturi, uz neprekidno miješanje. Slijepa proba napravljena je dodatkom standardne otopine Po-209 u otopinu čistog elektrolita, a ista metoda potom je primijenjena i na uzorcima dagnji prikupljenih na devet različitih lokacija duž Jadranske obale u kojima je određen Po-210. Dobiveni rezultati uspoređeni s rezultatima Po u dagnjama pripremljenim po proceduri iz reference [3].

1. Bezuidenhout, J. (2019.) The relationship among naturally occurring radionuclides, geology, and geography: Tsodilo Hills, Botswana, Journal of Radiation Research and Applied Science, 12 (1) 93-100.
2. Šoštarić, M., Petrinec, B., Avdić, M., Petroci, L., Kovačić, M., Zgorelec, Ž., Skoko, B., Bituh, T., Senčar, J., Branica, G. (2021.) a. Radioactivity of soil in Croatia I: naturally occurring decay chains, Arhiv Higijene Rada i Toksikologije 72(1):6–14.
3. Rožmarić M., Rogić M., Benedik Lj., Štrok M., Barišić D., Gojmerac Ivšić A. (2012.) ^{210}Po and ^{210}Pb activity concentrations in Mytilus galloprovincialis from Croatian Adriatic coast with the related dose assessment to the coastal population, Chemosphere, 1298-1300.

Ključne riječi: alfa spektrometrija, samodepozicija, dagnje, polonij

COMPARISON OF AUTO-DEPOSITION METHODS OF PO IN MUSSEL SAMPLES AS BIOINDICATORS OF MARINE ENVIRONMENT

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Abstract
Largest part of the dose absorbed by humans from natural radioactivity originates from so-called NORM (naturally occurring radionuclide material) radionuclides such as isotopes of U, Th, Ra, Rn, Pb, and Po. Activities of these radionuclides can increase and change with varying geological processes or by human interventions in the environment such as mining or industrial activity [1,2]. Because of this, correctly determining their activities is important, especially considering the effect radionuclides have on human health. Including external radiation to which humans are constantly exposed to, part of the annual dose received comes from radionuclides ingested with food. Even though radionuclide pathway from the environment to food is very complex, and depends on a series of factors, it is important to find a way to precisely monitor the state and trends inside the selected ecosystem. Bioindicators are used for this purpose. One of bioindicators whose analysis can result in a representative picture of radionuclides in marine environment are mussels. It is known that they filter more than 80 liters of water daily, which results in them accumulating heavy metals and radionuclides from seawater, making them excellent mirrors of the state of marine environment because of which they are often used as bioindicators for marine ecosystem pollution estimates [3]. Although they are used for this purpose for many years, the goal of this work was to examine the possibility of determining Po-210 using method from the reference [3] which includes auto-depositing the polonium onto a silver disk for four hours at 90 °C, using 0,1 mol dm^{-3} hydrochloric acid with addition of 0,5 g ascorbic acid as an electrolyte.
Activity concentration of polonium was also determined using the same electrolyte, but with auto-deposition duration of approximately 19 hours (overnight), at room temperature, with constant stirring. Blind tests were made by adding standard solution of Po-209 in a pure electrolyte, with the same method being used to determine Po-210 in mussel samples which were collected at nine locations along the Adriatic coast. Results obtained were compared with results of Po in mussels prepared by the procedure from the reference [3].

1. Bezuidenhout, J. (2019.) The relationship among naturally occurring radionuclides, geology, and geography: Tsodilo Hills, Botswana, Journal of Radiation Research and Applied Science, 12 (1) 93-100.
2. Šoštarić, M., Petrinec, B., Avdić, M., Petroci, L., Kovačić, M., Zgorelec, Ž., Skoko, B., Bituh, T., Senčar, J., Branica, G. (2021.) a. Radioactivity of soil in Croatia I: naturally occurring decay chains, Arhiv Higijene Rada i Toksikologije 72(1):6–14.
3. Rožmarić M., Rogić M., Benedik Lj., Štrok M., Barišić D., Gojmerac Ivšić A. (2012.) ^{210}Po and ^{210}Pb activity concentrations in Mytilus galloprovincialis from Croatian Adriatic coast with the related dose assessment to the coastal population, Chemosphere, 1298-1300.

Keywords: alpha-spectrometry, auto-deposition, mussels, polonium

PRIRODNA I UMJETNA RADIOAKTIVNOST U TLIMA POLUOTOKA PELJEŠCA

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Sažetak:
Prirodna radioaktivnost predstavlja primarni izvor izloženosti ljudi ionizirajućem zračenju, pri čemu su ključni prirodni radionuklidi poput izotopa uranija (U), torija (Th), radija (Ra), radona (Rn), olova (Pb) i polonija (Po). Njihove aktivnosti mogu značajno varirati ovisno o geološkoj podlozi ili ljudskim aktivnostima poput rudarenja i industrijskih zahvata. Precizno određivanje koncentracija ovih radionuklida od velike je važnosti, posebice zbog njihovog potencijalnog utjecaja na ljudsko zdravlje i okoliš.
U sklopu HRZZ projekta RiChFALL, provedena su istraživanja radioaktivnosti u tlima poluotoka Pelješca, koja su pokazala da su koncentracije aktivnosti prirodnih (^{210}Pb, ^{210}Po, ^{226}Ra, ^{232}Th) te umjetnih radionuklida (^{137}Cs, ^{90}Sr) u tlima poluotoka Pelješca značajno iznad prosjeka u odnosu na ostatak Hrvatske. Osim njih, identificirani su i ^{241}Am te $^{239+240}$Pu, čija se prisutnost povezuje s globalnom nuklearnom kontaminacijom, najvjerojatnije uzrokovanom testiranjima nuklearnog oružja provedenim u sjevernoj Africi tijekom 1960-ih godina.
Kako bi se potvrdila prisutnost ^{241}Am, provedena su dodatna mjerenja alfa spektrometrijom, pri čemu su uz ^{241}Am utvrđene i mjerljive koncentracije aktivnosti $^{239+240}$Pu. Budući da alfa spektrometrijska analiza zahtijeva složenu pripremu uzoraka, uključujući mikrovalnu digestiju i separaciju radionuklida pomoću specijaliziranih smola, optimiziran je postupak separacije izotopa Am, Pu i Th na TRU smoli. Ova optimizacija omogućila je skraćenje vremena analize. Dobivene vrijednosti koncentracija aktivnosti iznosile su do 2,5 Bq/kg za ^{241}Am te do 6 Bq/kg za $^{239+240}$Pu.
Zbog značajnih razlika u koncentraciji aktivnosti određenih radionuklida na Pelješcu u odnosu na prosječne vrijednosti određene u ostatku Hrvatske, (primjerice za ^{137}Cs prosječne izmjerene koncentracije aktivnosti su na poluotoku Pelješcu i oko pet puta veće) provedena je detaljna analiza uzoraka tla s različitih lokacija poluotoka. Osim toga, ispitana je i akumulacija radionuklida u biljkama koje su karakteristične za to područje, uključujući smilje, ružmarin i kadulju. Kroz ova istraživanja proučavaju se i transfer faktori radionuklida u svrhu razumijevanja mehanizma prijelaza radionuklida iz tla u biljke i daljnjeg utjecaja na hranidbeni lanac.
Ova istraživanja pružaju važne podatke za procjenu dugoročnih utjecaja prirodnih i umjetnih radionuklida na ekosustave i ljudsko zdravlje te doprinose razumijevanju njihove dinamike u okolišu.

Ključne riječi: poluotok Pelješac, prirodna radioaktivnost, umjetni radionuklidi, alfa spktrometrija

NATURAL AND ANTHROPOGENIC RADIOACTIVITY IN THE SOILS OF THE PELJEŠAC PENINSULA

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Abstract:
Natural radioactivity is the main source of human exposure to ionizing radiation. The most important natural radionuclides include the isotopes of uranium (U), thorium (Th), radium (Ra), radon (Rn), lead (Pb) and polonium (Po). Their activities can fluctuate considerably under the influence of geological processes or human activities such as mining and industry. The exact determination of the concentrations of these radionuclides is of great importance, especially because of their possible effects on human health and the environment.
As part of the HRZZ project RiChFALL, radioactivity analyses were carried out in the soils of the Pelješac peninsula. The results showed that the activity concentrations of natural (^{210}Pb, ^{210}Po, ^{226}Ra, ^{232}Th) and anthropogenic radionuclides (^{137}Cs, ^{90}Sr) were significantly higher than average values measured in the rest of Croatia. In addition, ^{241}Am and $^{239+240}$Pu were also detected. Their presence is probably related to global nuclear contamination, which was most likely caused by nuclear weapons tests in North Africa in the 1960s. To confirm the presence of ^{241}Am, additional measurements were carried out using alpha spectrometry. In addition to ^{241}Am, the measurable activity concentrations of $^{239+240}$Pu were also determined. As alpha spectrometric analysis requires complex sample preparation, including microwave digestion and separation of the radionuclides with special resins, the separation procedure for the isotopes Am, Pu and Th was optimized on TRU resin. This optimization made it possible to shorten the analysis time. The measured activity concentrations were up to 2.5 Bq/kg for ^{241}Am and up to 6 Bq/kg for $^{239+240}$Pu.
Since the activity concentration of certain radionuclides on Pelješac differs considerably from the average values determined in the rest of Croatia (for ^{137}Cs, for example, the measured average activity concentrations on the Pelješac peninsula are five times higher), a detailed analysis of soil samples from various locations on the peninsula was carried out. In addition, the accumulation of radionuclides in plants characteristic of the area, including immortelle, rosemary and sage, was analyzed. This research also investigated the transfer factors in order to understand the mechanism of radionuclide path from soil to plants and the wider impact on the food chain. This research provides important data for assessing the long-term effects of natural and anthropogenic radionuclides on ecosystems and human health and contributes to the understanding of their dynamics in the environment.

Keywords: Pelješac peninsula, natural radioactivity, anthropogenic radionuclides, alpha spectrometry

RADIONUKLIDI U POLJOPRIVREDNIM KULTURAMA I TLIMA OBITELJSKIH POLJOPRIVREDNIH GOSPODARSTAVA U HRVATSKOJ

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Sažetak

Radionuklidi, kako prirodni tako i umjetni, sveprisutni su u okolišu te dospijevaju i u hranidbeni lanac. Praćenje radioaktivnosti u okolišu i hrani te određivanje mogućeg utjecaja na zdravlje ljudi stoga je od posebnog značaja. U ovom radu prikazani su rezultati mjerenja radioaktivnosti u odabranim poljoprivrednim kulturama (žitarice, lisnato povrće, voće, nelisnato povrće, gomolji, korjenasto povrće, začinsko bilje te orašasti plodovi) i tlima s 26 obiteljskih poljoprivrednih gospodarstava (OPG) diljem Hrvatskoj.

Za obje vrste uzoraka, za kvantitativnu analizu radionuklida koje je moguće određivati gama-spektometrijski direktno ili posredno putem potomaka, korišteni su germanijski detektori visoke čistoće (HPGe). Beta emiter ^{90}Sr određivan je nakon radiokemijske separacije korištenjem proporcionalnog α/β brojača te Čerenkovljevim brojanjem tekućinskim scintilacijskim brojačem. Alfa emiter ^{210}Po određivan je alfa spektrometrijski nakon radiokemijske separacije.

Najveće koncentracije aktivnosti svih radionuklida utvrđene su u začinskom bilju, neovisno o lokaciji uzorkovanja, što se može objasniti visokim sadržajem suhe tvari. Lisnato povrće imalo je drugi najveći sadržaj radioaktivnosti većine radionuklida. Na temelju podataka o godišnjoj potrošnji analiziranih biljnih skupina, rezultati koncentracija aktivnosti korišteni su za procjenu godišnje ingestijske doze za tri dobne skupine: jednogodišnju i desetogodišnju djecu te odrasle. Izračunata je redom godišnja ingestijska doza od 0,533, 0,666 i 0,348 mSv. Svi rezultati su ispod preporučene granice od 1 mSv/god. 70 % procjenjene primljene doze dolazi od ^{228}Ra i ^{40}K, dok osim njih značajnije doprinose i ^{226}Ra, ^{210}Pb i ^{210}Po. Doprinos dozi po grupama namirnica u silaznom redoslijedu za djecu i odrasle je: žitarice > lisnato povrće > začinsko bilje > voće > nelisnato povrće > gomolji > korjenasto povrće ≫ orašasti plodovi.

Rezultati određeni u tlima na kojima su rasle analizirane kulture korištene su za proračun i istraživanje prijelaza radionuklida iz tla u biljku. Faktori prijelaza pokazuju široke raspone unutar iste kategorije bilja (više redova veličine) što ukazuje na složenost mehanizma prijelaza i potrebu za daljnjim istraživanjima. Prema lokaciji uzorkovanja, povećane koncentracije aktivnosti prirodnih i značajnija prisutnost umjetnih radionuklida u odnosu na ostatak Hrvatske uočena je u tlima uzorkovanima na poluotoku Pelješcu. Stoga su započeta daljnja istraživanja na tom području i u svrhu utvrđivanja podrijetla prisutnih radionuklida, kao i za podrobnije istraživanje mehanizama prijelaza radionuklida iz okoliša u biljku.

Ključne riječi: radioaktivnost, poljoprivredne kulture, godišnja ingestijska doza, transfer faktor

RADIONUCLIDES IN AGRICULTURAL CROPS AND SOILS FROM FAMILY FARMS IN CROATIA

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Abstract
Natural and artificial radionuclides are present in the environment and therefore reach the food chain. Monitoring of radioactivity in the environment and in food, as well as determining the possible impact on human health, is therefore of particular importance. This work presents the results of radioactivity measurements in selected agricultural crops (cereals, leafy vegetables, fruits, non-leafy vegetables, tubers, root vegetables, herbs and nuts) and soils from 26 family farms throughout Croatia.
For both types of samples, high purity germanium detectors (HPGe) were used for the quantitative analysis of radionuclides that can be determined directly or indirectly by their progenies using gamma-spectrometry. The beta emitter ^{90}Sr was determined after radiochemical separation using a proportional α/β counter and Cherenkov counting with a liquid scintillation counter. The alpha emitter ^{210}Po was determined by alpha spectrometry after radiochemical separation.
By far the highest activity concentrations of all radionuclides were determined in herbs, regardless of the sampling location, which can be explained by the high content of dry matter. Leafy vegetables are next in terms of the radioactivity content of most radionuclides. Based on the annual consumption data on the analyzed plant groups, the activity concentration results were used to estimate the annual ingestion dose for three age groups: one- and ten-year-old children and adults. The annual ingestion dose of 0.533, 0.666 and 0.348 mSv was calculated, respectively. All results are below the recommended limit of 1 mSv/year. 70 % of the estimated received dose comes from ^{228}Ra and ^{40}K. Other significant contributors are^{226}Ra, ^{210}Pb and ^{210}Po. Contribution per foodstuff groups in descending order for children and adults is: cereals > leafy vegetables > herbs > fruit > non-leafy vegetables > tubers > root vegetables ≫ nuts.
The results obtained in soils on which the analyzed crops grew were used to calculate and investigate the transfer of radionuclides from soil to the plant. Transfer factors show wide ranges within the same plant category (several orders of magnitude) indicating the complexity of the transfer mechanism and the need for further investigation. According to the sampling location, higher concentration activities of natural radionuclides and higher occurance of artificial radionuclides were found in the soils of Pelješac peninsula compared to the rest of Croatia. Therefore, further research continued in that area to determine the origin of the radionuclides present and to investigate the mechanisms of the dynamics and transition of radionuclides from the environment to plants.

Keywords: radioactivity, agricultural crops, annual ingestion dose, transfer factor

PROCJENA RADIOLOŠKOG RIZIKA ZA NELJUDSKU BIOTU U BRODSKO-POSAVSKOJ ŽUPANIJI POMOĆU SOFTVERSKOG ALATA ERICA

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Sažetak

Alat ERICA predstavlja softverski program namijenjen procjeni radiološkog rizika za neljudsku biotu, pružajući korisnicima vođeni proces procjene, vođenje evidencije te provođenje potrebnih izračuna za određivanje ukupne brzine apsorbirane doze za odabrane referentne organizme. Evaluacijski okvir ERICA softvera temelji se na integriranom pristupu procjene koji je organiziran kroz tri razine. U ovom istraživanju analiziran je radiološki rizik za neljudsku biotu u Brodsko-posavskoj županiji zbog svoje granice s Bosnom i Hercegovinom čiji industrijski pogoni poput rafinerija nafte i drugih postrojenja predstavljaju potencijalne izvore radiološke i druge kontaminacije. Na odabranih trinaest lokacija izmjerene su koncentracije aktivnosti radona u tlu te permeabilnost tla radi procjene geogenog radonskog potencijala, a na istim su lokacijama uzeti i uzorci tla za gama spektrometrijske analize.

U prvoj razini procjene, iz izbornika alata ERICA odabrani su ključni radionuklidi: ^{137}Cs, ^{232}Th, ^{238}U, ^{226}Ra, ^{210}Pb i ^{235}U čije su koncentracije aktivnosti prethodno izmjerene na Ortecovom HPGe gama spektrometrijskom sustavu. Softver uspoređuje unesene koncentracije s najrestriktivnijim EMCL vrijednostima (Environmental Media Concentration Limits) za svaki radionuklid te izračunava kvocijent rizika (RQ). Ako je RQ veći od 1, provodi se daljnja analiza na strožoj, drugoj razini procjene.

Na razini 2, odabrani su svi referentni kopneni organizmi te je primijenjen faktor nesigurnosti (UF=3). ERICA na ovoj razini računa prijenosne faktore za svaki radionuklid u pojedinim organizmima te procjenjuje koncentracije aktivnosti radionuklida u organizmima. Rezultati razine 2 uključuju očekivane i konzervativne kvocijente rizika (RQ) te ukupne težinske brzine doza. Za mahovine i lišajeve, očekivani RQ bio je manji od 1, dok je konzervativni RQ bio veći od 1. Zbog ovakvih rezultata, bilo je potrebno provesti dodatna istraživanja kako bi se procijenili potencijalni radiološki učinci na ove organizme.

Rezultati pokazuju kako softverski alat ERICA omogućava detaljnu i sustavnu procjenu radiološkog rizika za neljudsku biotu, pružajući informacije ključne za razumijevanje potencijalnih utjecaja radionuklida na okoliš. Uz primjenu podataka o koncentracijama radionuklida u tlu i organizmima, kao i određivanje geogenog radonskog potencijala, dobivene su vrijedne informacije koje mogu poslužiti u daljnjem istraživanju i radiološkoj zaštiti biote.

Ključne riječi: radiološki rizik, neljudska biota, ERICA softver, Brodsko-posavska županija

ASSESSMENT OF RADIOLOGICAL RISK TO NON-HUMAN BIOTA IN THE BRODSKO-POSAVINA COUNTY USING THE ERICA SOFTWARE TOOL

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Abstract

The ERICA tool is a software program designed for assessing radiological risk to non-human biota, providing users with a guided assessment process, record-keeping, and the necessary calculations to determine the total absorbed dose rate for selected reference organisms. The evaluation framework of the ERICA software is based on an integrated assessment approach organized into three levels. In this study, the radiological risk to non-human biota in the Brod-Posavina County was analyzed due to its border with Bosnia and Herzegovina, where industrial facilities such as oil refineries and other plants represent potential sources of radiological and other contamination. At thirteen selected locations, measurements were taken of radon activity concentrations in the soil gas and soil permeability to assess the geogenic radon potential. Additionally, soil samples were collected from the same locations for gamma spectrometry analysis.

In the first level of assessment, key radionuclides were selected from the ERICA tool's menu: ^{137}Cs, ^{232}Th, ^{238}U, ^{226}Ra, ^{210}Pb i ^{235}U whose activity concentrations had been previously measured using an ORTEC HPGe gamma spectrometry system. The software compares the entered concentrations with the most restrictive EMCL (Environmental Media Concentration Limits) values for each radionuclide and calculates the risk quotient (RQ). If the RQ exceeds 1, further analysis is conducted at the stricter second level of assessment.

At Level 2, all terrestrial reference organisms were selected, and an uncertainty factor (UF=3) was applied. At this level, ERICA calculates the transfer factors for each radionuclide in individual organisms and estimates the radionuclide activity concentrations within the organisms. The Level 2 results include expected and conservative risk quotients (RQ) and total weighted dose rates. For mosses and lichens, the expected RQ was less than 1, while the conservative RQ was greater than 1. Due to these results, further research was necessary to evaluate potential radiological effects on these organisms.

The results demonstrate that the ERICA software tool enables detailed and systematic assessment of radiological risk to non-human biota, providing crucial information for understanding the potential impacts of radionuclides on the environment. By applying data on radionuclide concentrations in soil and organisms, as well as determining geogenic radon potential, valuable information has been obtained that can support further research and radiological protection of biota.

Key words: Radiological risk, non-human biota, ERICA software, Brod-Posavina County

ANALIZA NAKUPLJANJA RADIONUKLIDA U VRETENCIMA (*ODONATA*) U PARKU BIOSFERE MURA-DRAVA-DUNAV

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Sažetak

Prisutnost radionuklida važna je odrednica zdravlja vodenih staništa. Međutim, radionuklide je u nekim slučajevima teško detektirati obzirom da mogu biti prisutni u vrlo malim koncentracijama. U svrhu razvoja metodologije mjerenja koncentracija radionuklida u okolišu, ispitana je mogućnost određivanja njihove aktivnosti analizom uzoraka životinjskih vrsta koje akumuliraju radionuklide. Vretenca su uzorkovana na 9 različitih lokacija unutar Rezervata biosfere Mura-Drava-Dunav, u blizini vodenih staništa. Metodom gama spektrometrije analizirane su aktivnosti ^{238}U, ^{228}Th i ^{40}K na detektorskom sustavu ORTEC HPGe. Izmjerene koncentracije aktivnosti u riječnoj vodi bile su u rasponu od 80 do 100 Bq/m^3 za ^{238}U, od 9 do 18 Bq/m^3 za ^{228}Th i od 210 do 370 Bq/m^3 za ^{40}K. S druge strane, koncentracije aktivnosti radionuklida u uzorcima vretenaca iznosile su od 1,3 do 28 Bq/kg za ^{238}U, od 2,6 do 6 Bq/kg za ^{228}Th te 110 do 250 Bq/kg za ^{40}K. Ovim istraživanjem pokazano je da su vretenca važna komponenta u cirkulaciji radionuklida u vodenim staništima te se mogu smatrati bioindikatorskim vrstama.

Ključne riječi: vretenca, gama spektrometrija, ^{238}U, ^{228}Th i ^{40}K

ANALYSIS OF RADIONUCLIDE ACCUMULATION IN DRAGONFLIES (*ODONATA*) IN THE MURA-DRAVA-DANUBE BIOSPHERE RESERVE

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Abstract

The presence of radionuclides is an important parameter for health of aquatic habitats. However, radionuclides are difficult to detect in certain cases, considering they could be present in very low concentrations. To develop methodology for detecting radionuclides in the environment, we analyzed the possibility of using animal species that accumulate radionuclides as indicator species. Dragonflies were sampled in 9 different locations within the Mura-Drava-Danube Biosphere Reserve, close to their aquatic habitats. Using the gamma-spectrometry method, activities of ^{238}U, ^{228}Th and ^{40}K were determined with ORTEC HPGe detector system. Measured activity concentrations in river water ranged from 80 to 100 Bq/m^3 for ^{238}U, from 9 to 18 Bq/m^3 for ^{228}Th, and from 210 to 370 Bq/m^3 for ^{40}K. On the other hand, activity concentrations in dragonfly samples ranged from 1.3 to 28 Bq/kg for ^{238}U, 2.6 to 6 Bq/kg for ^{228}Th and 110 to 250 Bq/kg for ^{40}K. This research has shown that dragonflies are an important component of radionuclide circulation in aquatic habitats, and could be as considered bioindicator species.

Key words: dragonfly, gamma-ray spectrometry, ^{238}U, ^{228}Th i ^{40}K

URANIUM ISOTOPES AND RADIUM IN GROUNDWATER: RADIOLOGICAL DOSE ASSESSMENT IN GOLD MINING REGIONS OF TANZANIA

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Abstract

Groundwater contamination by naturally occurring radionuclides is an increasing concern in gold mining regions of Tanzania, where numerous communities depend on shallow wells for drinking water. The 2022 Mara River pollution incident, along with unregulated well construction, has increased the risk of radioactive contamination from anthropogenic activities and natural geological formations in the regions. This study assessed the activity concentrations level of uranium isotopes and radium, in groundwater and their potential health implications to different age groups in Mara Region. The samples were analyzed for ^{234}U, ^{235}U, ^{238}U and ^{226}Ra activity concentrations using alpha spectrometry and the results were consequently used to assess health risk impact to infants, children and adults. The results revealed elevated activity concentrations in some wells found to be ^{238}U: 3130 ± 135 mBq L^{-1}, ^{235}U: 473.0 ± 37 mBq L^{-1}, ^{234}U: 6530 ± 260 mBq L^{-1} and ^{226}Ra: 169.3 ± 6.6 mBq L^{-1}. The estimated annual effective ingestion dose assessment was highest for infants (over 6 months) at 0.82 mSv y^{-1}, followed by children (1 – 15 years) at 0.36 – 0.57 mSv y^{-1}, and adults (over 15 years) at 0.38 mSv y^{-1}. ^{234}U had the maximum contribution to the dose, followed by ^{238}U and ^{226}Ra while the dose resulting from ^{235}U was the least. The maximum estimated doses assessed for all age groups exceed the WHO recommended value of 0.1 mSv y^{-1} for drinking water. However, the total dose remains below the ICRP/IAEA public exposure limit of 1 mSv y^{-1}. Infants and children are more vulnerable, demanding regular groundwater monitoring and possible mitigation strategies including alternative water sources to reduce exposure risks.

Keywords: Groundwater, Uranium, Radium, Dose assessment, Age groups

INVESTIGATION OF DISTURBED $^{226}Ra/^{238}U$ EQUILIBRIUM IN THE SOIL AS A PREDICTOR OF RPA

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Abstract

RPA Radon priority areas must be clearly delineated and classified into zones based on data that influence indoor radon. Based on measurements and long-term research, several basic predictors of radon can be distinguished: radium content in the soil, geology and tectonics of the examined area, radon concentration in the soil, and terrestrial dose rates. To investigate Niška Banja, a candidate for RPA, a detailed dose characterization of seven localities lying on faults between geomorphological units was carried out by dosimeter model bGeigie Nano. Surface soil samples were taken and radionuclide activity concentrations were determined by the gamma spectrometry method in two accredited national monitoring laboratories and intercomparison of the results was performed. Obtained radium concentrations were in the range (35 – 1500) Bq/kg and a significant disturbance of the natural equilibrium of $^{226}Ra/^{238}U$ in four samples was observed and discussed. Radon concentrations in the soil at a depth of 80 cm were measured by RAD7 active monitor in accordance with the standard international protocol. In order to predict the geogenic radon potential, the granulometric composition of the soil was analyzed, and the surface exhalation of radon from the soil was estimated within (0.36 - 218) Bq m^{-2} h^{-1}.

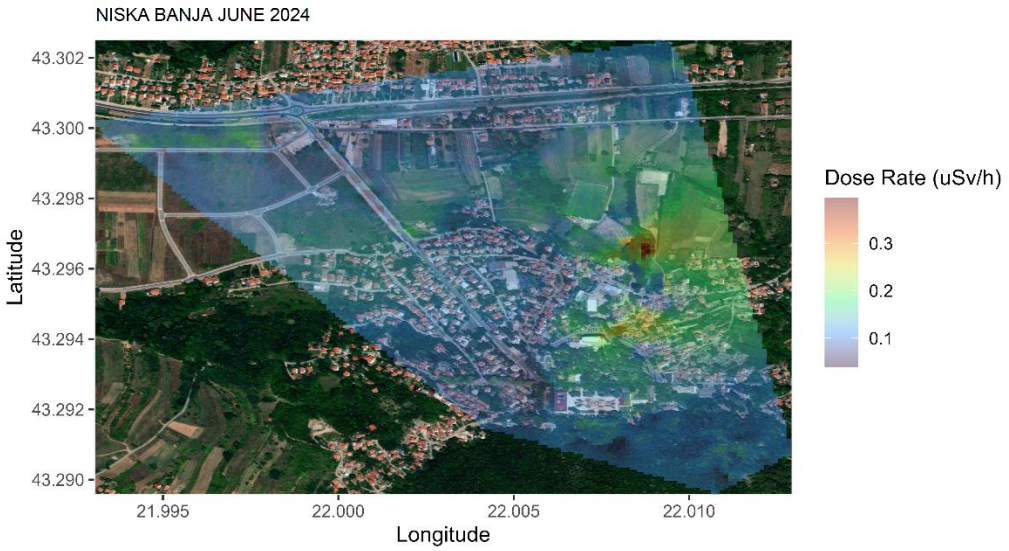

Figure 1: Figures are allowed. Description font: Calibri, size 10.

Key words: Radon priority areas, gamma spectrometry, geogenic radon potential

RADON

RADON

RAZNOVRSNA ZBRKA/NEDOUMICE VEZANE UZ PLIN RADON IZ IZVORIŠTA PITKE VODE U RH

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Sažetak

Načelo predostrožnosti izričito je utvrđeno direktivom EU-a i jedno je od polazišta njezine politike zaštite okoliša. Europska komisija dala je izjavu u veljači 2000. u vezi s praktičkim korištenjem načela predostrožnosti u kojoj je naznačeno da se to načelo treba primijeniti tamo gdje postoji opravdana sumnja na postojanje rizika za zdravlje ljudi ili okoliš (biotu). Nadalje, Komisija ukazuje da mjere temeljene na načelu predostrožnosti ne bi trebale biti usmjerene na potpuno isključivanje bilo kakvog rizika; pretpostavlja da je takav napor nerealan [1]. EU je usvojio preinačenu Direktivu o vodi za piće u prosincu 2020., a Direktiva je stupila na snagu u siječnju 2021. Koncentracija aktivnosti prirodnih radionuklida (ili čak umjetnih) mora se pratiti u vodi i regulatorno je pokrivena posebnim nacionalnim propisima. Direktiva Vijeća 2013/59/Euratom kroz Prilog XVII. pokriva dugoročne rizike od izloženosti radonu i osnova je za sve akcijske planove za radon (RAP) država članica EU-a [2]. Dugoročni cilj hrvatskog RAP-a je primjenom promišljenih i koordiniranih mjera doprinijeti smanjenju izlaganja radonu osoba koje žive u Republici Hrvatskoj te posljedično smanjiti rizik od raka pluća povezanog s povećanim ozračenjem od radona. Neka regulatorna pravila su postavljena, ali glavna hrvatska strategija koja pokriva upravljanje i praćenje plina radona u pitkoj vodi nije u potpunosti uspostavljena. Na razini EU-a u tijeku su završne konzultacije o praktičnoj primjeni doznih koeficijenata radona za radnike u industriji proizvodnje vode i očekuje se da će za sve države članice biti izdane obvezujuće Smjernice EU-a (https://energy.ec.europa.eu/topics/nuclear-energy/radiation-protection/scientific-seminars-and-publications/radiation-protection-series-publications_en). Ovaj rad ima za cilj pridonijeti raspravi o Strategiji upravljanja hrvatskim bogatstvom pitke vode u okviru zaštite biološke raznolikosti i zdravlja ljudi od svake zamislive radioaktivne „zlouporabe“.

Ključne riječi: radon, PRM; voda za piće, monitoring

[1] Commission of the European Communities. Communication from the Commission on the precautionary principle. Brussels: Commission of the European Communities, 2000; (publication nr COM(2000)1).
[2] National Radon Action Plans in Europe and Need of Effectiveness Indicators: An Overview of HERCA Activities; International Journal of Environmental Research and Public Health - doi: 10.3390/ijerph1907411

VARIOUS PUZZLES CONCERNING RADON GAS IN CROATIAN DRINKING WATER DWELLINGS

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Abstract:
The precautionary principle is explicitly laid down in the EU treaty and is one of the starting points of its environmental policy. European Commission made a statement in February 2000 regarding the use of the precautionary principle indicating that the principle should be applied where there is a reasonable suspicion of the existence of a health or environmental risk. Furthermore, the Commission indicates that measures based on the precautionary principle should not be aimed at completely precluding any risk; it assumes that such an effort is unrealistic [1]. The EU adopted the recast Drinking Water Directive in December 2020 and the Directive entered into force in January 2021. The activity concentration of natural radionuclides (or even artificial) has to be monitored in water and is regulatory covered with special national regulations. Council Directive 2013/59/Euratom covers the long-term risks from radon exposures through Annex XVII and is a base for all EU Member States Radon Action Plans (RAP) [2]. The long-term goal of Croatian RAP is, by applying well-thought-out and coordinated measures, to contribute to the reduction of radon radiation of people living in the Republic of Croatia and consequently to reduce the risk of lung cancer associated with increased radon radiation.
Some of the regulatory issues are performed, but a major Croatian strategy covering the management and monitoring of Radon gas in drinking water is not jet fully established. On the EU level, final consultations on practical implementation of Radon dose coefficients for workers in "water production" industry are in progress and it is expected that, for all MS mandatory, EU Guidance will be issued (https://energy.ec.europa.eu/topics/nuclear-energy/radiation-protection/scientific-seminars-and-publications/radiation-protection-series-publications_en). This paper aims to contribute to discussion about the managing Strategy of Croatian drinking water wealth in a scope of protecting the biodiversity and human health from any imaginable radioactive abuse.

Keywords: radon; NORM; drinking water; monitoring

[1] Commission of the European Communities. Communication from the Commission on the precautionary principle. Brussels: Commission of the European Communities, 2000; (publication nr COM(2000)1).
[2] National Radon Action Plans in Europe and Need of Effectiveness Indicators: An Overview of HERCA Activities; International Journal of Environmental Research and Public Health - doi: 10.3390/ijerph1907411

MJERENJE RADONA U STAMBENIM ZGRADAMA U GRADU ZAGREBU

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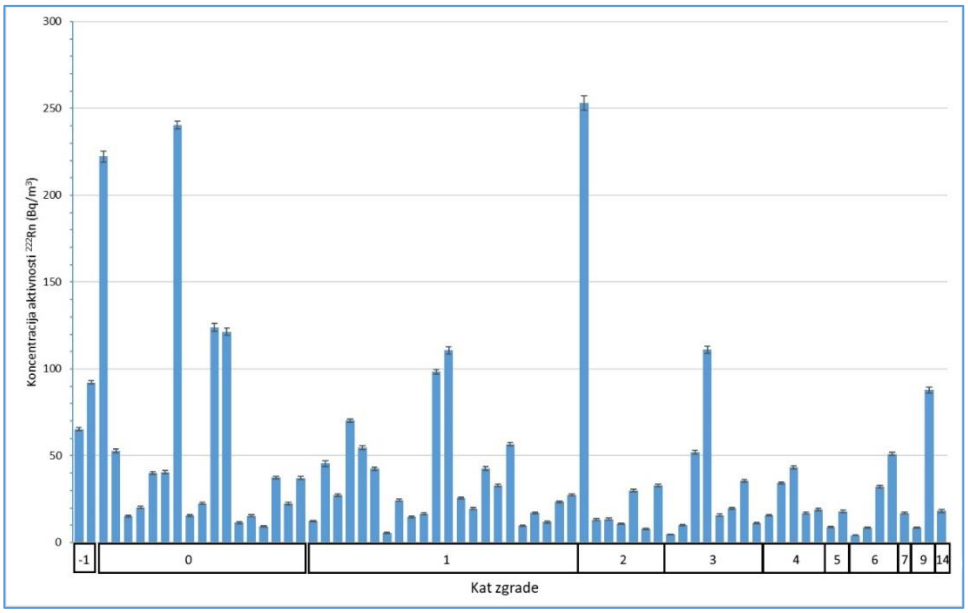
Radon je prirodni radioaktivni plin koji se može naći u visokim koncentracijama u zatvorenim prostorima, kao što su domovi i radna mjesta. Poznato je da je radon jedan od vodećih uzroka raka pluća, stoga je praćenje koncentracija radona neophodno i njime se upravlja kroz nacionalne politike i propise. Prema Direktivi Vijeća EU 2013/59/Euratom, referentna razina za godišnju prosječnu koncentraciju aktivnosti u zraku je 300 Bq/m3. Mjerenja radona mogu se provoditi aktivnim (za kratkotrajna mjerenja) ili pasivnim (za dugotrajna mjerenja) detektorima. U sklopu projekta EDIAQI (Evidence driven indoor air quality improving – HORIZON-HLTH-2021-ENVHLTH-02 Grant Agreement No. 101057497) provedena su mjerenja radona u stanovima u Gradu Zagrebu na 71 lokaciji. Mjereno je akreditiranom metodom (sukladno Normi ISO 11665-4) koristeći detektore nuklearnih tragova koji su bili izloženi 90 dana. Rezultati mjerenja prikazani su na Slici 1. Iako postoji nekoliko stambenih prostora u kojima je povišena koncentracija aktivnosti radona, niti na jednoj lokaciji nije premašena referentna vrijednost od 300 Bq/m^3.



Slika 1. Koncentracije aktivnosti ^{222}Rn [Bq/m^3] s prikazanim mjernim nesigurnostima (k=1) mjereno na 71 lokaciji u Gradu Zagrebu

Ključne riječi: radon, stambene zgrade, radioaktivnost

MEASUREMENTS OF RADON CONCENTRATIONS IN DWELLINGS IN THE CITY OF ZAGREB

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Radon is a naturally occurring radioactive gas that can be found in high concentrations in enclosed spaces, such as homes and workplaces. Radon is known to be one of the leading causes of lung cancer; therefore, monitoring of radon is essential and managed through national policies and regulations. According to EU Council Directive 2013/59/Euratom, the reference level for the annual average concentration of activity in the air is 300 Bq/m^3. Radon measurements can be carried out with active (for short-term measurements) or passive (for long-term measurements) detectors. As part of the EDIAQI project (Evidence driven indoor air quality improving – HORIZON-HLTH-2021-ENVHLTH-02 Grant Agreement No. 101057497), radon measurements were carried out in dwellings in the City of Zagreb at 71 locations. Radon activity concentrations were measured by an accredited method (according to Standard ISO 11665-4) using solid state nuclear track detectors exposed for 90 days. The results of the measurements are shown in Figure 1. Although there are several locations where the concentration of radon activity is elevated, the reference level of 300 Bq/m^3 has not been exceeded in any location.

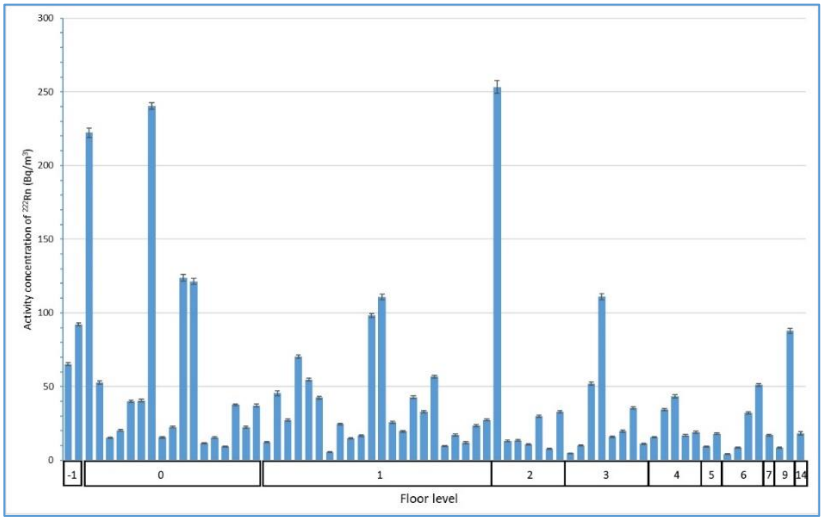

Figure1. Activity concentration of ^{222}Rn [Bq/m^3] with measurement uncertainty (k=1) measured at 71 locations in dwellings in the Citiy of Zagreb

Key words: radon, dwellings, radioactivity

MJERENJE KONCENTRACIJE RADONA U ŠPILJI VETERNICA

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Špilje su specifična prirodna staništa u kojima se često bilježe povišene koncentracije radona, prirodnog radioaktivnog plina. Radon i njegovi produkti raspada mogu predstavljati rizik za zdravlje vodiča i posjetitelja, stoga je sustavno praćenje koncentracija radona u špiljama od iznimne važnosti. Tijekom lipnja i srpnja 2023. i 2024. godine, djelatnici Zavoda za zaštitu od zračenja Instituta za medicinska istraživanja i medicinu rada, proveli su mjerenja koncentracije aktivnosti ^{222}Rn unutar Špilje Veternice koja se nalazi u Parku prirode Medvednica. Uzorkovanje je provedeno unutar špilje na ključnim lokacijama koje su odabrane zbog dužeg zadržavanja posjetitelja i potencijalnog povećanog izlaganja radonu. Prva lokacija („Koncertna dvorana“) nalazi se u glavnom dijelu špilje, dok je druga lokacija („Pračovjek (separe)“) smještena u nešto užem prostoru s ograničenom ventilacijom. Cilj ovog istraživanja bio je usporediti dvije metode mjerenja radona: aktivnom i pasivnom. Za aktivna mjerenja korišten je uređaj AlphaE (Bertin GmbH) koji bilježi srednju vrijednost koncentracija aktivnosti ^{222}Rn u intervalu od 10 minuta, vlagu, temperaturu prostorije, te računa akumuliranu efektivnu dozu koja potječe od ^{222}Rn. Za pasivnu metodu mjerenja korišteni su ugljeni filtri koji su izlagani tijekom tri dana (metoda je sukladna Normi ISO 11665-4). Odmah nakon ekspozicije, filtri su analizirani visokorezolucijskom gama spektrometrijom. Također, koristeći konzervativni pristup maksimalnog mogućeg izlaganja, izračunata je efektivna doza koju vodiči i posjetitelji prime tijekom jednog boravka u špilji.
Na lokaciji „Koncertna dvorana“ srednje vrijednosti koncentracije radona izmjerene aktivnim uređajem iznosile su 13633 ± 149 Bq/m³ (2023.) i 13661 ± 149 Bq/m³ (2024.) dok su na istoj lokaciji pasivnom metodom izmjerene su koncentracije od 18079 ± 203 Bq/m³ (2023.) i 15500 ± 123 Bq/m³ (2024.). Na lokaciji „Pračovjek (separe)“ rezultati dobiveni pasivnom metodom također su ukazali na visoke koncentracije radona, s izmjerenim srednjim vrijednostima od 16259 ± 165 Bq/m³ (2023.) i 15100 ± 165 Bq/m³ (2024.).
Iako su mjerenja provedena na svega dvije lokacije, rezultati su pokazali slične vrijednosti koristeći obje metode. Efektivna doza od ^{222}Rn koju primi osoba tijekom jednog posjeta kreće se u rasponu od 0,04 mSv do 0,11 mSv. Istraživanje je potvrdilo potrebu za detaljnim praćenjem i procjenom izloženosti radnika i posjetitelja u špiljama.

Ključne riječi: radon, špilja Veternica, Park prirode Medvednica, radioaktivnost,

MEASUREMENT OF RADON CONCENTRATION IN VETERNICA CAVE

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Caves represent specific natural habitats where elevated concentrations of radon, a naturally occurring radioactive gas, are frequently observed. Radon and its decay products can pose health risks to guides and visitors, making systematic monitoring of radon concentrations in caves extremely important. In June and July of 2023 and 2024, the Division of radiation protection of the IMROH conducted the measurements activity concentrations of ^{222}Rn inside Veternica cave (a part of Medvednica Nature Park) with the aim of risk assessment for workers and visitors. The aim of this study was to compare two radon measurement methods: active and passive. For active measurements, the AlphaE radon monitor (Bertin GmbH) was used, which records the mean value of ^{222}Rn activity concentrations in a 10-minute interval, humidity, room temperature, and calculates the accumulated dose originating from ^{222}Rn. For the passive measurement method, charcoal filters were used over a three-day period (in accordance with ISO Standard 11665-4) at the locations: “Concert hall” and location “Cavemen”. Immediately after exposition, filters were hermetically sealed and measured in the laboratory using high-resolution gamma-ray spectrometry. A conservative approach was used to estimate the maximum possible exposure, and the effective dose received by guides and visitors during a single cave visit.
The mean values of ^{222}Rn activity concentrations measured at the "Concert Hall" location with an active monitor were 13633 ± 149 Bq/m³ (2023.) and 13661 ± 149 Bq/m³ (2024.), while with the passive method we obtained concentrations of 18079 ± 203 Bq/m³ (2023.) and 15500 ± 123 Bq/m³. At the "Cavemen" location, the results obtained using passive methods also indicated high radon concentrations, with mean values of 16259 ± 165 Bq/m³ (2023.) and 15100 ± 165 Bq/m³ (2024).
Although measurements were conducted at only two locations, the results showed similar values for both methods. The effective dose from ^{222}Rn received by a person during a single visit range from 0.04 mSv to 0.11 mSv. The study confirmed the need for detailed monitoring and assessment of exposure for workers and visitors in caves.

Key words: radon, Veternica Cave, Medvednica Nature Park, radioactivity

INSTRUMENTACIJA I MJERNE TEHNIKE

INSTRUMENTATION AND MEASURING TECHNIQUES

RAZVOJ ICP-MS METODE ZA ODREĐIVANJE IZOTOPA U-234, U-235, U-238 I RA-226 U UZORCIMA VODE

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Sažetak

Voda je značajan potencijalni izvor izravne unutarnje izloženosti radionuklidima. Prirodne vode sadrže radionuklide koji emitiraju alfa i beta zračenje, čija koncentracija varira u širokom rasponu ovisno o geološkim i okolišnim uvjetima. Aktivnost alfa emitera u uzorcima voda uglavnom se pripisuje otopljenim izotopima uranija (U-234, U-235 i U-238) te Ra-226. Njihovo određivanje korištenjem konvencionalnih radiometrijskih tehnika zahtijeva znatan volumen uzorka (50 mL – 10 L), a same analize mogu biti dugotrajne. Kako bi se prevladala ova ograničenja, u ovom istraživanju razvijena je metoda za određivanje izotopa uranija i Ra-226 pomoću spektrometrije masa s induktivno spregnutom plazmom (ICP-MS). Navedenim pristupom analize je moguće provesti u znatno kraćem vremenu i bez dugotrajne pred pripreme uzoraka.

Kvadropolni spektrometar masa s induktivno spregnutom plazmom ICP-QQQ-MS korišten je u načinu rada s jednim kvadrupolom, sa ili bez reakcije s plinom helija u ćeliji, pri čemu je prvi kvadrupol služio kao filtar masa. Konačni protokol za određivanje izotopa uranija postavljen je u načinu rada s jednim kvadrupolom uz protok helija od 2 mL/min, pri čemu nisu zabilježene značajne interferencije. Ra-226 je također analiziran u načinu rada s jednim kvadrupolom korištenjem metode standardnog dodatka kako bi se prevladao efekt matriksa.

Razvijena metoda je validirana i uspješno primijenjena na realnim uzorcima vode. ICP-MS tehnika pruža brzu, učinkovitu i preciznu alternativu za određivanje radionuklida u vodi, čineći je vrijednim alatom za ekološki monitoring i radiološke procjene.

Ključne riječi: radioaktivnost, uranij, radij, alfa spektrometrija, ICP-MS

Ovaj rad je sufinancirala Hrvatska zaklada za znanost projektom (HRZZ-MOBODL-23-08-3540), program Europske unije za istraživanje i inovacije Horizont 2020 u sklopu Marie Sklodowska-Curie ugovora br. 101003359, program Slovenske agencije za istraživanje in inovacije P2 0075 i projekt 21GRD09 MetroPOEM.

DEVELOPEMENT OF AN ICP-MS METHOD FOR U-234, U-235, U-238 AND RA-226 DETERMINATION IN WATER SAMPLES

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Abstract
Water is a significant potential source of direct internal exposure to radionuclides. Natural waters contain both alpha and beta emitter radioisotopes, which are present in widely varying concentrations depending on the geological and environmental conditions.
Activity of alpha emitters in water samples is predominantly attributed to dissolved uranium isotopes (U-234, U-235, and U-238) and Ra-226.
The accurate determination of these radionuclides necessitates a substantial sample volume (50 mL-10 L) and can be labor-intensive when employing conventional radiometric techniques.
To address these limitations, a method for the determination of uranium isotopes and Ra-226 using inductively coupled plasma mass spectrometry (ICP-MS) was developed in this study. This approach enables the analysis of these radionuclides using just 10 mL of water samples, significantly reducing the time required for sample preparation and analysis to mere minutes and eliminating the need for complex pretreatment procedures.
The triple quadrupole inductively coupled plasma mass spectrometer (ICP-QQQ-MS) was operated in a single quadrupole mode with or without using helium cell gas where the first quadrupole served as a mass filter. The final protocol for uranium isotopes was set in a single quadrupole mode with a helium flow rate of 2 mL/min, where no significant interferences were observed. Ra-226 was analyzed in a same mode using the standard addition method to overcome matrix effects.
The developed method was validated and successfully applied to real water samples. This technique provides a rapid, efficient, and accurate alternative for radionuclide determination in water, making it a valuable tool for environmental monitoring and radiological assessments.

Keywords: radioactivity, uranium, radium, alpha spectrometry, ICP-MS

This work was supported in part by the Croatian Science Foundation under the project number HRZZ-MOBODL-23-08-3540, the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 101003359, the Slovenian Research and Innovation Agency programme P2 0075 and the project 21GRD09 MetroPOEM.

COSMIC MUON SPECTRUM AS A TOOL FOR QUENCH CORRECTION DURING NUCLEAR EMERGENCY SCREENING OF ^{137}Cs IN WATER

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Abstract:
In the case of nuclear emergency leakage from nuclear power plant it is necessary to perform quick screening for long lived fission products that are hazardous to the environment. In this work a screening method of one of those long lived radionuclides ^{137}Cs, is preformed via Liquid Scintillation Counter Quantulus 1220. Technique is fast, simple and does not require any complex sample preparation. Colored samples were doped with ionic liquid 1-butyl-3-methylimidazolium salicylate [Bmim][Sal], which introduces wavelength shift of Cherenkov photons. It was proven in previous studies that wavelength-shifting mechanism increases detection efficiency and reduces detection limit of the method more than 4 times. Color quench correction curve was plotted via muonic peak shift (Figure 1.) , caused by the quench.

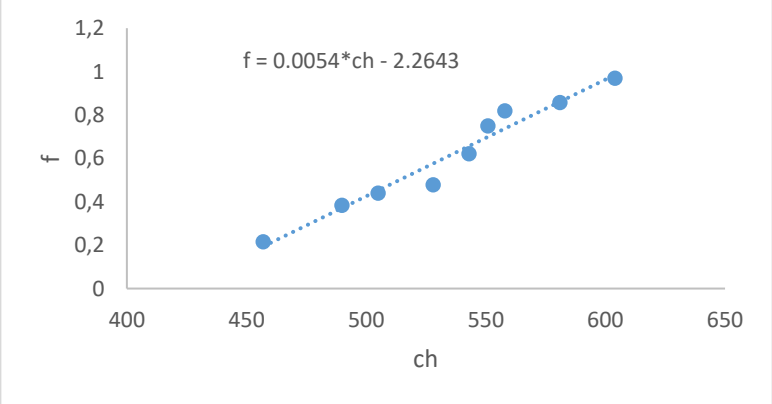

Figure 1. Color factor (f) as a function of the channel number (ch)

Eight test samples were spiked with the known concentration of ^{137}Cs. This method was tested with application of color quench correction factor to determine activities of samples. All results were within 30% relative uncertainty, which is within limits for screening purposes. Another advantage of this method is that it can be applied to other long lived radionuclides that are of interest in case of nuclear disasters.

Key words: Colour quench, Quantulus™, Cherenkov radiation, muonic peak, nuclear emergency, Liquid scintillation counting

ADVANTAGES OF FRAM SOFTWARE FOR NUCLEAR MATERIAL ANALYSIS

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Abstract
Gamma spectrometry serves as a valuable non-destructive method for characterizing nuclear materials. While routine gamma spectrometry laboratories primarily focus on analyzing environmental samples, i.e., Naturally Occurring Radioactive Materials (NORM), the utilization of the FRAM software in such settings is limited. However, the commercial potential of the FRAM software is realized in laboratories specialized in the analysis of nuclear materials. There are other commercial software on the market that are used to analyze nuclear material such as MGA++ and MGAU packages. They are very convenient and easy to use because the entire isotopic analysis of uranium and plutonium is reduced to just a few steps. On the other hand, the mentioned features are in the same time their disadvantage, since they represent a kind of black box, that is, they do not provide the users with the flexibility to influence the course of the analysis in any way. FRAM software makes this possible by allowing users to tailor the analysis to the specific requirements of a given measurement. This is achieved by a different selection or by creating a completely new set of parameters which defines the type of detector as well as the suitable energy region for analysis, then the shape (type) of the efficiency function, the selection of photopeaks used for energy, shape and efficiency calibrations as well as many other options within the software itself. This advantage allows the users to achieve higher control level over the analysis process.
This work presents an assessment of the FRAM software by the analysis of gamma spectra of a range of standard reference nuclear materials. Consistency between mass fractions calculated with FRAM and reference values of certain radioisotopes was investigated. To this end, spectra of certified standard uranium and plutonium reference materials were studied. The spectra were recorded at the Joint Research Centre–Institute for Transuranium Elements (ITU) in Karlsruhe as part of the co-operation activities to improve non-destructive measuring techniques for nuclear materials. The achieved results using the FRAM software show an excellent agreement with the reference values.

Keywords: Keywords: FRAM, gamma spectrometry, nuclear materials, isotope ratios

PRIMJENA EKSTRAKCIJE ČVRSTO-TEKUĆE ZA AUTOMATIZIRANO SEKVENCIJALNO ODIJELJIVANJE RADIONUKLIDA

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Sažetak

Značajan udio godišnjoj primljenoj dozi zračenja dolazi od radionuklida unesenih hranom. Analize projekta „RiChFALL" procjenile su primljene doze djece, adolescenata i odraslih u Hrvatskoj (<1 mSv godišnje), te pokazale doprinose pojedinačnih radionuklida. Dozi najviše doprinose ^{40}K, ^{228}Ra, ^{210}Pb, ^{210}Po, ^{226}Ra, te su zbog toga dugoročna ponašanja tih radionuklida u okolišu značajna za proučavanje. Ako se njihove koncentracije aktivnosti određuju detekcijom alfa ili beta zračenja, potrebna je prethodna priprema uzoraka koja zahtjeva upotrebu ionskih izmjenjivača, taložne reakcije, otapanja i drugo. Takvi postupci često su dugotrajni i skupi, uz potrošnju veće količine kemikalija, što posljedično ograničava broj analiza u danom vremenu. Novije metode koriste ekstrakciju čvrsto-tekuće što smanjuje obujam posla i potrošni materijal, no svejedno mogu biti vremenski zahtjevne za analitičara. Takve metode pogodne su za automatizaciju, koja se razvija na Institutu Ruđer Bošković, u Laboratoriju za radioekologiju, pomoću modularnog sustava sačinjenog od peristaltičkih pumpi, ventila, jedinice za frakcioniranje te kontrolne jedinice. Automatizacijom se efikasnije koristi vrijeme analitičara koji nanosi razoren uzorak u tekućem obliku i potrebne otopine u predviđene spremnike sustava, te odabire program i parametre analize. Sustav propušta uzorke kroz kolone punjene specijalnom smolom, primjerice silikagelom, za koji je vezan kruna eter ili drugi kompleksirajući agens. Ciljani radionuklidi se zajedno sa svim nuklidima odgovarajućih elemenata vežu za smolu te se na njoj zadržavaju i ukoncentriravaju. Sekvencijalnim propuštanjem otopina drugih kompleksirajućih agensa različitih koncentracija odnosno pH vrijednosti, ispiru se pojedini ciljani (radio)nuklidi u zasebne frakcije. Ovisno o ciljanom analitu, dalje se provode analize radiometrijskim metodama poput alfa spektrometrije odnosno tekućeg scintilacijskog brojenja.

Razmatraju se dva pristupa automatizaciji. Priprema većeg broja uzoraka na jednoj smoli ili sprega dviju smola, kojom bi se izvodile kompleksnije pripreme jednog uzorka. Preliminarni, ručno izvođeni eksperimenti s uzorcima referentnog materijala i okolišnim uzorcima prikupljenim tijekom projekta „RiChFALL" rezultirali su odijeljivanjem Pb, Sr te Ra s prinosom od 65-85% korištenjem AnaLig® smole, odnosno odijeljivanjem Th s prinosom od 85-95% korištenjem TRU smole. Eksperiment u kojem su spregnute te dvije smole pokazao je da nema značajnih gubitaka prinosa ako je redoslijed kolona AnaLig® pa TRU, dok prinos Ra pada na oko 20% ako je redoslijed obrnut. Razvijene metode implementirat će se u postojeći sustav nakon programiranja i ugađanja pojedinih modula. Budući da je sustav modularan, po potrebi se može presložiti i isprogramirati za nove ili izmjenjene analize. Razvijenim sustavom postignut će se brža priprema uzoraka, omogućit će se priprema većeg broja uzoraka, te se smanjit vrijeme koje analitičar treba provesti u laboratoriju.

Ključne riječi: ekstrakcija čvrsto-tekuće, automatizacija, alfa spektrometrija, tekućinsko scintilacijsko brojenje

APPLICATION OF SOLID PHASE EXTRACTION FOR AUTOMATED SEQUENTIAL SEPARATION OF RADIONUCLIDES

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Abstract

Radionuclides ingested by food consumption contribute significantly to annual radiation exposure. Main contributors to the annual doses for children, adolescents and adults (< 1mSv) were assessed within „RiChFALL“ project. The largest contributors are ^{40}K, ^{228}Ra, ^{210}Pb, ^{210}Po and ^{226}Ra. Therefore, the study of long-term environmental behaviour of these radionuclides is of great interest. For determination of their activities by alpha or beta detection, sample preparation, which requires the use of ion exchangers, precipitations, dissolution, etc, is necessary. Such time-consuming procedures are expensive, waste chemicals and thus limit the number of analyses in a given time. By incorporating solid-phase extraction, newer methods reduce the work load and consumables, while still being time-consuming. Such methods are suitable for automatization, which is being developed at Ruđer Bošković Institute, in the Laboratory for Radioecology, using a modular system consisting of peristaltic pumps, valves, fractionation and control units. Automatization enables efficient use of the analyst's time, who needs to fill system's containers with digested, liquid sample and necessary solutions, select desired program with right parameters and start the procedure. The pump passes the samples through columns filled with a special resin, e.g. silica-gel modified with crown ether or another complexing agent. The targeted radionuclides, along with all nuclides of specific elements, are retained and concentrated by resin. Separation is achieved by sequentially passing solutions of other complexing agents of varying concentrations or pH values, which removes targeted (radio)nuclides into separate fractions. Further radiometric analyses are carried out.

Two approaches to automatization are considered: 1) Batch operation using single resin and multiple samples and 2) coupling of two resins for complex analyses on a single sample. Preliminary, manually performed experiments with reference material and environmental samples from "RiChFALL" project resulted in the separation of Pb, Sr and Ra with a yield of 65-85% using AnaLig® resin, and the separation of Th with a yield of 85-95% using TRU resin. In coupled resins experiments no significant decrease of yield was observed, if the order of the columns is AnaLig® then TRU, while the yield of Ra drops to 20% if the order is reversed. The developed methods will be implemented within system after programming and individual module tuning. Since the system is modular, it can be rearranged and programmed for new or modified analyses if necessary. The developed system will speed up sample preparation, enable preparations of more samples and reduce analyst's time in the laboratory.

Keywords: solid phase extraction, automatization, alpha spectrometry, liquid scintillation counting

USPOREDBA REZULTATA ED-XRF ANALIZE $PM_{2.5}$ LEBDEĆIH ČESTICA SAKUPLJENIH NA KVARCNIM I TEFLONSKIM FILTRIMA

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Sažetak
Elementna analiza sastava lebdećih čestica važna je za procjenu dominantnih izvora onečišćenja. Standardizirane metode za analizu elemenata zahtijevaju razgradnju lebdećih čestica sakupljenih na filtarskom mediju i pripravu tekućeg uzorka za analizu. Energetsko disperzivna rendgenska fluorescentna spektrometrija (ED-XRF) je višeelementna, nerazarajuća analitička tehnika koja broji po valnim duljinama razdvojene energetske prijelaze iz X-zrakama ozračenog uzorka. Dodatna priprava uzoraka nije potrebna jer se analizira elementni sastav lebdećih čestica direktno s filtra na kojima su sakupljene. Nedostaci ove metode su absorpcija X-zraka niske energije koje emitiraju elementi manjeg atomskog broja. Do absorpcije dolazi na lebdećim česticama, ali i unutar filtra ovisno o dubini ulaska čestica unutar filtarskog medija. U ovom radu prikazana je usporedba rezultata ED-XRF analize lebdećih čestica aerodinamičkog promjera manjeg od 2,5 μm (PM 2.5) istovremeno sakupljenih na dvije različite filtarske podloge – na teflonskim filtrima (PTFE pora 2 μm, promjera 46,2 mm, Whatman) i na filtrima od kvarcnih vlakana (QMA Whatman). Dnevni uzorci su sakupljani svaki treći dan, tijekom 2023. godine, na gradskoj pozadinskoj mjernoj postaji, istovremeno s dva odvojena referentna sakupljača. Svaki uzorak je uzorkovan 24 h, pri čemu je kroz filtarski medij prošlo oko 55 m^3 zraka. Analiza ED-XRF metodom provedena je na uređaju Epsilon 5 (Malvern Pananalytical) koji je opremljen rendgenskom cijevi snage 100 kV u vakuumu i berilijevim detektorom u tekućem dušiku. Za kalibraciju su upotrijebljeni standardni višeelementni Mylar filtri i standardni referentni materijal NIST 2783 (Air Particulate on Filter Media). Uspoređeni su rezultati analize sumpora, kalija, titana, željeza, cinka i olova. Rezultati pokazuju visoke koeficijente korelacije ($r > 0,8$) između vrijednosti izmjerenih na teflonskim i na kvarcnim filtrima za sve odabrane elemente. Značajno više vrijednosti sumpora i kalija izmjerene su na teflonskim filtrima. Srednja vrijednost sumpora analiziranog na teflonskim filtrima iznosila je 2112 ng/cm^2, a na kvarcnim filtrima 767 ng/cm^2, dok su za kalij srednje vrijednosti iznosile 1178 ng/cm^2 na teflonskim filtrima i 413 ng/cm^2 na kvarcnim. Usporedba rezultata dobivenih za titan, željezo, cink i olovo pokazuje znatno bolje podudaranje između uzoraka, s odstupanjima koja iznose do 20 %. Razine titana i olova u većini uzoraka su bile ispod granice detekcije metode tako da je usporedba bila moguća samo za 37 % paralelnih uzoraka za titan i 19 % za olovo. Srednje vrijednosti željeza, cinka, titana i olova izmjerene na teflonskim filtrima iznosile su redom 383 ng/cm^2, 60,1 ng/cm^2, 19,5 ng/cm^2 i 44,2 ng/cm^2. Rezultati pokazuju da su teflonski filtri bolji odabir za analizu elemenata ED-XRF metodom, dok je za filtre od kvarcnih vlakana potrebno primijeniti korekciju rezultata za elemente nižeg atomskog broja.

Ključne riječi: elementna analiza, lebdeće čestice, zrak

COMPARISON OF ED-XRF ANALYSIS OF $PM_{2.5}$ PARTICULATE MATTER COLLECTED ON QUARTZ FIBRE AND TEFLON FILTERS

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Abstract
Elemental analysis of particulate matter is important for conducting studies on source apportionment. Standardized methods for elemental analysis include the digestion of particulate matter collected on the filter media and preparation of liquid samples for analysis. Energy Dispersive X-ray Fluorescence (ED-XRF) is a multi-elemental, nondestructive analytical technique that counts energy transitions from an X-ray irradiated sample. The elemental composition of particulate matter is analyzed directly from collected filters without additional sample preparation. The disadvantage of this method is the absorption of low energy X-rays emitted by low Z elements. Absorption occurs on the aerosol particles themselves and also within the filter, depending on the depth of penetration of the particles through the filter media. The objective of this work was to compare the results of ED-XRF analysis of particulate matter with an aerodynamic diameter of less than 2.5 µm ($PM_{2.5}$) simultaneously collected on two different substrates – on PTFE filters (2 µm pore size, 46.2 mm diameter, Whatman) and on Quartz Fibre Filters (Whatman, QMA grade). Daily samples were collected every third day during 2023 at an urban background monitoring station, simultaneously with two separate reference samplers. Each sample was collected for 24 hours, with approximately 55 m^3 of air passing through the filter. ED-XRF analysis was performed on an Epsilon 5 (Malvern Pananalytical) equipped with a 100 kV X-ray tube which is in vacuum and a beryllium detector in liquid nitrogen. Standard multi-element Mylar filters and standard reference material NIST 2783 (Air Particulate on Filter Media) were used for the calibration. The results of the analysis of sulphur, potassium, titanium, iron, zinc and lead were compared. The results show high correlation coefficients ($r > 0.8$) between the values measured on teflon and quartz fibre filters for all selected elements. Significantly higher values of sulphur and potassium were found on teflon filters. The average value of sulphur analysed on teflon filters amounted to 2112 ng/cm^2 and on quartz filters 767 ng/cm^2 respectively, while for potassium the average values were 1178 ng/cm^2 on teflon filters and 413 ng/cm^2 on quartz filters. A comparison of the results obtained for titanium, iron, zinc and lead showed much better matching between samples, with deviations lower than 20 %. The levels of titanium and lead in most samples were below the detection limit of the method, therefore a comparison was made only for 37 % of the parallel samples for titanium and 19 % for lead. The average values of iron, zinc, titanium and lead measured on the teflon filters were 383 ng/cm^2, 60.1 ng/cm^2, 19.5 ng/cm^2 and 44.2 ng/cm^2, respectively. The results showed that teflon filters are a better choice for the analysis of elements by the ED-XRF method, while for filters made of quartz fibres it is necessary to apply a correction of results for elements with a lower atomic number.

Key words: elemental analysis, particulate matter, air

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KARAKTERIZACIJA BAČVI S RADIOAKTIVNIM OTPADOM IN-SITU GAMA-SPEKTROMETRIJOM VISOKE RAZLUČIVOSTI

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Sažetak

U okviru djelomične sanacije inozemnog skladišta radioaktivnog otpada, u čeličnim bačvama od 200 L bilo je potrebno utvrditi prisutnost i potvrditi sadržaj radioaktivnog otpada odnosno izvršiti karakterizaciju otpada. Bačve su sadržavale različite vrste niskoradioaktivnog institucionalnog otpada (razni radionuklidi raznih aktivnosti) kao što su kontaminirane rukavice, staklene cijevi, vrhovi pipeta, filter papiri, ampule, metalni dijelovi zrakoplova, kolimatori glave ^{60}Co i dr. U većem dijelu bačvi otpad je bio cementiran, a dio bačvi sadržavao je željeznu trosku (granulirani materijal) koja nije bila cementirana.

Bačve su karakterizirane in-situ gama-spektrometrijom visoke razlučivosti (HPGe detektor), uz primjenu softvera Genie 2000 za prikupljanje i analizu podataka i programskog paketa za kalibraciju ISOCS (engl. *In Situ Object Counting System*). Korištena je i industrijska vaga odnosno viljuškar s mjerenjem težine, za mjerenje mase svake bačve. Bačve su mjerene u više koraka, postavljanjem detektora na više mjernih točaka/strana bačve kako bi cijela bačva bila analizirana. Uređajem za mjerenje brzine doze zračenja određene su 3-4 mjerne točke s većom brzinom doze za svaku bačvu, a koje mogu biti na različitim visinama ovisno o sadržaju u bačvi. HPGe detektor postavljen je na udaljenosti oko 20-30 cm od bačve te su izvršena mjerenja. Pri analizi radioaktivnog materijala u bačvama korišteni su složeni modeli cilindrične geometrije za određivanje krivulja efikasnosti detektorskog sustava.

Provedena mjerenja su pokazala da je radioaktivnost u bačvama koncentrirana u nekoliko visoko radioaktivnih fragmenata u bačvama. Veličina bačve, sastav i gustoća materijala u bačvi bitni su parametri za modeliranje realnog geometrijskog sustava. Na temelju istih određuje se samoatenuacija i krivulja efikasnosti detektorskog sustava za navedeni geometrijski sustav u svrhu što točnijeg određivanja aktivnosti i specifičnih aktivnosti detektiranih radionuklida. Najveća brzina ambijentalnog doznog ekvivalenta izmjerena je na bačvi sa željeznom troskom u kojoj je detektiran ^{60}Co, a iznosila je 160 μSv/h. U bačvama su detektirani radionuklidi ^{226}Ra, ^{60}Co, ^{137}Cs, ^{234}mPa, ^{238}U, ^{241}Am, ^{125}Sb, ^{152}Eu. Radionuklide kratkog vremena poluraspada kao što su ^{131}I, ^{99}Mo, i dr., nije bilo moguće detektirati jer su im aktivnosti pale ispod granice detekcije ili su se potpuno raspali. Nakon završenih analiza gama-spektrometrijom visoke razlučivosti, stare bačve prepakirane su u nove.

Ključne riječi: in-situ gama-spektrometrija visoke razlučivosti, radioaktivni otpad, bačve

CHARACTERIZATION OF RADIOACTIVE WASTE BARRELS BY IN-SITU HIGH-RESOLUTION GAMMA SPECTROMETRY

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Abstract

As part of the partial remediation of a foreign radioactive waste storage facility, it was necessary to determine the presence and confirm the content of radioactive waste in 200 L steel drums, i.e. to characterize the waste. The drums contained various types of low-level institutional waste (various radionuclides of various activities) such as contaminated gloves, glass tubes, pipette tips, filter papers, ampoules, metal parts of aircraft, ^{60}Co head collimators, etc. In most of the drums, the waste was cemented, and some of the drums contained iron slag (granular material) that was not cemented.

The drums were characterized by in-situ high-resolution gamma-spectrometry (HPGe detector), using the Genie 2000 software for data collection and analysis and the ISOCS (In Situ Object Counting System) calibration software package. An industrial scale, or forklift with a weight measurement, was also used to measure the mass of each drum. The barrels were measured in several steps, by placing the detectors at several measuring points/sides of the barrel so that the entire barrel could be analyzed. The radiation dose rate measuring device determined 3-4 measuring points with a higher dose rate for each barrel, which could be at different heights depending on the contents in the barrel. The HPGe detector was placed at a distance of about 20-30 cm from the barrel and measurements were performed. When analyzing the radioactive material in the barrels, complex models of cylindrical geometry were used to determine the efficiency curves of the detector system.

The measurements performed showed that the radioactivity in the barrels is concentrated in several highly radioactive fragments in the barrels. The size of the barrel, the composition and density of the material in the barrel are important parameters for modeling a real geometric system. Based on them, the self-attenuation and the efficiency curve of the detector system for the specified geometric system are determined in order to determine the activity and specific activities of the detected radionuclides as accurately as possible. The highest ambient dose equivalent rate was measured on a barrel with iron slag in which ^{60}Co was detected, and it was 160 μSv/h. The radionuclides detected in the barrels were ^{226}Ra, ^{60}Co, ^{137}Cs, ^{234}mPa, ^{238}U, ^{241}Am, ^{125}Sb, ^{152}Eu. Short-lived radionuclides such as ^{131}I, ^{99}Mo, etc., could not be detected because their activities had fallen below the detection limit or had completely decayed. After high-resolution gamma-spectrometry analyses were completed, the old barrels were repacked into new ones.

Keywords: in-situ high-resolution gamma-spectrometry, radioactive waste, barrels

MOGUĆNOST IMPLEMENTACIJE KVANTNIH KORELACIJA ANIHILACIJSKIH FOTONA U POZITRONSKU EMISIJSKU TOMOGRAFIJU

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Pozitronska emisijska tomografija (PET) je medicinska tehnika oslikavanja u kojoj se pozitron emitiran iz radiofarmaka anihilira sa elektronom u tkivu pacijenta. U tom procesu nastaju dva gama fotona, koji se gibaju u suprotnim smjerovima s energijama od 511 keV. Dodatna karakteristika ovog procesa, koja nije implementirana u standardne PET uređaje, je kvantna sprega u polarizacijama nastalih fotona. Ovo svojstvo bi potencijalno moglo poslužiti kao nezavisan kriterij u selekciji istinskih koincidencija jer pozadinski šum i nasumične koincidencije nemaju ovu karakteristiku, što posljedično poboljšava kvalitetu rekonstruirane slike. Kako bismo ispitali ovu pretpostavku, razvili smo demonstracijski PET uređaj koji može mjeriti korelacije u polarizaciji anihilacijskih gama fotona putem Comptonskog raspršenja, što omogućava da se po prvi put ispita potencijalno poboljšanje u kvaliteti slike s obzirom na standardne PET uređaje koji koriste skoro isključivo fotoelektrični efekt. Uređaj se sastoji od četiri segmentirana scintilacijska detektorska modula, montirana na kružni nosač s postoljem. Detektorski moduli su jednoslojni Comptonski polarimetri koji se sastoje od matrice veličine 16×16 od kristala GAGG ili LYSO duljine 20 mm, s matričnom udaljenošću od 3,2 mm ili 2,2 mm, spojenih na silicijske fotomultiplikatore. Budući da kružni nosač može rotirati oko izvora zračenja, time oponaša puni krug detektora od 16 transaksijalnih prstena. Uređaj je testiran u Kliničkom bolničkom centru Zagreb s izvorima koji imaju klinički relevantne aktivnosti: dva linijska izvora Ge-68 (promjer 1,6 mm, aktivnost ~45,5 MBq) te NEMA fantom ispunjen izvorom Ga-68 (NU 4-2008, inicijalna aktivnost izvora Ga-68 ~400 MBq). Nakon prikupljanja podataka i analize, rekonstrukcija slike napravljena je u programskom paketu za rekonstrukciju slike OMEGA, koristeći algoritam *Ordered Subset Expectation Maximization* (OSEM) u okružju MATLAB. U sklopu predavanja, prikazat ćemo karakteristike demonstracijskog PET uređaja, te prikazati rekonstruirane slike dva linijska izvora Ge-68 te NEMA fantoma ispunjenog izvorom Ga-68. Rezultati pokazuju kako je moguće oslikavanje izvora koristeći isključivo kvantno spregnute anihilacijske fotone, te kako je potiskivanje nasumičnog šuma u mjerenjima polarizacijskih korelacija i do 40% bolje od mjerenja dobivenih fotoefektom. Diskutirat ćemo i potencijalna poboljšanja omjera signala i šuma u mjerenjima anihilacijskih fotona s korelacijama u polarizaciji, te daljnje usavršavanje PET demonstratora.

Ključne riječi: pozitronska emisijska tomografija, kvantna sprega, polarizacijske korelacije, Comptonski polarimetri, rekonstrukcija slike

TOWARDS THE IMPLEMENTATION OF QUANTUM CORRELATIONS OF THE ANNIHILATION PHOTONS IN POSITRON EMISSION TOMOGRAPHY

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Positron emission tomography (PET) is a medical imaging modality, that relies on the process of annihilation of a positron, emitted from a radiopharmaceutical, with an electron in a patient's tissue. In that process, two gamma photons are emitted, with opposite momentum and 511 keV energy. An additional characteristic of this process, not yet implemented into common PET devices, is the entanglement of the polarizations of the emitted photons. This property could potentially be exploited as an energy-independent criterion for recognition of true coincidences since the background noise and random coincidences do not exhibit this property. That consequently improves the quality of the reconstructed image. To examine this possibility, we developed a PET demonstrator device, capable of measuring the correlations in the polarization of the annihilation gamma photons through Compton scattering. This gives an opportunity to test for the first time the improvement in the image quality compared to the standard PET devices that use almost exclusively photoelectric effect. The device consists of four segmented scintillating detector modules, mounted on a circular construction. The detector modules are single-layer Compton polarimeters that consist of 16x16 matrices made of GAGG or LYSO crystals, 20 mm in length, with matrix pitch of either 3.2 mm or 2.2 mm, read-out by silicon photomultipliers. The structure can rotate around the annihilation source, hence it emulates a full ring of detectors with 16 trans-axial detector rings. The device was tested at the University Hospital Centre Zagreb with sources that have clinically relevant activities: two line Ge-68 sources (1.6 mm in diameter, activity ~45.5 MBq) and NEMA phantom filled with Ga-68 (NU 4-2008, initial activity ~400 MBq). After the analysis of the acquired data, image reconstruction was done in OMEGA software package for image reconstruction, utilizing the *Ordered Subset Expectation Maximization* (OSEM) algorithm in MATLAB environment. We will report on characteristics of the PET demonstrator and show the reconstructed images of the two line Ge-68 sources and the NEMA phantom filled with Ga-68. The results show that imaging of the annihilation sources using exclusively entangled annihilation photons is possible, and the measurements of the polarization correlations show up to 40% reduction in the signal-to-random-background compared to measurements of the photons with single-pixel interaction. We will discuss further refinements in the PET demonstrator and possible signal-to-background improvements through measurements of the correlated quanta at different activities.

Key words: positron emission tomography, quantum entanglement, polarization correlations, Compton polarimeters, image reconstruction

RAZMATRANJA U EVALUACIJI I ANALIZI PERFORMANSI MODERNOG RENDGENSKOG GENERATORA U OKVIRU USPOSTAVE STANDARDNIH SNOPOVA: PRELIMINARNI REZULTATI STUDIJE SLUČAJA

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Sažetak
Rendgenski generatori igraju ključnu ulogu u medicinskoj dijagnostici i zaštiti od zračenja, dok norme IEC 61267 i ISO 4037-1 pružaju smjernice za uspostavu rendgenskih snopova. Međutim, nedostatak jasnih opisa mjernih tehnika i propusti u normama mogu otežati procjenu performansi modernih generatora i uvesti pogreške koje negativno utječu na točnost i pouzdanost procesa uspostave snopova. U ovom istraživanju analizirane su performanse modernog rendgenskog generatora s fokusom na točnost i kolebanje napona te na mjerne tehnike, pri čemu je ispitana usklađenost s navedenim normama. Korištena je kombinacija invazivnih i neinvazivnih mjerenja uz pomoć raznih instrumenata, poput visokonaponskog djelitelja napona, osciloskopa, multimetara, rendgenskog multimetra i detektora zračenja. Analize su uključivale mjerenja napona i kolebanja napona u različitim uvjetima rada te spektralnu analizu u stvarnom vremenu. Preliminarni rezultati pokazuju da je generator zadovoljio većinu zahtjeva norme, pri čemu su odstupanja u naponskim mjerenjima bila manja od 0,5%. Usporedba mjerenja praktičnog vršnog napona (en. *practical peak voltage* - PPV) i prosječnog napona nije pokazala značajne razlike, što sugerira da se za DC generatore napona može koristiti širi raspon instrumenata za mjerenje srednje vrijednost napona. Detaljna analiza kolebanja napona ukazala je na razlike u mjerenju *peak-to-peak* i RMS vrijednosti te na važnost širine pojasa i izazova vezanih uz umjeravanje u invazivnim metodama. Nadalje, utvrđeno je da ograničenja koja se odnose na maksimalno kolebanje napona, temeljena mjerenjima s DC pomakom, ne odražavaju stvarni utjecaj kolebanja napona na dozimetrijske veličine, što sugerira potrebu za daljnjim istraživanjima. Rezultati također ukazuju na mogućnosti poboljšanja normi ISO 4037 i IEC 61267 kroz preciznije definiranje mjernih tehnika, karakterizaciju kolebanja i odgovarajuće granice mjerne nepouzdanosti. Zaključno, iako analizirani generator pokazuje visoku razinu usklađenosti s normama, rezultati ovog istraživanja ističu potrebu za revizijom postojećih smjernica kako bi se osigurale točnije procjene i veća pouzdanost rendgenskih sustava u kliničkim, istraživačkim i drugim specijaliziranim primjenama.

Ključne riječi: rendgenski generator, medicinska dijagnostika, zaštita od zračenja, IEC 61267, ISO 4037-1, mjerne tehnike

CONSIDERATIONS IN EVALUATION AND PERFORMANCE ANALYSIS OF A MODERN X-RAY GENERATOR WITHIN BEAM COMMISSIONING PROCESS: PRELIMINARY RESULTS OF A CASE STUDY

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Abstract

X-ray generators play a crucial role in medical diagnostics and radiation protection, while the IEC 61267 and ISO 4037-1 standards provide guidelines for the establishment of X-ray beams. However, the lack of clear descriptions of measurement techniques and omissions in these standards can hinder the performance evaluation of modern generators, introducing errors that negatively impact the accuracy and reliability of the beam commissioning process. This study analyzed the performance of a modern X-ray generator, focusing on voltage accuracy, ripple, and measurement techniques, with an assessment of compliance with these standards. A combination of invasive and non-invasive measurements was performed using various instruments, including a high-voltage divider, oscilloscope, multimeters, X-ray multimeter, and radiation detectors. The analyses included voltage and ripple measurements under different operational conditions and real-time spectral analysis. The preliminary results show that the generator met most of the standard requirements, with deviations in voltage measurements consistently below 0.5%. A comparison of practical peak voltage (PPV) and average voltage measurements revealed no significant differences, suggesting that a broader range of instruments could be used for average voltage measurements in DC voltage generators. A detailed analysis of voltage ripple highlighted differences between peak-to-peak and root mean square (RMS) measurements, emphasizing the importance of bandwidth and calibration challenges in invasive methods. Furthermore, it was found that ripple limits based on DC offset measurements do not fully reflect the actual impact of ripple on dosimetric quantities, indicating the need for further research. The findings also suggest opportunities for improving ISO 4037 and IEC 61267 standards by providing more precise definitions of measurement techniques, ripple characterization, and appropriate uncertainty limits. In conclusion, while the analyzed generator demonstrated a high level of compliance with the standards, the results of this study underline the need for revising existing guidelines to ensure more accurate assessments and enhance the reliability of X-ray systems in clinical, research, and other specialized applications.

Key words: X-ray generator, medical diagnostics, radiation protection, IEC 61267, ISO 4037-1, measurement techniques

UTJECAJ ORIJENTACIJE DETEKTORA NA UČINAK VOLUMNOG USREDNJAVANJA U DOZIMETRIJI FOTONSKIH SNOPOVA UREĐAJA GAMA NOŽA PERFEXION

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Sažetak
U dozimetriji fotonskih snopova Co-60 uređaja gama nož (*eng. Gamma Knife*, GK) Perfexion koriste se različiti detektori malog volumena. Pritom orijentacija detektora može biti paralelna sa z osi uređaja ili okomita na nju. S obzirom na sumjerljivost veličine detektora i veličine polja GK uređaja (16 mm, 8 mm i 4 mm) i elipsoidni oblik raspodjele apsorbirane doze GK uređaja, ovu dozimetriju karakterizira učinak volumnog usrednjavanja mjerenog signala, koji može ovisiti o orijentaciji detektora. Cilj ovog istraživanja je odrediti korekcijske faktore mjerenog signala za učinak volumnog usrednjavanja, za okomitu i paralelnu orijentaciju detektora te pritom odrediti utjecaj orijentacije detektora na ovaj učinak. S obzirom na manjak objavljenih istraživanja o utjecaju orijentacije detektora u dozimetriji uskih fotonskih snopova GK uređaja, u ovom radu provedena je analiza za 14 različitih detektora malog volumena, koji se standardno koriste u dozimetriji GK uređaja.

Elipsoidna raspodjela apsorbirane doze GK Perfexion uređaja modelirana je koristeći profile doza određene Monte Carlo simulacijama, a točnost dobivenog modela verificirana je usporedbom s raspodjelom apsorbirane doze određene računski u sustavu za planiranje radiokirurškog postupka. Pomoću MATLAB-a (TheMathWorks, Inc., USA) i numeričke integracije, raspodjela apsorbirane doze integrirana je preko aktivnog volumena detektora za dvije orijentacije detektora. Model apsorbirane doze je pokazao srednju točnost od 1,79%, 1,15% i 0,43% za veličine polja od 16 mm, 8 mm i 4 mm u usporedbi sa sustavom za planiranje. Korekcijski faktori volumnog usrednjavanja izračunati su za sve detektore u okomitim i paralelnim orijentacijama. Za ionizacijske komore i plastične scintilacijske detektore dobiveni korekcijski faktori su manji za okomitu nego paralelnu orijentaciju. Poluvodički i dijamantni detektor zbog malenog aktivnog volumena ne pokazuju značajne razlike u korekcijskim faktorima između okomite i paralelne orijentacije detektora.

Ova studija pruža temeljitu analizu korekcijskih faktora volumnog usrednjavanja za različite detektore u uskim fotonskom snopovima uređaja GK Perfexion. Rezultati pokazuju razlike između paralelne i okomite orijentacije, posebno kod ionizacijskih komora i plastičnih scintilacijskih detektora. Zaključci naglašavaju važnost uzimanja u obzir orijentacije pojedinih detektora u dozimetriji uskih snopova Co-60 koje koristi Gamma Knife uređaj kako bi se minimizirali učinci volumenskog usrednjavanja.

Ključne riječi: volumeno usrednjavanje, Gamma Knife, detektori zračenja, dozimetrija malih polja

THE IMPACT OF DETECTOR ORIENTATION ON THE VOLUME-AVERAGING EFFECT IN THE DOSIMETRY OF GAMMA KNIFE PERFEXION PHOTON BEAMS

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Abstract
In the dosimetry of Co-60 photon beams used by Gamma Knife (GK) Perfexion device, various small-volume detectors are used. The orientation of the detector can be either parallel to or perpendicular to the device's z-axis. Given the comparable size of the detectors and the GK device's field sizes (16 mm, 8 mm, and 4 mm), as well as the ellipsoidal shape of the absorbed dose distribution, this dosimetry is characterized by the volume averaging effect of the measured signal, which may depend on the detector's orientation. The aim of this study is to determine correction factors for the measured signal to account for the volume averaging effect for both perpendicular and parallel detector orientations, and to assess the influence of detector orientation on this effect. Due to the lack of published research on the impact of detector orientation in the dosimetry of narrow photon beams from the GK device, this study analyzes 14 different small-volume detectors commonly used in GK dosimetry.

The ellipsoidal absorbed dose distribution of the GK Perfexion device was modeled using dose profiles obtained from Monte Carlo simulations, and the accuracy of the model was verified by comparison with the absorbed dose distribution calculated in a radiosurgery treatment planning system. Using MATLAB (TheMathWorks, Inc., USA) and numerical integration, the absorbed dose distribution was integrated over the active detector volume for both detector orientations. The ellipsoidal absorbed dose model showed an average accuracy of 1.79%, 1.15%, and 0.43% for field sizes of 16 mm, 8 mm, and 4 mm, respectively, compared to the treatment planning system. Volume averaging correction factors were calculated for all detectors in both perpendicular and parallel orientations. For ionization chambers and plastic scintillation detectors, the obtained correction factors were lower for the perpendicular orientation than for the parallel orientation. Semiconductor detectors and the diamond detector, due to their small active volume, did not show significant differences in correction factors between the two orientations.

This study provides a comprehensive analysis of volume averaging correction factors for different detectors in narrow photon beams of the GK Perfexion device. The results indicate differences between parallel and perpendicular orientations, particularly for ionization chambers and plastic scintillation detectors. The conclusions highlight the importance of considering detector orientation in the dosimetry of narrow Co-60 beams used in the Gamma Knife device to minimize the effects of volume averaging.

Keywords: volume averaging, Gamma Knife, radiation detectors, small field dosimetry

KARAKTERIZACIJA I PODRUČJE PRIMJENE PRIJENOSNIH MJERNIH UREĐAJA NAMIJENJENIH AMBIJENTALNIM ISPITIVANJIMA IONIZIRAJUĆEG ZRAČENJA

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Sažetak

Cilj: Uvažavajući specifičnosti u načinu rada niza izvora ionizirajućeg zračenja korištenih pri obavljanju različitih djelatnosti, cilj je okarakterizirati i usporediti nekoliko prijenosnih mjernih uređaja primarno namijenjenih mjerenju brzine ambijentalnog doznog ekvivalenta H*(10)/t (brzina doze) te odrediti područja primjene u kojima opisani uređaji mogu dati vjerodostojne rezultate ispitivanja. Razmatra se upotreba ovih uređaja u kontinuiranim poljima ionizirajućeg zračenja, pulsnim poljima, kratkotrajnim pulsovima zračenja te promjenjivim i promjenjivo-pulsnim poljima. Svi uspoređeni uređaji raspolažu ispisom mjerenja ambijentalnog doznog ekvivalenta H*(10) (doze) kao sekundarne veličine od interesa. Od posebnog su interesa niske razine zračenja u okolnostima kada se vrši procjena ozračenja stanovnika ili izloženih radnika B kategorije čije se ozračenje procjenjuje na godišnjoj osnovi putem proračuna.

Rezultati: Općenito, za većinu izvora zračenja mjerenje doze pokazalo se kao mnogo vjerodostojnije od mjerenja brzine doze, osim u kontinuiranim poljima zračenja gdje svi uređaji daju dobre rezultate izražene brzinom doze. Visoke nesigurnosti u rezultatima mjerenja pri niskim razinama zračenja nisu prepoznate kao značajan nedostatak uređaja uvažavajući pripadne niske radiološke rizike za ljude koji borave u takvim poljima zračenja. Značajno podcjenjivanje rizika pripisuje se mjerenjima brzine doze u kratkotrajnim pulsovima zračenja, osobito pri niskim razinama zračenja. Opcija mjerenja srednje energije zračenja dostupna kod jednog od uređaja otvara mogućnost procjene ostalih operativnih veličina u zaštiti od zračenja kao omjera konverzijskih faktora između mjerene i operativne veličine od interesa.

Zaključak: Svaki od karakteriziranih mjernih uređaja raspolaže specifičnostima kojima se razlikuje od drugih mjernih uređaja što uključuje vrstu detektora zračenja, vremensku konstantu, programsku podršku te način mjerenja doze koji može biti potpuno neovisan od mjerenja brzine doze ili integral mjerene brzine doze u vremenu, gdje se neovisnost mjerenja ove dvije veličine pokazuje kao značajna prednost uređaja. Jednostavnim očitanjem rezultata mjerenja s opisanih mjernih uređaja bez uvažavanja konkretnih mjeriteljskih karakteristika uređaja i prirode izvora zračenja moguće je značajno podcijeniti, ali i precijeniti rizike od ozračenja te svaki uređaj ove vrste zahtijeva pojedinačnu karakterizaciju uz neovisnu kontrolu uvjeta u korisnom snopu zračenja upotrebom dodatne karakteristične mjerne opreme.

Ključne riječi: Procjena ozračenja, ambijentalni dozni ekvivalent, brzina ambijentalnog doznog ekvivalenta

CHARACTERIZATION AND AREA OF APPLICATION OF PORTABLE MEASURING DEVICES INTENDED FOR AMBIENT IONIZING RADIATION TESTING

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Abstract

Objective: Considering very different operation principles for a number of ionizing radiation sources used in various practices, the aim is to characterize and compare some portable measuring devices primarily designed for ambient dose equivalent rate H*(10)/t (dose rate) measurements, and to determine the application area where compared devices can provide reliable test results. The use of these devices in continuous ionizing radiation fields, pulsed fields, short-duration radiation pulses, and variable or variable-pulsed fields is considered. All devices have a readout of the ambient dose equivalent H*(10) (dose) measurement as a secondary quantity of interest. Low radiation levels are considered in circumstances when radiation exposure of residents or exposed workers of category B is calculated annually, based on ambient radiation levels testing.

Results: In general, for most radiation sources, dose measurement has found to be more reliable than dose rate measurement, except in continuous radiation fields where all devices perform similar. High uncertainties in measurement results at low radiation levels were not recognized as a significant deficiency of the device, taking into account associated low radiological risks for people exposed to low-level radiation fields. Significant underestimation of the risk is attributed to measurements of dose rate in short-term radiation pulses, especially at low radiation levels. Option of mean radiation energy reading available on one device gives the possibility of assessing other operational quantities in radiation protection as the ratio of conversion factors between measured quantity and operational quantities of interest.

Conclusion: Each of the characterized measuring devices has specific features that distinguish it from other, including radiation detector type, time constant, software support, and the method of dose measurement that can be independent from dose rate measurement, or dose rate is integrated over measurement time, where dependence of measured quantities is found to be a disadvantage. Simple reading of measurement results without taking into account specific metrological characteristics and the nature of the radiation source can result in significant underestimation or overestimation of radiation. For conclusion, each device of this type should be characterized using independently controlled irradiation conditions where additional measuring equipment could be required.

Keywords: Radiation exposure assessment, ambient dose equivalent, ambient dose equivalent rate

ISPITIVANJE EFEKTA PETE U MODERNOM RENDGENSKOM METROLOŠKOM SUSTAVU

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Sažetak
Ovo istraživanje proučava efekt pete u modernom rendenskom metrološkom sustavu na Institutu za medicinska istraživanja i medicinu rada u Zagrebu. Efekt pete odnosi se na varijacije u intenzitetu emitiranog zračenja rendgenske cijevi. On nastaje zbog geometrije cijevi i ovisi o smjeru emisije zračenja. Efekt pete znatno doprinosi neuniformnosti polja u modernim rendgenskim sustavima. Unatoč njihovoj rasprostranjenosti u medicini i industriji, detaljni uvidi u efekt pete su rijetki. Sustav se sastoji od rendgenske cijevi od 225 kV nazivne snage 3 kW (model M2, Waygate Technologies, Pennsylvania, SAD) koja se napaja generatorom visokog napona Waygate Isovolt Titan Neo (Waygate Technologies). Uniformnost snopa je mjerena na udaljenosti 2 m od fokusa pod naponom cijevi 100 kV sa zanemarivom filtracijom od 0,1 mm aluminija i inherentnom filtracijom od 0,8 mm berilija. Mjerenja su provedena pomoću sferne ventilirane ionizacijske komore PTW TK-30 i elektrometara PTW Unidos Tango (PTW, Freiburg, Njemačka). Za osiguranje postojanosti snopa korištena je monitor komora PTW 786 (planparalelna ventilirana ionizacijska komora). Primijenjene su korekcije na temperaturu i tlak. Rezultati ukazuju na odstupanja od uniformnosti do 3,5%. Uz navedeni nefiltrirani snop, mjerenja su provedena i za odabrane standardne kvalitete snopa N-serije (N-10, N-40, N-100, N-200 prema normi ISO 4037-1). Neuniformnost odabranih snopova je znatno manja u odnosu na nefiltrirani snop. Dani uvid u karakterizaciju efekta pete u modernom rendgenskom sustavu značajan je za široko polje primjena, od poboljšanja kvalitete kalibracije detektora zračenja do medicinskog oslikavanja, gdje rezultira boljom kvalitetom slike i nižom predanom dozom pacijentu.

Ključne riječi: efekt pete, metrološki sustav, ISO 4037-1

INVESTIGATING THE HEEL EFFECT IN A MODERN X-RAY METROLOGY SYSTEM

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Abstract
This study investigates the heel effect in a modern metrology X-ray irradiation system located at the Institute for Medical Research and Occupational Health in Zagreb, Croatia. The heel effect refers to the variation in the intensity of the X-rays emitted by the X-ray tube. It comes as a consequence of the tube geometry and is dependent on the direction of the X-ray emission. The heel effect significantly contributes to field non-uniformity in modern X-ray systems. Despite their widespread use in medicine and industry, detailed examinations of the heel effect remain scarce. The system features a 225 kV X-ray tube with a 3 kW power capacity (M2 model, Waygate Technologies, Pennsylvania, USA), powered by a Waygate Isovolt Titan Neo high voltage generator (Waygate Technologies, Pennsylvania, USA). Beam uniformity measurements were conducted at 100 kV with a negligible filtration consisting of 0.1 mm aluminum and the inherent filtration of 0.8 mm beryllium at a distance of 2 m from the focal point using a PTW TK-30 vented spherical ionization chamber and PTW Unidos Tango electrometers (PTW, Freiburg, Germany). Consistency was ensured with a PTW 786 vented plane-parallel ionization chamber as a monitor. Corrections for deviations in temperature and air pressure were applied. Results indicate dose uniformity deviations of up to 3.5%. In addition to the aforementioned unfiltered beam, measurements were conducted for select N-series standard beam qualities (N-10, N-40, N-100, N-200 as per ISO 4037-1). The beam non-uniformity was significantly lower in measurements conducted for the selected beam qualities than for the unfiltered beam. These insights into the characterization of the heel effect in modern X-ray systems have implications for a wide array of applications, from improved calibration of radiation detectors to enhanced diagnostic imaging, resulting in higher image quality and lower patient doses.

Key words: heel effect, metrology system, ISO 4037-1

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