RadoNorm
Managing risks from radon and NORM

Deliverable 1.6

Minutes from the Final Meeting

Work Package 1

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Disclaimer

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Executive Summary of the RadoNorm project

EU member states, associated countries and the European Commission are implementing the European Basic Safety Standards (BSS) Directive for radiation protection. The EU-funded RadoNorm project focuses on all radiation risk management cycle levels for radon exposure, as well as situations of exposure to naturally occurring radioactive materials (NORM). The project intends to reduce scientific, technical and societal concerns by introducing research and technical developments, integrating education and training (E&T) and disseminating the results of the project through targeted actions to the public, stakeholders and related institutions. RadoNorm directs research and development on all levels of the management cycle, combines biomedical and ecological research with mitigation development and social science research and brings together researchers from national radiation protection entities, universities and SMEs.

Executive Summary of this deliverable

This report is a deliverable related to work package 1: Coordination, Management and Administration and deliverable D1.6 - Minutes from the Final Meeting. The report aims to report the main activities carried out in the frame of this work package deliverable, the presentations made for each work package, interactions among different WPs in relation to the execution of deliverables and the overall legal, ethical, financial and administrative arrangement of the consortium.

The RadoNorm project held its Final Meeting on 3 – 5 June 2025 in Budapest, Hungary. The first day, consisting of internal task and work package meetings, was specifically for consortium members only. Since the project approaches its end, the goal was to discuss progress and coordinate contributions for the final few deliverables as well as conduct a review of what went well and what could be improved.

The 4th and 5th June then featured open sessions where work packages presented their progress in three sessions: “Health and Beating Cancer”, “Environmental Risks” and “Measures to Protect People”. Here, stakeholders and advisory board members could also participate. There were multiple panel discussions within each session featuring an external stakeholder, addressing relevant topics that stakeholders, such as regulatory authorities and members of international organisations, are concerned with.

This deliverable comprises a summary of the proceedings of the Final Meeting and aims to give the reader an overview what was discussed at the meeting and how the results of the project finally came together to achieve the initial goals that RadoNorm set out to achieve. Detailed information regarding the presentations is omitted from this report for the sake of brevity and all presentations of the open sessions can be found on the RadoNorm website at https://www.radonorm.eu/event/event-material/#245-528-wpfd-presentations-radonorm-final-meeting.

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1. Organisation, scope and overview and structure of the meeting

The RadoNorm Project held its Final Meeting in Budapest, Hungary on 3 – 5 June 2025. This was the opportunity for RadoNorm partners to gather to report about the RadoNorm results and progress since the start of the project, in particular of the last year, and to get an overarching picture of what has been achieved. The two-and-a-half-day programme was a comprehensive hybrid event, where 161 registered participants took part either online or in-person. The participants consisted of members of the consortium as well as stakeholders and advisory board members (external participants). Of these, 99 participants (86 consortium members and 13 external) took part in-person and 62 participants (39 consortium members and 23 external) took part online. In total, 65 institutions (from the consortium and external participants) were represented.

Internal meetings took place on the first day (3rd June) within work packages (WPs) and between WPs. The 4th and 5th June then featured scientific presentations from the work packages to the theme of "Sustainable radiation protection for radon and NORM". Here, WPs 2, 3, 4, 5 and 6 oriented their talks according to three topics: "Health and Beating Cancer", "Environmental Risks" and "Measures to Protect People". To encourage discussion of the latest results, there were considerably more panel discussions incorporated into the programme, with each session featuring multiple discussions involving external experts who could discuss potential implementation of the results. In addition to scientific talks, time was also given to the RadoNorm Early Career Researchers (ECRs) to reflect on their experiences over the five years of RadoNorm and look into what perspectives lie in store for them following the end of the project. An agenda can be found in Appendix A of this document.

At the end of the Final Meeting, the advisory board members who were present met together to discuss the progress of the project and came out with their report, found in Section 0 of this document.

2. Minutes of the Annual Meeting

2.1. Internal Meetings (3rd June)

Day 1 opened with internal meetings within the WPs and certain tasks between WPs. The purpose of the meetings was to discuss progress within the tasks and what sort of interdisciplinary collaborations are possible between WPs.

2.1.1. Work Package 3 General Meeting

Balázs Madas (EK) welcomed the on-site and on-line participants, short self-introduction of all participants. A task-by-task update was given.

Task 3.1: Quantification of the effect of smoking on absorbed doses from radon exposure

David Broggio (ASNR) provides an overview of the activities within Task 3.1. A literature search was performed on studies addressing the issue of differences in physiology, morphology and kinetics between smokers and non-smokers. Dose modifying factors were calculated, showing that the dose to lung is lower in smokers than in non-smokers (factor 0.8-0.9), but for some organs like kidneys, brain and bone marrow the doses to smokers may be up to 4 times the corresponding doses to non-smokers. The results support a sub-multiplicative interaction between radon and smoking on lung cancer risk. Two presentations on the progress of Task 3.1 would be held during the Plenary Session of the RadoNorm Final Meeting by Peter Füri and Dalma Günter (EK).

Open issues:

- study performed for workers, is it worth to extend it to members of the public?
- what is the impact of the increase in organ doses?
- need to integrate dosimetry and radiobiological models
- interactions with the effects caused by other pollutants (e.g., diesel gas, particulate matter, etc.)

Task 3.2: Dosimetric calculations for epidemiological studies

Tracy Gooding, who took over the Task lead after James Marsh's retirement, introduces Task 3.2. Mission of this task is to calculate input parameters for the Monte Carlo calculations with the ICRP models. Both miners and millers are considered, exposed to similar radionuclides but under different scenarios in terms of chemical processes and aerosol conditions. Measurements mostly date back to the 60s and 70s, published data have low resolution (e.g., hand-drawn graphs), low traceability, lots of uncertainties.

Six scenarios were defined for miners, identifying values for AMTD, AMAD, σ_g, nucleation mode, F (0.2 for good ventilation, 0.6 for poor ventilation), hgf. Monte Carlo calculations were performed using UKHSA PLEIADES code, equivalent doses calculated for ^{222}Rn and progeny for several organs, and breathing rates of 1.2 and 1.4 $m^3\ h^{-1}$.

Task 3.3: Dose assessment for specific subgroups of the population

Augusto Giussani (BfS) provided an overview of Task 3.3. Details of the model of the biokinetics for embryo and foetus were presented. Ämilie Degenhardt (BfS) spent one month at the Oak Ridge National Laboratory to work with R. Leggett and C. Samuels. David Broggio (ASNR) said it would be interesting to compare foetal organ doses to doses calculated for the foetus as a whole. Tracy Gooding suggested that the results should be published also in an accessible way for regulators.

An Excel-tool for the calculation of organ dose coefficients including individualisation of exposure conditions (Milestone 37) was provided to Task 4.3 for their epidemiological analyses of leukaemia and tumours of the central nervous system in children. There will be a presentation on the dose coefficients. by Vladimir Spielmann (BfS) during the Plenary Session of the RadoNorm Final Meeting (and another presentation by Ben Spycher of WP4 about the use of these data).

In Subtask 3.3.2 and 3.3.3 the deposition of radon and its progeny and the resulting doses to different sections of the respiratory tract were compared between adult and children, between healthy persons and asthmatic patients and between smokers, heavy smokers and non-smokers. The observed patterns are the results of complex interactions between the effect of mucus thickness, airway diameters and modified breathing rates.

Task 3.4: Assessment of uncertainties affecting dosimetric calculations

Wolfgang Raskob (KIT) provided a status report of the activities within Task 3.4. It was very intensive work to look for the parameter distributions and the scenarios and there was good interaction within partners. Presentation by Thomas Makumbi (KIT) during the Final Meeting. Two scenarios were defined: wet drilling with good ventilation (Job Type 1) and dry drilling with poor ventilation (Job Type 4). Two different models were developed in BfS and KIT with different approaches and implementation schemes, with differences in the results: geometric means (GM) are slightly higher for the BfS vs KIT, but geometric standard deviations (GSD) lower. 95% confidence interval is very broad (e.g., 25-133 $mSv/mJ{\cdot}h{\cdot}m^{-3}$ for Job Type 4).

Three papers have been published, one more is in the pipeline. One presentation on the progress of Task 3.4 will be held by Thomas Makumbi (KIT) during the General Session of RadoNorm Final Meeting.

Possible further research topics: better design workplace-specific protective measures against thoron, contribution of thoron to radon doses, develop reference parameter distributions, develop mechanical understanding of the behaviour of radon and its progeny.

Task 3.5: Computational microdosimetry supporting the preparation and evaluation of experiments

Árpád Farkas (EK) provided an overview of the work in Task 3.5. First Subtask was the calculation of bronchial doses due to inhalation of progeny. Enhancement factor in correspondence of bifurcation (higher deposition and slower clearance). Simulations were performed to inform planned studies in animal (rats) in collaboration with Barcelona Hospital Clinic, different morphology and physiology were considered, and also in cell cultures (in this case calculations were compared with TLD-measurements). Comparison with results by BfS (Michaela Kreuzer / Nora Fenske), large differences. Differences in regional deposition is not the main cause of the observed discrepancies, maybe biology or other factors.

Task 3.6: Comparison of the effects of homogeneous and inhomogeneous dose distributions

Balázs Madas (EK) presented an overview of the tasks and progress regarding the effect of inhomogeneous deposition. The planned deliverable has been shifted to the project's end. Adjustment of the local effect model was performed by Kim Sennhenn (GSI). The original plan to identify differences between homogeneous and inhomogeneous exposures turned out to be very ambitious, however they are apparently not relevant for radiation protection.

Two PhD projects were financed within this Task: Kim Sennhenn at GSI and Szabolcs Polgár at HUN-REN EK. One presentation on the progress of Task 3.6 will be held by Kim Sennhenn (GSI) during the Plenary Session of RadoNorm Final Meeting.

2.1.2. Task 4.3 Meeting: Joint data-analysis on radon and childhood leukaemia (Switzerland, France, Norway, Finland)

Task 4.3 will be contributing to the WP4 overview paper by providing a general overview of the results of the joint data-analysis as well as some short descriptions of the datasets used.

Amount of cases: Switzerland has the most subjects ([cohort] roughly 100 000, of which 3000 cases of leukaemia), France has roughly 700 cases in two separate studies, Finland, Denmark and Norway roughly 3000 cases.

Basic logistic model: The best would be unconditional logistic regression, linear exposure term was discussed, adjusted for age at diagnosis, sex and year of birth.

Calculation of cosmic radiation, a new method will be published in the summer. The question is whether the results be perhaps recalculated with it.

Leukaemia

Denmark data does not have a real gamma dose, used a constant gamma dose. Switzerland and Norway have data from 1990s - 2020.

Radon concentrations vary from 51 Bq/m^3 (Denmark) to 76 Bq/m^3 (Switzerland). Cumulative radon in red bone marrow (RBM) proportion over cumulative total RBM roughly 7 - 9% throughout the national studies.

Total dose - Surprisingly only France has an odds ratio (OR) of 1.10 or 1.08 with a 95% confidence interval (CI) varying from 1.04 - 1.15. The common effect model OR of 1.07. France did not do conditional model as there were no case-control matching.

Radon dose – OR most probably higher than one on all of the national studies, however 95% CI varies from 0.83 - 1.52

Gamma dose – France and Switzerland have OR > 1 with 95% CI also above 1. Similar results when using the conditional model.

Central Nervous System

Radon dose varies from 53 Bq/m^3 (Denmark) to 76 Bq/m^3 (Switzerland). Cumulative radon RBM proportion over cumulative total RBM is roughly 3 % throughout the national studies. Radon contributes only minutely to the cumulative dose of the brain.

Total dose - France and Switzerland OR > 1 with 95% CI 1.01 - 1.24. Denmark and Norway OR < 1.

Radon dose – France and Switzerland OR > 3 but 95% CI varies greatly. Swiss data is surprising as its OR is 1.87 [1.04 - 3.35], data must be checked again. No conclusive evidence.

Gamma dose – France and Switzerland OR > 1, Norway < 1.

Norway has negative results throughout for CNS (total dose, radon dose, gamma dose). Data for CNS are far more heterogenous than for leukaemia.

Summary/discussion

Should we ignore locations other than home? Use homes as the uncertainties are wider elsewhere. Use the ICRP standard assumptions (F=0.4; fp=0.1 etc.). Use of country specific attempts to approximate indoor exposure and better information on building materials would improve the quality of the study. Calculating terrestrial outdoor gamma radiation * indoor/outdoor factor and then add cosmic radiation*shielding factor.

Diagnostic groups – Acute leukaemias (I.a + I.b + I.e), acute myeloid leukaemia (AML) as an exploratory.

CNS tumours, gliomas (III.a.1, III.b, III.d, NO III.e.4), embryonal tumours, based on tumour behaviour (malignant vs non-malignant).

It was proposed to use Pilocytic astrocytoma and multiple different types of acute lymphoblastic leukaemia (ALL) but not to go into too fine details as the study might not have enough statistical power in those.

Exclude cases with Down-syndrome as it can act as a strong effect modifier. Clarify inclusion/exclusion criteria for cancer predisposition syndromes (CPS)

Discussions on additional analyses to run revolved around consideration of timing of exposure (birth or diagnosis) and linear dose response. It was decided that these analyses would only be done for ALL and CNS, not the different types of tumours.

Discussion about the publication included a possible submission to Nature medicine. Authorship for the planned joint publication was agreed as: Wafa Alimam as first author, Jad Abuhamed as second author, and Ben Spycher as last author. Another meeting will be held to discuss the contents of the paper. The protocol used should be published, as it may be useful in publishing the results.

2.1.3. Tasks 3.3 and 4.3 Joint Meeting

Main Objectives of the Joint Task:

- Development of a compendium of organ dose coefficients calculated over several small intervals, using reference models and assumptions
- Inter-country comparison of dose-related information
- Webinar on epidemiology (October 2024)
- Literature review focused on brain doses and inhomogeneous exposure
- Biokinetic model modifications (direct/indirect brain absorption and sensitivity analysis)

Task 4.3 Update – Epidemiology (Ben Spycher)

A previous Task 4.3 meeting reviewed preliminary epidemiological results. The focus was on external environmental and cosmic radiation exposures. Standard assumptions were used, such as attached fractions and no adjustments for dwelling occupancy.

The study includes national cancer registries from Denmark, France, Finland, Norway, and Switzerland. Mean external and cosmic radiation exposure dose rates ranged from 67.3 to 91.8 nSv/h, and mean radon concentrations from 51.2 to 75.9 Bq/m^3. Dose calculations were based on coefficients from Vladimir Spielmann, and equivalent external doses were derived from a publication by Sato and Petoussi-Henss[1]. For radon, an alpha radiation weighting factor of 20 was applied. Radon's contribution to the overall dose was smaller compared to external exposures. As expected, cumulative equivalent dose increased with age, however age was adjusted for in the analyses. Combined effect estimates from meta-analyses of country specific results show a significant increase of leukaemia risk with organ doses.

Brain Dosimetry Discussion

In the brain dosimetry discussion, it was noted that, similar to red bone marrow (RBM), radon contributed less to brain doses compared to external and cosmic exposures. However, there remains uncertainty in the exposure scenarios, highlighting the need for sensitivity analyses. Adjustments to biokinetic models were discussed, including accounting for inhomogeneous brain dose distribution, adding a brain compartment into the model, and considering RBM as fatty tissue.

Tumour Classification

The tumour classification discussion focused on further specifying tumour types, such as differentiating between brain tumours and including spinal cord tumours, although the latter are not traditionally considered target tissues for radiopharmaceuticals. Augusto Giussani will follow up with a specific model for a radiopharmaceutical case. There was also consideration of germ cell tumours, but the decision is leaning towards including only primary brain tumours. Emphasis was placed on dosimetry for risk grading and on obtaining data about building materials, although a previous attempt at collaboration on building material data did not yield useful results. Additionally, the group plans to explore the effects of reference levels and assumptions in dose estimation.

[1] Satoh, D., Petoussi-Henss, N. Dose-Rate Coefficients for External Exposure to Radionuclides Uniformly Distributed in Soil to an Infinite Depth. PLOS ONE 2024, 19 (9), e0310552. https://doi.org/10.1371/journal.pone.0310552.

Possible Publication

For dosimetry, it is important to include sensitivity analyses and detailed exposure scenarios. The initial focus will be on national-level studies. Preparation of a paper combining dosimetry and epidemiology could begin in October 2025.

Country-specific notes:

In Finland, data on building materials is available. Information on equilibrium factors and their dependency on building material may be found in the literature. Switzerland does not have data on building materials in the epidemiological study. A measurement survey on a small sample suggested a strong effect of building materials external dose rates. Even small datasets can help support comparisons to reference values. Norway has potential building material data for apartments. Generally, there is a correlation observed between doses and building materials, highlighting the importance of building materials for assumptions about radon emanation and diffusion.

Foetal Exposure and Dosimetry

There is limited data available on foetal exposure and dosimetry, including epidemiology and physiology. Notable differences exist in tissue distribution within the foetus, and there remain open questions regarding the assumptions about foetal physiology.

Next Steps

- Explore funding options and possibility of involving a PhD student
- Involve individuals capable of carrying out field measurements
- Potential topics:
    - Building material analysis
    - Home dosimetry
- Data protection limitations in Finland for in-home measurements
- Balazs shared a funding opportunity link – possible joint submission
- Idea: measure gamma exposure in schools/playgrounds
    - Task 2 focused on residences, not schools
- Regulatory distinction: children as public, teachers as potentially occupationally exposed
- Interest in engaging multiple work packages (WP2, WP3, WP4, WP5)
- Ben Spycher may revisit study families for potential dosimeter placement
- Linking hospital data with building material data was suggested
- General caution against using short-term radon measurements due to high uncertainty

Remaining questions

Clarification on:

- Pregnancy and dosimetry assumptions
- Limiting focus to brain, excluding spinal cord
- Possible inclusion of spine dosimetry
- Uncertainty analysis methods and dose calculation explanations

Final report to include:

- Epidemiological overview
- Interaction between Tasks 3.3 and 4.3
- Submission to special issue under consideration

2.1.4. Task 5.5 Meeting

The meeting discussed the finalisation of Deliverable 5.13 – Report on scientific rationales for improving regulatory approaches of NORM treatment and management. During the meeting reasonable and scientifically justified suggestions for possible modifications to the existing radiation protection system were presented, improving its effectiveness and efficiency towards overall NORM management based on radiation protection principles such as hazard optimization and evaluation tailored for a NORM perspective. During the meeting the following suggestions were presented and discussed:

- common (ordinary waste) regulations vs NORM (options analysis and modification suggestions;
- radioactive waste vs NORM residues – proposed solution - justification (legislative as well as practical);
- suggestion on occupational exposure mitigation (interactions with regular occupational health and safety systems)
- optimisation of reference (clearance) levels considering possible disequilibrium in thorium and uranium decay series;
- development of new mitigation/preventive methods.

Issues and significant gaps requiring supplementation that should be included (such as metrology issues) in the report were identified. In addition, the method of exchanging information and data between institutions responsible for preparing the report was identified, as well as the dates of online meetings enabling finalisation of the final version of the report.

In addition, the issues included in the draft of the article *Development of legal and practical framework for NORM treatment* were discussed.

2.1.5. Tasks 2.5 & 5.5 Joint Meeting

The goal of the meeting was to discuss the finalisation of the legacy paper planned in task 2.5 and 5.5. Participants from both tasks were present both in person and online. The structure of the paper, drafted some time ago, was discussed among the co-authors, and a schedule for next steps and finalisation of work was defined. As inputs on paper were given by co-authors in the previous months, certain issues, still in question, were discussed:

- definition of legacy and how to describe and explain national approaches in the paper;
- clearer way to include information and data on legacies in European countries gathered by developed tools;
- how to supplement limited data gathered in the RadoNorm with those from literature sources;
- if case studies, and which ones, should be included in the paper or it will stay as per today based on general data and information.

The following steps were agreed upon: (1) all co-authors will provide additional input whether legacy sites are included in national legislation and if regulatory approaches are developed in line with international practices (IAEA, EU BSS), (2) main author, Bogusław Michalik will compile inputs and make a new version of paper, (3) after revision, paper should be submitted to the RadoNorm special issue in journal Radiation and Environmental Biophysics as soon as possible.

2.1.6. Navigating ethical challenges in RadoNorm

The RadoNorm Ethics Committee organised a meeting to discuss various challenges faced by the consortium over the span of project.

The topic of open data was brought up, where the consortium was reminded to make sure that the raw data is published and made available according to FAIR (findable, accessible, interoperable, retrievable) principles.

Identifying predatory or questionable journals was another topic of discussion, where institutional practices differ among project partners in the sense that some partners recommend avoiding journals that others do not. Whilst impact factor may not be a deciding factor for some while publishing, it was mentioned that for early career researchers (ECRs) and their principal investigators, publishing in journals with decent impact factor (and therefore high publishing costs) is generally sought after to help in career development of ECRs. Prudence was called for in selecting journals for publishing RadoNorm results.

2.1.7. Early Career Researcher Council Meeting

The meeting was opened by Kim Sennhenn, who welcomed the participants and summarised the purpose of the ECR Council. This was followed by a round of short introductions, where each participant shared their name, institution, role in the RadoNorm project and duration of involvement. Sennhenn then shared a video collage of behind-the-scenes moments and highlights from past ECR activities.

An interactive survey was conducted using the online tool Mentimeter. The survey results, along with the discussion among participants, are summarised below:

Networking and peer support:

- The ECR Council provided opportunities for networking, informal exchange, and peer support.
- The council meetings were highlighted as a “safe space” to ask questions and share experiences.

Travel grants:

- Travel grants were widely used for training courses, conferences, and research stays.
- Participants noted they were easy to apply for and helpful in securing supervisor approval for travel.
- One participant criticised funding was only enough for travelling within Europe; others responded by noting that RadoNorm travel grants provide more funding than most others and also a larger travel grant that could be used for international conferences was later introduced (although this was not clear to everybody).
- It was criticized that the research stay grant was introduced only late in the project, but others who were able to use it were very satisfied with it.

Training courses:

- Training courses (Stockholm, Prague, Granada) were rated as the most appreciated ECR activity.
- Content on communication, career management, and AI in science addressed skills not typically covered in formal academic training.

Participation:

- The question about the lack of engagement for some participants was not easily answered.
- Possible reasons: Varying levels of supervisor support, short-term contracts, late entry into the project or lack of awareness

Areas for improvement:

- Suggestions included more outreach to participants, earlier establishment of the council, and providing links to industry.
- A few participants expressed the need for more structured engagement with the project board, with the suggestion of including an ECR in the board; others were satisfied with the connection to the board.

Career perspectives:

- All participants of the survey indicated plans to stay in the field of radiation protection.

- Many of them found positions in their home institutions.
- Others are still looking for opportunities either in academia or industry.

The meeting concluded with a brief introduction to the ECRad (Early Career in Radiation Protection) network as a potential platform for maintaining the established network after the RadoNorm project concludes. A few participants expressed interest in joining, but found the process unclear. According to the founders of ECRad, future development will depend on the general interest and availability of funding. The organisers will provide further information as soon as possible.

2.2. Open Sessions (12th and 13st June)

Days 2 and 3 of the Final Meeting involved external members such as stakeholders and members of the advisory board, as well as invited panellists. Presentations from consortium members were given in the three sessions titled “Health and Beating Cancer”, “Environmental Risks” and “Measures to Protect People”. Within each session, there were several panel discussions featuring external experts who could discuss potential implementation of the results. The online feature of the meeting, allowed stakeholders to also participate online as panellists.

Day 3 opened with a message from the project coordinator, where W. John (BfS) welcomed the delegates, and presented an overview of the progress from WPs 1, 7 and 8. Here an update was given regarding the status of deliverables and milestones, the final report, amendments to the grant agreement, travel grants and courses, ECR council activities and dissemination activities. A recap of the RadoNorm Showcase Meeting in March 2025 along with the identified challenges for future research for radon and NORM were also presented. It was briefly mentioned that members of RadoNorm Early Career Research (ECR) Council will continue their efforts to network among other ECRs in radiation protection through the newly-formed ECRad initiative. Moreover, it was announced that an e-collection titled “Health and environmental risks from radon and NORM exposure situations” has been made available in the journal Radiation and Environmental Biophysics for papers incorporating work in the RadoNorm project. Currently, several ideas are also being discussed to explore how the RadoNorm consortium can continue to partner in future projects.

Mr. John then presented the goal of the Final Meeting, namely that research and efforts within RadoNorm should be as sustainable as possible, in that the legacy of RadoNorm continues through the implementation of its results not just in radiation protection but also for the wholesome protection of both people and environment. Consequently, the presentations of the Final Meeting will highlight how the results also contribute to achieving the United Nations Sustainable Development Goals (UN SDGs).

The summaries of the presentations are found in the Book of Abstracts (Appendix B) made available for the final meeting. The following subsections will therefore only elaborate on the discussions for each block.

All presentations from the open session of the Final Meeting can be found on the RadoNorm website[2]. Video recordings of the presentations can be found on the YouTube channel[3].

2.2.1. Session 1: Health and Beating Cancer, Block 1

The panel was composed of Werner Rühm (International Commission on Radiological Protection; ICRP) as the external expert and presenters of the Health and Beating Cancer – block 1: Laura Mezquita (HCB), Ben Spycher (U Bern), Vladimir Spielmann (BfS), Nora Fenske (BfS) and Olivier Laurent (ASNR). The panel was moderated by Anssi Auvinen.

[2] www.radonorm.eu/event/event-material/#245-528-wpfd-presentations-radonorm-final-meeting
[3] www.youtube.com/playlist?list=PLmTvmsnkOYoRlrp7X25vt70qxwqJ97inm&si=6tPS1HMt6rR4vPF5

During the meeting, Werner Rühm highlighted the critical importance of the RadoNorm project from the standpoint of the ICRP, emphasising that radon constitutes a significant public health concern. Investigating its details thoroughly, as RadoNorm has done, is therefore essential.

L. Mezquita was asked about the definition of high radon areas in ecological studies, to which she explained that these areas were characterised in partnership with IRSN (now ASNR). She noted that high radon groupings were determined by comparing exposure levels to the median levels observed in France.

Anssi Auvinen expressed astonishment at the extensive data gathered from minimal sample sizes and asked whether the findings would be validated in rats and miners. Laura Mezquita replied that future plans include confirming these results in the forthcoming BioRadon follow-up study.

Nora Fenske was asked about whether radon presents risks other than lung cancer, given the uniformly negative results. She stated that current data, aligned with dosimetry, only reveals minor increases associated with high doses without significant effects at low doses, suggesting no apparent risks beyond lung cancer. However, she noted that final conclusions await further data from the PUMA and CONSTANCES cohorts.

Participants discussed the remaining open questions in each of their lines of work. Vladimir Spielmann plans to calculate dose coefficients for various age groups and improve brain dosimetry through refined Monte Carlo simulations. Ben Spycher pointed out the major challenge of exposure dosimetry and mentioned that additional data on building materials could enhance the quality of the results. Laura Mezquita seeks to advance precision medicine by identifying specific molecules for radon-induced lung cancer and identifying high-risk populations for consideration in personalised healthcare. Fenske emphasised the need to incorporate incidence data alongside mortality figures and to refine methodologies to eliminate uncertainties.

Werner Rühm inquired about the potential for ground-breaking results in epidemiology over the next decade, particularly from an ICRP perspective. It was suggested that integrating molecular data with epidemiological findings and utilising biomarkers in studies could significantly improve result precision.

2.2.2. Session 1: Health and Beating Cancer, Block 2

The panel was composed of Katalin Luminczky (MELODI) as external expert and presenters of the Health and Beating Cancer – block 2: Fieke Dekkers (RIVM), Péter Füri (HUN-REN CER) and Kim Sennhenn (GSI). The panel was moderated by Árpád Farkas.

Katalin Luminczky (Multidisciplinary European Low Dose Initiative; MELODI) remarked on how large scientific efforts have been made to investigate radon-related risks, especially into cancerous and non-cancerous effects. It seems to be extremely difficult to measure and discriminate between radon, radon progeny, and gamma radiation to strengthen the evidence related to radon directly. In addition to smoking contributing to the effects of radon, air pollution would also have to be considered as it is an important environmental hazard in today's world. MELODI is interested in researching the combined effects of different environmental hazards which includes tobacco smoke and radon but does not focus particularly on new e-cigarettes for example.

Fieke Dekkers mentioned that the manufacturers of measuring devices should take responsibility to specify if an instrument is sensitive to thoron or not. At the moment many manufacturers do not know the details. Earlier studies may be influenced by the fact that instruments used may have been sensitive to thoron without the researchers knowing about it.

Péter Füri stated that e-cigarette smoking would be an interesting question to address by using the modelling presented in his talk as it could be done rather easily by changing the parameters.

Kim Sennhenn commented on her talk that other cell death mechanisms could also be interesting to model similarly as she modelled in her low-dose hypersensitivity studies. The relevance of the results from the point of view of health risks should be discussed with experts on the matter.

2.2.3. Session 2: Environmental Risks, Block 1

The panel was composed of Stefan Röttger (EURADOS) as external expert and presenters of the Environmental Risks – block 1: Olivier Armant (ASNR), Thomas Makumbi (KIT) and Dalma Günter (HUN-REN CER). The panel was moderated by Augusto Giussani.

Stefan Röttger commented on how impressively really complex scenarios in RadoNorm were investigated. He posed the question if uncertainties could be helpful in research and mentioned that RadoNorm results should be very helpful for upcoming radon-related projects.

Augusto Giussani also stated that one big problem is to know the distribution of the initial parameters when assessing the uncertainties and asked the panellists for their insights on how one should go about including uncertainties into epidemiological analyses. Moreover, variability should be better taken into account. Augusto asked the panel how these sustainable development goals of UN and what would be potential impacts on worker health.

Olivier Armant was interested in dose-response relationships where uncertainties could offer additional insights. Human activity should be taken into account towards effects on nature and ecological impact, climate change, and sustainable development goals; more so on a global health aspect. AOPs really try to answer problems in the future going from small to large scale. Biology, through AOPs, can help with functional/mechanistic analyses to understand effects in humans in which the functional/mechanistic analyses are not possible to perform.

Thomas Makumbi responded that uncertainties really are a big problem. We can still do a lot for uncertainties and get more reliable results. In mining activities and nuclear industry, worker health issues are present as are climate change issues in sustainable development context.

Dalma Günter stated that open modelling platforms are important in radon dose estimations, providing an easier and more accessible approach.

2.2.4. Session 2: Environmental Risks, Block 2

The panel was composed of Laura Urso (IAEA) as external expert and presenters of the Environmental Risks – block 2: Hallvard Haanes (DSA), Sara Antignani (ISS), Miquel Vidal (UB), Viktor Dück (HZDR) and Jelena Mrdakovic Popic (DSA). The panel was moderated by Estela Reinoso-Maset.

Laura Urso from the Radiation Protection Unit of IAEA briefly presented some of the activities done in her unit in line with the RadoNorm presentations. One main activity is the establishment of standards to support member states implementing international recommendations and directives. It also includes the production of safety guides, Tec Doc reports, etc. One of the safety guides currently under development deals with the radiation protection (RP) safety in existing exposure situations. In link with the RadoNorm project, it is very important for such existing exposure situation to have a proper characterisation. Radon is one main issue regarding existing exposure situations. Laura Urso highlighted that the outputs of the RadoNorm project may be very helpful to identify the different situation of interest and support the national government and regulatory bodies in the implementation of international recommendations regarding RP in existing exposure situations.

Another aspect is the effort done in the project to understand what the key processes governing the exposure of public and environment (including the transfer of radionuclides) are. Even if regulatory RP models need conservative outcomes and prediction, they have also to be simple, transparent, and

explainable. Thus, all scientific research outputs on processes related to the transfer of RNs is useful to explain and support these regulatory models.

Laura Urso continued that the issue of NORM and co-stressors is also very important, and it is a subject still poorly studied. However, in the case of multiple exposure situations where there is radiological concern, it may help at a practical level to see that the radioactivity is sometimes not the main issue or that the implementation of remediation/mitigation activities for other type of contaminants may also be helpful to reduce the radioactive impact.

Regarding High Background Radiation Areas, characterisation of the Fen site in Norway (although it is both a HBRA and a NORM site) helps to create baseline information and then to evaluate at a later stage the impact of any human activities

Miquel Vidal highlighted that the work done in RadoNorm has opened a way for future research. In particular, the very high heterogeneity levels of the NOR materials make the characterisation of these materials a huge challenge. Although the RadoNorm project has supported a lot of progress on how to predict the K_d values for a number of individual NOR, what is missing now is the role of the source term. For example, the leachability or the chemical behaviour of the NORs are really dependant on the materials in which they are. Little is known about the effect of the presence of other pollutants in the source term that can interfere with NOR regarding these two aspects.

Jelena Mrdakovic Popic pointed out the difficulty to interpret the data from multiple exposure sites to account for the presence of multiple parameters, contaminants, etc. About legacy sites and existing exposure situation, she highlighted that it is not easy to define what legacy sites and more specifically NORM legacy sites are. It is something that has to be done at an international level. The same issue also exists for HBRA, for which a clear definition is still lacking.

Sara Antignani iterated that the work she has presented focused on the methods used to characterise the exposure to Rn, more specifically to highlight the high level of exposure. There is a need of transparency on the methods used to interpret the data, and the goal of her work was to assess if the mathematical methods used can drive the results in some direction or not.

Hallvard Haanes highlighted that ventilation of mines in addition to exhalation can have a great impact on radon and thoron outdoor levels at HBRA and legacy sites

Laura Urso answered a question about whether the IAEA is ready to revise the K_d tables used in radioecological models, that she did not know the exact answer to this question, but the good thing is that the results of the RadoNorm project have been published and so the advances made on the K_d values will be known internationally.

Sara Antignani answered a question on the effect of ventilation and ventilation habits on the indoor radon level - if this parameter was taken into account in the survey done in Italy. She stated that in the Italian context, ventilation is not a parameter of interest (ventilation is not used as a mean of changing air in houses, at least 10 years ago when the survey was done). So, in the study, they used other variables that can be used as a proxy of ventilation in dwelling. For example, they showed that the presence of smokers is associated to lower Rn concentrations (more used to opening windows), but the presence of small children is associated to higher Rn concentration (perhaps because mothers avoid opening windows to keep heat inside).

Hallvard Haanes answered a question on whether there is a remediation plan for the Fen site, and how it is affecting the population. He mentioned that there are some communications with municipalities. DSA promised to perform more measurements to reduce uncertainty in the assessment of exposure at the iron legacy sites. The niobium legacy site is planned to be cleaned up. However, for the ventilation of the iron mines, or the iron legacy site itself, even if there is a lot of waste rock exhalating and contribution to dispersion of dust, there is no plan of remediation. Regarding the impact on population,

the closest houses are 300 meters far from the site, but most houses are 500 - 600 meters or further from the site. Therefore, the legacy site is not really an issue for them. However, use of the site in certain cases (due to campers, or use of the beach) may require some attention.

2.2.5. Session 3: Measures to Protect People, Block 1

The panel was composed of Christian Schwenk (ExRadon) as the external expert and presenters of the Measures to Protect People – block 1: Sara Antignani (ISS), Sebastian Feige (BfS), Miroslav Havelka (SURO) and Karel Jílek (SURO). The panel was moderated by Tuukka Turtiainen.

The panel discussion focused on the challenges and advancements in radon detection, measurement uncertainties and variabilities, and their impact on measurement protocols. The effects of meteorological characteristics were mentioned, such as the impact of wind direction and air pressure on radon levels. Country-specific and context-specific measurement protocols were also discussed. Existing standards lack clarity on sampling uncertainty, which can lead to misunderstandings of results.

An interesting discussion was devoted to specific measurement protocols, emphasising the importance of long-term and short-term measurement protocol existence due to various purposes of measurement, such as real estate transactions, radon mitigation system efficiency checks and radon diagnosis aiming at radon source identification and radon entry rate quantitative analyses serving as the essential inputs for high-quality and effective radon remedial measures design and implementation.

The need for specialised measurement protocols and better communication of uncertainties to the public was emphasised, however contrary to past concerns and experience, people are willing to accept uncertainties when properly explained. Communicating uncertainty does not deter the radon testing or mitigation decision-making process (uncertainty is not a barrier).

The discussion raised the issue of thoron exposures and their rare occurrence (e.g. NORM workplaces such as titanium oxide production facilities), which might be the result of thoron’s fundamental physical properties (very short half-life and corresponding small diffusion length and limited advective entry rate) but could also be affected by insufficiency in testing due to limited measurement campaigns and lack of instrumentation and procedures.

There is a specific need for better measuring techniques and regulations to address nomadic (itinerant) workers' radon exposure. New fast-response electronic devices are needed to capture pulse-like exposure events.

Lack of regulation requiring measurement of radon progeny has led to limited production of suitable instruments. There is an obvious shortage of certified instruments with proper traceability and consistency across the EU. Regulatory authorities can initiate the process that can trigger the industry to develop more accurate and appropriate electronic devices.

2.2.6. Session 3: Measures to Protect People, Block 2

The panel was composed of Cristina Nuccetelli as the external expert and presenters of the Measures to Protect People – block 2: Federica Leonardi (INAIL) and Bogusław Michalik (GIG). The panel was moderated by Gareth Law.

The discussion focused on regulatory, scientific, and practical challenges in handling radioactive materials, especially residues from natural and artificial sources (e.g., NORM—Naturally Occurring Radioactive Materials).

A part of the discussion was devoted to the development of clearance levels for specific pathway residues, aligning with the approach in the nuclear industry and extending to natural materials. The

Italian approach shifted from activity concentration to dose calculations. A dose threshold of 0.3 mSv/year was referenced as a boundary for classifying waste.

The conversation also highlighted the importance of proper interpretation of gamma spectrometry results and the need for additional information on sample history. Identifying disequilibrium in decay chains requires advanced sensitivity and experience. Proper techniques and cross-validation (e.g., gamma vs. alpha spectrometry) were also discussed.

The panel emphasised the significance of operational safety and communication in differentiating between artificial and natural radionuclides, noting that natural radioactivity is often misinterpreted as less detrimental due to practical reasons.

Interest in extracting valuable elements like radium for medical applications and reusing NORM residues in other industries as a part of the circular economy was suggested as a sustainable practice.

Aligning radiation protection with existing occupational safety frameworks can ease adoption and improve effectiveness.

2.2.7. Session 3: Measures to Protect People, Block 3

The panel was composed of Zsolt Homoki (NCPHP) and Ämilie Degenhardt (ECRad) as external experts and presenters of the Measures to Protect People – block 3: Tanja Perko (SCK CEN), Kim Sennhenn (GSI) and Francesca Tugnoli (BfS). The panel was moderated by Robbe Geysmans.

Zsolt Homoki provided insights into the use of the Radon Behavioural Atlas (RBA) in Hungary, highlighting that it can provide important information to know who people think is trustworthy in radon risk communication. He also noted how RadoNorm has made it results easily accessible to the public and that the methods employed for the RBA will be useful for the future surveys planned in Hungary.

The survey highlighted that there is no gender bias in regard to radon behaviour but what matters more is societal context (costs, peer pressure, etc.). Authorities and policymakers now need to think of how to implement the results of the RBA to improve national radon action plans (RAP); e.g. the use of financial incentives to encourage remediation varies from country to country and investments in such financial incentives can prove unfruitful in some countries. A future project to look into specific country contexts to implement the results of the RBA would be useful, such as in providing advice to countries like Hungary planning to undertake future surveys. While indicators to measure success of RAPs are available, the means on how to achieve success can be provided through the RBA and such surveys.

Ämilie Degenhardt shared her experiences with the RadoNorm Early Career Researcher (ECR) council, the many opportunities that it and the project offered her as an ECR. She highlighted that it is important to offer opportunities for ECRs in radiation protection and that the new ECRad (Early Career in Radiation Protection) initiative provides a sustainable continuation of the ECR initiatives started with RadoNorm. The European Radiation Protection Week will offer opportunities for ECRs to meet and network.

3. Participant Feedback

A total of 50 responses were collected from the participants using a feedback form. Of these, 32 were senior scientists / task leaders / work package leaders / administrators, 8 were ECRs / PhD students and 10 were stakeholders / advisory board members / external guests. The outline of the form can be found in Appendix C. The purpose of the feedback form was, as in previous years, not just to gauge satisfaction levels, but also to understand how effectively the progress was communicated among consortium members. Details of the results can be found in Figure **1**.

The general consensus was that the meeting was very useful and well-organised. Around 95% of the respondents answered with a score of 4 and above (5 being the best score) to the first question indicating their general satisfaction. Participants were also highly satisfied with the information being passed around. Over the years, the hybrid format has been less preferred than solely face-to-face meetings (question 5), with this meeting having shown the lowest preference. This year, the answers to questions 2 and 4 tended towards a more positive rating, indicating that the programme this year allowed participants to better comprehend the content of the presentations and to agree more that the progress within the project lines up with its goals. The comments in particular mentioned that the talks had a high quality. This could mainly stem from the presentations being more all-rounded and now illuminating a global outline of the tasks from start to finish.

This year, too, the centrality of the venue in Budapest was highly appreciated and the themes chosen were appropriate. Taking into consideration feedback from last year, there were more panel discussions included in the programme and the added time for discussion was appreciated. One thing worth mentioning is that the scale of the multidisciplinarity and collaboration was praised in the comments. Moreover, several external participants from Australia and the US/Canada mentioned the relevance of these results for their own radiation protection programmes.

Group photos of the RadoNorm Final Meeting can be found in Appendix D.

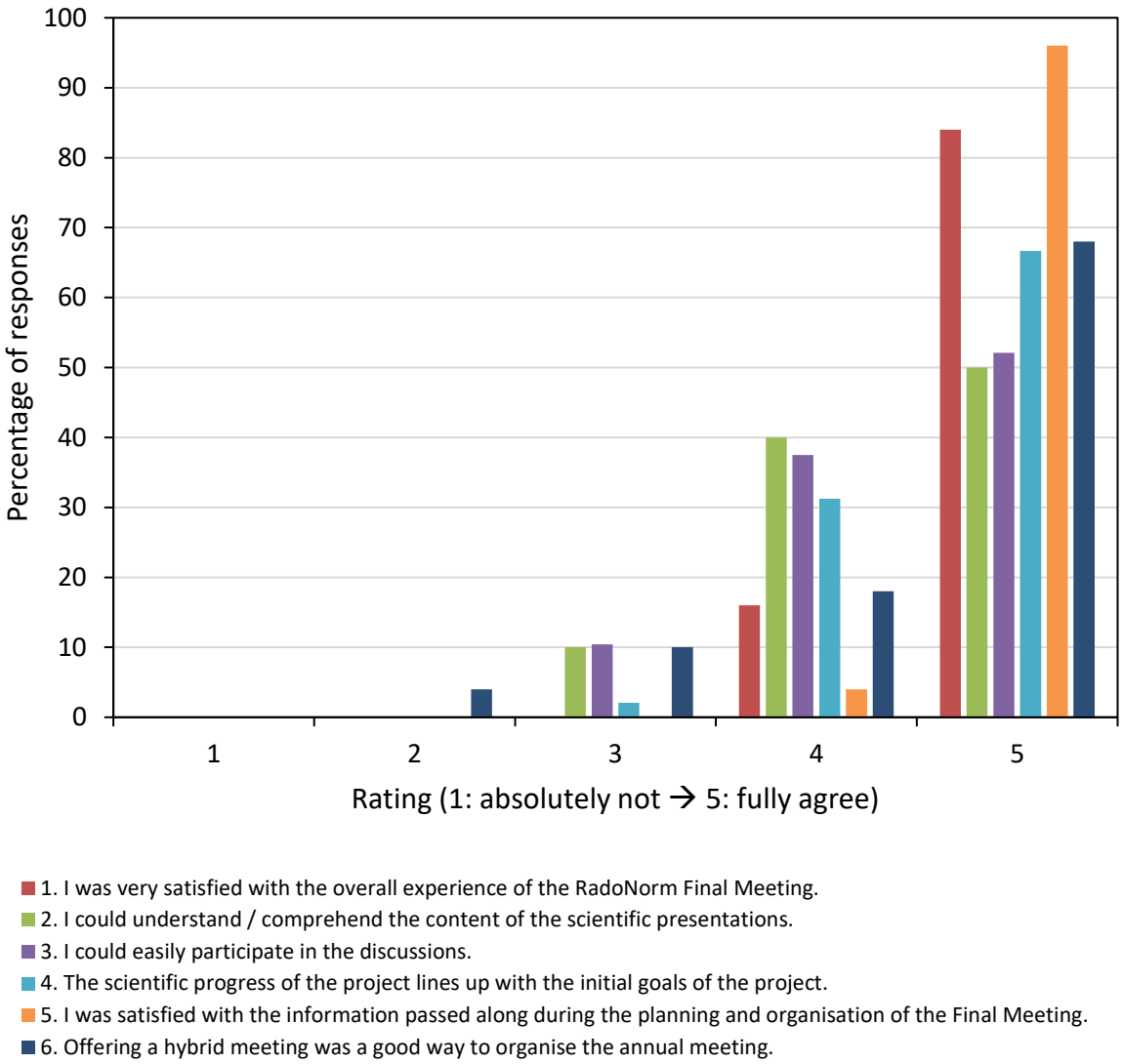

Figure 1: Results from the participant feedback form. The percentage of all answers for each rating is shown, where a rating of 5 was the best and 1 was the worst.

4. Advisory Board Report

The Advisory Board (AB) congratulates the achievements made by the RadoNorm project participants. There are so many topics dealt with in the project, which covers measurement, dosimetry, risk assessment and communication together with education and training for young scientists. For further development based on the success of this project, the AB put some comments as below:

General comments:

As a result, the project was successful together with a lot of high-quality publications, open data and so on. According to AB suggestions, new topics and their issues were discussed in some WPs. Although AB understood that there were many Work Packages and they had their own aim, on the other hand, it was not clear how much they were accomplished in the meeting. In addition, some WPs were not coherent each other. Radon and NORM were subject to study in the project, but each of them was dealt with independently. AB suggested that radon should have been included as one of NORM. The necessity of several studies was not understandable because some of them have already been studied. Throughout sufficient literature reviews, clarification of the issue to be solved will be needed.

Specific comments:

1. Measurement protocols were discussed in the project. In the meanwhile, the international standardization organization (ISO) has been discussed. They should have been internationally harmonized.
2. Smoking is strongly connected to lung cancer incidence. Characteristics of cigarette smoke were given and their risk was discussed in the project. Synergic effects with radon and smoking should be clarified. For instance, Pb-210 and Po-210 are accumulated in cigarette leaves. While smoking, their radioisotopes also may be inhaled into the lung and be accumulated for a long term. Smoking fraction may need to be clarified from the radiological point of view.
3. The following co-exposures need to be considered: radon and smoking, radon and thoron, radon and air pollutant (PM2.5), etc.
4. Findings at iron legacy mines, reported by Norway, were very impressive. This was the first case where thoron was of concern in Europe. It is well known that radon is strongly connected with uranium mines. There are many other mines in Europe. Investigation of radiological hazard due to thoron exposures in various mines may be worthwhile.
5. With respect to NORM, it was concluded that their treatment and management could be accomplished with existing regulations and systems based on several possible scenarios. Depending on the case, however, an unusual case should be assumed. For instance, unexpected incident with NORM can be taken into account.
6. Even though the project is finished, human resource development should always be kept in mind.

Appendix A. Agenda

Internal Meetings - RadoNorm Final Meeting

3rd June 2025 Venue: Novotel Budapest Danube *v 28.05.2025*

Room **Parliament**	Room **Buda**	Room **Danube**
WP3 General Meeting *09:00 – 10:45*	Task 4.3 Joint data-analysis on radon and childhood leukaemia (Switzerland, France, Norway, Finland) *09:00 – 10:45*	Task 5.5 (Part 1) Finalisation of D5.13 *09:30 – 10:45*
Coffee Break (10:45 – 11:15)	Coffee Break (10:45 – 11:15)	Coffee Break (10:45 – 11:15)
Tasks 4.3 and 3.3 *11:15 – 13:00*		Task 5.5 (Part 2) Finalisation of D5.13 *11:15 – 13:00*
Lunch (13:00 – 14:00)		
Navigating ethical challenges in RadoNorm Δ * *14:00 – 15:30*		Tasks 2.5 and 5.5 (Part 1) Finalise the legacy paper *14:00 – 15:30*
Coffee Break (16:00 – 16:30)	Coffee Break (16:00 – 16:30)	Coffee Break (15:30 – 16:00)
	ECR Council Meeting *16:30 – 18:00*	Tasks 2.5 and 5.5 (Part 2) Finalise the legacy paper *16:00 – 17:30*

Δ *Invitation to all consortium members*

* *This session will offer the opportunity to look back and reflect on some of the ethical challenges during RadoNorm. The RadoNorm ethics committee will give a short overview of the work they have carried out over the past 3 years. What did we learn? What could we have done better? Topics likely addressed but not limited to would be open data and transparency, predatory journals, justice and equity in NORM management.*

Final Programme
RadoNorm Final Meeting 2025

RadoNorm
Managing risks from radon and NORM

Day: Wednesday, 4th June 2025 **Venue: Novotel Budapest Danube** *Version 28.05.2025*

8:15 – 9:00	Registrations	
9:00 – 9:20	Welcome from Director General of HUN-REN CER	*Ákos Horváth*
9:20 – 9:30	Welcome from President of BfS	*Inge Paulini*
9:30 – 9:50	Opening message from RadoNorm Coordinator	*Warren John (BfS)*
9:50 – 10:10	Coffee break	
	Session 1: Health & Beating Cancer; Block 1 *chair: Anssi Auvinen (TAU)*	
10:10 – 10:25	Molecular characterization of radon exposure	*Laura Mezquita (HCB)*
10:25 – 10:40	Results of the joint analysis of national datasets related to childhood cancer and radon	*Ben Spycher (U Bern)*
10:40 – 11:00	Dose coefficients for chronic intake of radon gas and progeny by children. Improvements in brain dosimetry.	*Vladimir Spielmann (BfS)*
11:00 – 11:15	Radon-related risks other than lung cancer among adults	*Nora Fenske (BfS), Estelle Rage (ASNR), Olivier Laurent (ASNR)*
11:15 – 11:40	**Q&A and Panel Discussion** Invited panellist: Werner Rühm (ICRP, BfS)	
11:40 – 12:00	Coffee break	
	Session 1: Health and Beating Cancer; Block 2 *chair: Árpád Farkas (HUN-REN CER)*	
12:00 – 12:15	Uncertainties in radon risk assessment due to thoron	*Fieke Dekkers (RIVM)*
12:15 – 12:30	The effect of smoking on the absorbed dose rates in the nuclei of the basal and secretory cells of the bronchial airway epithelium	*Péter Füri (HUN-REN CER)*
12:30 – 12:45	Investigating the impact of radiation quality and LET on low-dose hyper-radiosensitivity	*Kim Sennhenn (GSI)*
12:45 – 13:10	**Q&A and Panel Discussion** Invited panellist: Katalin Luminczky (MELODI, NCPHP)	
13:10 – 14:10	Lunch Break	
	Session 2: Environmental Risks; Block 1 *chair: Augusto Giussani (BfS)*	
14:10 – 14:25	Modelling cumulative risks: An AOP perspective	*Olivier Armant (ASNR)*
14:25 – 14:45	Parameter uncertainty analysis of the committed equivalent lung dose coefficient for the intake of radon progeny in underground mines.	*Thomas Makumbi (KIT)*
14:45 – 15:00	OpenSLM - an open access tool for deposition calculations in the lungs	*Dalma Günter (HUN-REN CER)*
15:00 – 15:25	**Q&A and Panel Discussion** Invited panellist: Stefan Rottger (EURADOS, PTB)	
15:25 – 15:50	Coffee Break	
	Session 2: Environmental Risks; Block 2 *chair: Estela Reinoso-Maset (NMBU)*	
15:50 – 16:05	Fen complex: a High Background Radiation Area with NORM, high outdoor Rn levels due to soil exhalation and ventilating legacy	*Hallvard Haanes (DSA)*
16:05 – 16:20	Comparing methods for high radon levels: a cross-dataset analysis	*Sara Antignani (ISS)*
16:20 – 16:45	Report on the capability of models to predict site-specific NOR K_d	*Viktor Dück (HZDR), Miquel Vidal (U Barcelona)*
16:45 – 17:10	Overview and impact of NORM in different exposure situations across Europe, including work on development of a holistic assessment methodology for multiple hazards exposures	*Jelena Mrdakovic Popic (DSA)*
17:10 – 17:35	**Q&A and Panel Discussion** Invited panellist: Laura Urso (IAEA)	
19:00	**RadoNorm Dinner: *Cruise on the Danube*** *Meeting point: Várkert Bazár Ferry Terminal (GMaps Link). Please plan for a 3-hour cruise.*	

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Final Programme
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RadoNorm
Managing risks from radon and NORM

Day: Thursday, 5th June 2025 **Venue: Novotel Budapest Danube** *Version 28.05.2025*

Session 3: Measures to Protect People; Block 1	*chair: Tuukka Turtiainen (STUK)*	
9:00 – 9:15	Exploring spatial and temporal variability: new insights	*Sara Antignani (ISS)*
9:15 – 9:30	Quality infrastructure and methods needed to answer a question: Is Thoron of concern or not?	*Sebastian Feige (BfS)*
9:30 – 9:45	Potential use of continuous radon monitors for active radon control systems, current equipment quality, challenges for future research	*Miroslav Havelka (SURO)*
9:45 – 10:00	Air exchange rate measurement protocol, ventilation as a possible effective tool for improving indoor air quality (including radon levels)	*Karel Jílek (SURO)*
10:00 – 10:30	**Q&A and Panel Discussion** Invited panellist: Christian Schwenk (ExRadon)	
10:30 – 11:00	Coffee break	
Session 3: Measures to Protect People; Block 2	*chair: Gareth Law (U Helsinki)*	
11:00 – 11:15	Radiological dose assessments due to effluents of NORM industries discharged in municipality sewers	*Federica Leonardi (INAIL)*
11:15 – 11:30	Scientific rationales for improving regulatory approaches of NORM treatment and management	*Bogusław Michalik (GIG)*
11:30 – 11:55	**Q&A and Panel Discussion** Invited panellist: Cristina Nuccetelli	
11:55 – 12:05	Group Photo	
12:05 – 13:05	Lunch break	

Session 3: Measures to Protect People; Block 3	*chair: Robbe Geysmans (SCK CEN)*	
13:05 – 13:50	European radon Behavioural Atlas and practical implementation of results in Radon Action Plans	*Tanja Perko (SCK CEN)*
13:50 – 14:05	Reflections on RadoNorm E&T activities and perspectives from ECRs	*Kim Sennhenn (GSI), Francesca Tugnoli (BfS)*
14:10 – 14:30	**Q&A and Panel Discussion** Invited panellists: Zsolt Homoki (NCPHP); Ämilie Degenhardt (ECRad)	
14:30 – 14:45	Closing	*Balázs Madas (HUN-REN CER), Warren John (BfS)*
14:45 – 15:15	Coffee break	

15:30 – 16:30	RadoNorm Advisory board meeting (closed meeting)
15:45 – 16:45	RadoNorm Executive board meeting (closed meeting)

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Appendix B. Book of Abstracts

RadoNorm
Managing risks from radon and NORM

RadoNorm Final Meeting 2025

Book of Abstracts

This project has received funding from the Euratom research and training programme 2019-2020 under grant agreement No 900009.

Table of Contents

Health and Beating Cancer

Block 1

Molecular characterization of radon exposure

Mezquita L

Hospital Clinic Barcelona, Spain

Radon is a well-established carcinogen and the second leading cause of lung cancer after tobacco. However, its molecular and immunological impact on lung carcinogenesis remains insufficiently characterised. In this presentation, we explore whether radon exposure is associated with distinct histological, molecular, and immunological tumour profiles in non-small cell lung cancer (NSCLC), integrating data from radon-exposed rat models, uranium miners, and patients exposed to indoor radon. In experimental rat models exposed to radon demonstrated activation of RTK-RAS, disruption of DNA repair pathways, and an increased frequency of oncogenic fusions, particularly in high or prolonged exposure scenarios. In parallel, in uranium miners chronically exposed to radon, recurrent genomic alterations included TP53, KEAP1, NOTCH1, and MUC4. The most frequently affected cancer pathways were RTK-RAS and NOTCH, and the highest tumour mutational burden (TMB) was observed in individuals with combined radon and tobacco exposure. In parallel, Mutational signatures in both models were dominated by C>T and T>C transitions, consistent with radiation exposure, although double base substitution and DNA repair signatures differed between species. Differences in the mutational landscape between miners and rats may be partially explained by the synergistic effect of tobacco in the human cohort. These results support the existence of a radon-associated molecular profile in NSCLC and highlight the need for further validation. The prospective patient's cohort (Task 4.5.2), which is nearing completion with 950 patients already recruited, will include a comprehensive biobank, a curated dataset, and individual indoor radon measurements of 975 patients with NSCLC in Europe (1920-EORTC Bioradon). This will be instrumental for further validating studies of the findings observed in rats and miners and will enable in-depth investigation of radon-related molecular alterations, immune mechanisms, and their clinical implications in patients with lung cancer.

Results of the joint analysis of national datasets related to childhood cancer and radon

Spycher B

University of Bern, Switzerland

Background: Children are known to be more susceptible to the effects of ionising radiation. There is growing evidence that this applies even at low doses, although quantifying these effects remains challenging. Based on standard risk models, it has been estimated that up to 20% of childhood leukaemia cases are attributable to natural background radiation. Previous studies of childhood cancer risk in relation to background radiation have yielded conflicting results.

Aims: We aimed to estimate the risks of childhood leukaemia and central nervous system (CNS) tumours in relation to cumulative radiation doses to the red bone marrow (RBM) and the brain from inhaled radon and gamma radiation in children's homes.

Methods: We combined nationwide case–control studies from five European countries (Denmark, Finland, France, Norway, and Switzerland) using random-effects meta-analysis. Childhood cancer cases were drawn from national cancer registries; controls were randomly sampled from the general childhood population. Indoor radon concentrations and gamma-ray dose rates were estimated with country-specific exposure models based on extensive measurement datasets. Cumulative organ doses since birth from radon were calculated using dose coefficients recently developed within RadoNorm WP3. Organ doses from gamma radiation were estimated using age- and sex-specific weighting factors from Satoh & Petoussi-Henss[4]. Cancer risks were analysed with logistic regression models adjusted for age and sex.

Results: The preliminary analysis includes approximately 4,500 childhood leukaemia cases and 2,600 CNS tumours. Mean cumulative equivalent doses to the RBM and brain ranged from 4 to 7 mSv across studies, with gamma radiation as the dominant contributor. The overall odds ratio (OR) for childhood leukaemia was 1.08 (95% CI 1.05–1.11), with no indication of between-study heterogeneity. For CNS tumours, the summary OR was 1.08 (95% CI 0.99–1.17), with some heterogeneity across studies.

Conclusions: Our findings provide support for an effect of background radiation on cancer risks in children. By strengthening the evidence on low-dose radiation effects in paediatric populations, this study advances UN Sustainable Development Goal 3: "Ensure Healthy Lives and Promote Well-Being for All at All Ages."

[4] Satoh, D., Petoussi-Henss, N. Dose-Rate Coefficients for External Exposure to Radionuclides Uniformly Distributed in Soil to an Infinite Depth. PLOS ONE 2024, 19 (9), e0310552. https://doi.org/10.1371/journal.pone.0310552.

Dose coefficients for chronic intake of radon gas and progeny by children. Improvements in brain dosimetry.

Spielmann V

Federal Office for Radiation Protection, Germany (BfS)

In recent years an increase in the incidence of brain tumour cases among children was observed, yet the underlying causes remain unclear. Studies correlating radon exposure and incidence are inconclusive. To investigate the existence of a possible relationship between doses to the brain and the observed incidence, appropriate dose coefficients for residential chronic intake of radon gas and progeny were calculated using the most recent biokinetic and dosimetric models of the ICRP. Different starting times for exposure age intervals from 0 till 20 years and exposure duration until 70 years of age were simulated, dividing the exposure times into a total of 130 small intervals to take changes in the anatomical and physiological characteristics into account. The breathing rate was dynamically changed according to the age. For comparative purposes different equilibrium factors and daily time budgets were assumed to show differences in indoor and outdoor exposure scenarios. 180 dose coefficients for each of 130 ages were calculated. The new dose coefficients allow to determine more precisely the doses to the organs of children and adults at any age due to a chronical exposure over period of time with any start and end point and provide thus a reliable basis for cancer risk analysis. The results are connected to the SDG 3 goal “Ensure healthy lives and promote well-being for all at all ages”.

Radon-related risks other than lung cancer among adults

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There is still no conclusive answer to the question whether radon poses a substantial risk for any other disease than lung cancer. Absorbed organ doses from inhalation of radon to organs other than lung and respiratory tract are estimated to be substantially lower than absorbed doses to the lung (about 100 times lower). Thus, potential risks are expected to be small and large studies with wide exposure ranges are needed to investigate them. Even a small excess risk may not be negligible for diseases with high prevalence in the general population and thus could have implications for radiation protection, since large populations are exposed and current radon dose conversion factors might need revision. Based on the largest study of uranium miners – the international pooled uranium miners analysis (PUMA) – and the large population-based French Constances cohort, radon-related health risks other than lung cancer were investigated in RadoNorm Task 4.2. The presentation will give an overview of the work and results in this task.

PUMA combines data of seven uranium miner cohorts from five different countries in Europe and North America with mortality follow-up between 1946 and 2014. In RadoNorm, radon-related risks for mortality from solid cancers other than lung cancer (subtask 4.2.1) and circulatory system diseases (CSD, subtask 4.2.2) were investigated. Among the almost 120 000 male miners in PUMA, 7 720 deaths from solid cancers other than lung cancer and 17 494 deaths from CSD were observed. The mean value of cumulative radon exposure in individual cohorts ranged between 31 and 580 working level months (WLM). Based on exposure-risk analyses, slightly elevated excess relative risks were found for the group of solid cancers other than lung cancer, in particular at very high radon exposures. However, no individual cancer site was clearly responsible for this increase. For CSD and subgroups of ischemic or cerebrovascular diseases, no increase in risk was observed with increasing radon exposure. Overall, results do not show a clear increase in risk for solid cancers other than lung cancer or CSD due to radon, neither considered in groups nor for individual diseases.

Regarding the Constances cohort (subtask 4.2.3), the first preparatory step was a literature review and meta-analysis on other potential health effects of radon than lung cancer (Henyoh et al. 2024). In the meta-analyses, none of the investigated exposure-risk associations reached statistical significance, although some were closed to significance, justifying further investigation.

Furthermore, for a subset of about 76 000 individuals of the Constances cohort, data on radon exposure, outcomes and potential confounders were collected and prepared in an elaborate process. Based on this epidemiological database, associations between radon exposure and incidence of diseases were investigated. Preliminary results showed some associations for specific exposure windows of age at exposure and cancers, but not for total lifetime exposure. Results are being consolidated and need to be interpreted with caution at this stage.

Beyond that, a radon measurement campaign in homes of around 1 000 volunteers of the Constances cohort was successfully implemented. This campaign aims at a comparison of measured vs. estimated radon concentrations in this subset of the Constances cohort.

Related to SDG 3: Good health and well-being.

Block 2

Uncertainties in radon risk assessment due to thoron

Dekkers F

National Institute for Public Health and the Environment, The Netherlands (RIVM)

Studies on exposure to and biological effects of radon usually focus on the isotope Rn-222, commonly referred to as radon. Thoron (Rn-220) is typically assumed to be less relevant than its sister isotope due to its short half-life, which limits the possibilities for thoron to enter the indoor environment. Under some circumstances though, Rn-220 can contribute substantially to uncertainty in the measurements of Rn-222 in the indoor environment, and to uncertainties in estimates of radon risk. In addition to these more indirect effects of Rn-220 on the uncertainty in Rn-222 assessment, the direct contribution of Rn-220 itself to lung cancer risk is uncertain as well. In this presentation, both aspects will be addressed.

Some radon detectors that are routinely used in radon surveys are sensitive to thoron. The 'radon' concentration reported by such detectors is the sum of the actual radon concentration and an uncertain thoron contribution. This can lead to an overestimate of the real radon concentration, in particular in low/medium radon settings and when a detector is placed in the vicinity of a source of thoron. We will present findings from a RadoNorm-survey on sensitivity to thoron of detectors that have been used in radon surveys.

The average (over time and space) concentration of radon in a room can be related to the concentrations of its progeny if information on the so-called equilibrium factor is available, allowing to derive estimates for the exposure of occupants of the room. The interpretation of an equilibrium factor for thoron is not as straightforward as for radon. We will show how an equilibrium equivalent concentration can nevertheless be meaningfully defined.

Relevant SDGs: SDG3, SDG11&13 (optimal implication of sustainability measurements in relation to radon/thoron).

The effect of smoking on the absorbed dose rates in the nuclei of the basal and secretory cells of the bronchial

Füri P

HUN-REN Center for Energy Research, Hungary (HUN-REN CER)

Smoking is the most important cause of lung cancer worldwide. Globally, there are more than one billion smokers and tobacco kills more than 8 million people each year[5].

Smoking has various effects on the absorbed dose rates from radon progeny in the human airways. The first group of effects is the environmental changes caused by the high particle concentration found in cigarette smoke. If there is cigarette smoke in a room, the unattached radon progeny fraction is usually much lower than in rooms with clean air. In addition, the size distribution of the attached progeny is influenced strongly by the smoke particles. These lead to altered progeny deposition pattern in the human airways.

The second group is physiological changes of a smoker. For a light smoker, according to Baias et al.[2] only the airway mucus is thicker, but for a heavy smoker, the breathing is faster but shallower and the exhalation is longer than the inhalation. The airway geometry is usually also influenced by the smoking. For a long-time heavy smoker, the bronchial airways are contracted, the alveoli are dilated, and the mucociliary clearance is slower with very thick mucus layers compared to a non-smoker[6]. These changes have a strong effect on both the progeny deposition rate and the radiation burden from the decay of them.

In our study, we compare the deposition rates and cell nucleus dose rates for a non-smoker (NS), a long-term light smoker (LLS) (6 cigarette/day) and a long-term heavy smoker (LHS) (24 cigarette/day).

The deposition rate is influenced by both the breathing pattern and the size distribution of the radon progeny, so 4 phases need to be separated. Phase 1 is the inhalation of cigarette smoke (bolus inhalation of 70 cm^3 “fresh” cigarette smoke into the mouth, 1 sec. breath hold, inhalation of the smoke from the mouth with 750 cm^3 air volume for 2-1-2 sec (inhalation-breath hold-exhalation) pattern. Phase 2 is inhalation of “aged” smoke (the air of the room) after the smoke bolus with 750 cm^3 volume and 2-1-2 sec pattern. Both for phase 1 and 2 mouth breathing was modelled.

For these phases, the deposition rate of the attached + unattached progeny is much more for the heavy smoker. This is caused by the airway contraction, what enhance both diffusion and sedimentation.

Phase 3 was sitting between two cigarettes and the puffs. The breathing pattern for the NS and LLS was 750 cm^3 inhaled volume and the breathing frequency was 12/min. Nose breathing was modelled. For the heavy smoker, only 530 cm^3 was the inhaled air volume, but the breathing frequency was 17/min and the exhalation was 1.5 times longer than the inhalation. Phase 4 was sleeping with 625 cm^3 and f=12/min for the NS and LLS and 441 cm^3 with f=17/min for the LHS.

For phase 3 and 4, the deposition rate until airway generation 14 is higher for the heavy smoker due to the smaller airway diameters, after that, the deposition is higher for the NS or the LLS, what is caused by the smaller inhaled airway volume for the HS.

Regarding the dose rates, for the long-term heavy smoker, the shielding effect of the thicker mucus is competing with the dose elevating effect of the airway contraction.

[5] World Health Organization (WHO): Tobacco

[6] Paul F. Baias, Werner Hofmann, Renate Winkler-Heil, Constantin Cosma and Octavian G. Duliu:Lung dosimetry for inhaled radon progeny in smokers. Radiation Protection Dosimetry (2010), Vol. 138, No. 2, pp. 111–118

The dose rates for all of the phases in the big bronchial airways are highest for the non-smoker. It is caused by the shielding effect of the five times thicker mucus of the HS. In contrast with that, in the small bronchial airways, the dose rates for the secretory cells are much higher for the heavy smoker. This is the effect of the contracted airways, what reduces the distance between the ^{218}Po, ^{214}Po atoms and the target cell nuclei. The actual ratio of the radiation burden for the non-smoker and the heavy smoker depend on the mucus thickness and the airway contraction and breathing pattern what are influenced by the severity of the lung disease. For smokers, often COPD is developed, what cause higher inhaled air volume with heavy airway contraction. This can lead even in the big bronchial airways bigger doses for the heavy smoker.

Our results clearly showed, how the altered environmental and physiological properties caused by cigarette smoke can strongly influence the absorbed dose rates in the nuclei of the basal and secretory cells of the bronchial airway epithelium. For the same exposure (e.g. 40 Bq/m^3 for 1 hour) for a heavy smoker in the small bronchial airways the absorbed dose rate in the nuclei of the secretory cells is higher, what can facilitate more carcinogen mutations. This suggest, that the individual characteristics of the subjects should be considered during radon dosimetry.

These results contribute to to SDG 3 Good health and well-being.

Investigating the impact of radiation quality and LET on low-dose hyper-radiosensitivity

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This study investigates the phenomenon of low-dose hyper-radiosensitivity (HRS) and its modulation by radiation quality, with a focus on high linear energy transfer (LET) ions such as alpha particles. While HRS, characterised by increased cell sensitivity at doses typically below 0.5 Gy, has been well-documented for low-LET photon radiation, its behaviour under high-LET conditions remains less understood. To address this, we integrate two modelling frameworks previously developed within RadoNorm Work Package 3.6: the Minimum Mutation Load (MML) model, which explains HRS as a self-protective tissue mechanism to reduce mutation burden via apoptosis (i.e. voluntary cell death), and a Low Energy Adaption (LEA) of an established RBE model, which predicts the biological effectiveness of low-energy ions based on the cell's response to photon radiation and the physical characteristics of the respective ion species. Our combined modelling approach demonstrates that LET significantly alters cellular survival responses, also at low doses. Whereas survival curves for low-LET radiation often exhibit an initial dip (HRS region) followed by an induced radioresistance (IRR), our predicted survival curves show a steep initial decline in survival after high-LET radiation (compressed HRS region) and a more monotonic decrease thereafter. Validation against published experimental datasets confirms this trend and demonstrates the model's capacity to capture key survival features across a range of LET values. These findings have direct relevance for radiation protection, particularly in situations involving localized low-dose exposure to high-LET radiation, such as from radon progeny. Predicting cell survival at low doses helps to clarify how different types of radiation influence the likelihood of cell death versus long-term persistence of damaged cells. This distinction is critical, as the survival of cells with unrepaired or mis-repaired DNA can contribute to long-term health risks such as cancer. Mechanistic modelling of these processes supports the development of more accurate and biologically informed risk estimates that go beyond empirical dose-response assumptions, thereby contributing to Sustainable Development Goal 3 (Good Health and Well-being).

Environmental Risks

Block 1

Modelling cumulative risks: An AOP perspective

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Traditional regulatory frameworks largely assess stressors in isolation, relying on additive models of exposure and effect. However, this approach fails to capture the non-linear and potentially synergistic interactions observed in combined exposures. Recent advances, including the development of the exposome and Adverse Outcome Pathway (AOP) frameworks, offer promising avenues to improve risk assessment by integrating mechanistic and exposure-based information. The exposome provides a comprehensive model of lifelong environmental exposure, while AOPs delineate the causal chains linking molecular perturbations to adverse health outcomes. When combined with the Aggregate Exposure Pathway (AEP) framework, which maps sources to internal exposure, these tools enable a systems-level understanding of how combined stressors interact at key biological nodes. This presentation highlights how applying AOP and AEP concepts to radon and tobacco-induced lung carcinogenesis—incorporating biomarkers such as mutation load and signature profiles—can improve the prediction of non-linear effects for combined exposures.

UN SDGs addressed: 3 (Good health and wellbeing) & 9 (Life on Land).

Parameter uncertainty analysis of the committed equivalent lung dose coefficient for the intake of radon progeny in underground

Makumbi T

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This study investigates uncertainties in the committed equivalent lung dose coefficient resulting from the inhalation of radon progeny in underground uranium mines. Two occupational exposure scenarios were considered i.e. wet drilling with good ventilation (Job 1) and dry drilling with poor ventilation (Job 4). Monte Carlo simulations informed by the latest biokinetic models from the International Commission on Radiological Protection (ICRP), as well as parameter distributions from existing literature, were employed to evaluate these uncertainties. Despite comparable levels of uncertainty in both scenarios, Job 4 conditions produced higher lung dose coefficients. The dose coefficients followed lognormal distributions, with geometric means of 47.05 mSv/(mJh/m³) and 61.87 mSv/(mJh/m³) for Jobs 1 and 4, respectively, and geometric standard deviations of 1.58 and 1.56, respectively. The alveolar-interstitial region exhibited the greatest uncertainty, while bronchial secretory cells received the highest radiation doses. Of the systemic organs, the kidneys were the most affected. Sensitivity analysis revealed that tidal volume was the main factor contributing to uncertainty in dose coefficients. These results highlight the importance of improved ventilation, stricter air quality standards and better personal protective equipment in radon-exposed mining environments. The study supports several Sustainable Development Goals (SDG): SDG 3 (good health and wellbeing), due to its focus on occupational health; SDG 7 (affordable and clean energy), due to the promotion of the safe extraction of uranium for low-carbon nuclear power; SDG 12 (responsible consumption and production), due to the advocacy of sustainable mining practices; and SDG 13 (climate action), due to the contribution to the responsible development of nuclear energy as a climate mitigation tool. Overall, this research provides essential insights for refining radiation protection standards and advancing sustainable practices in the nuclear energy sector.

OpenSLM - an open access tool for deposition calculations in the lungs

Günter D

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Inhaled aerosols can pose significant health risks depending on their deposition patterns within the human respiratory system, making accurate estimation essential for both public health and environmental risk assessment. The Stochastic Lung Model (SLM) addresses this need by incorporating individual anatomical variability and realistic breathing behaviours. To make this modelling tool accessible to researchers, healthcare professionals, and any other interested users we developed OpenSLM, a web-based platform that enables users to simulate aerosol deposition by customising input parameters such as particle and breathing characteristics. The platform, implemented with Rust for computational efficiency and a web interface for ease of use, provides downloadable results detailing regional and airway generation-specific deposition patterns. OpenSLM supports applications ranging from environmental exposure assessment to the opportunity of personalised inhalation therapy planning, contributing to improved risk assessment. By making high precision simulation tools publicly accessible, OpenSLM promotes broader adoption of respiratory modelling in scientific research, education, and clinical practice. FAIR-compliant design aligns with SDG 9, fostering innovation and equitable access to high-performance digital infrastructure for health and environmental research. A key part of the presentation will be a demo-like demonstration of the OpenSLM web application.

Block 2

Fen complex: a High Background Radiation Area with NORM, high outdoor Rn levels due to soil exhalation and

Haanes H, Hoftuft J, Rudjord A-L, Mrdakovic Popic J.

Norwegian radiation and nuclear safety authority (DSA)

Fen igneous complex in southern Norway has enhanced levels of both rare earth elements and naturally occurring radionuclides, especially of the thorium decay series. Natural ventilation of the Fen iron legacy mines has a large local impact on outdoor levels of radon and especially thoron in this area. Our newest RadoNorm study shows that exhalation from the soil of radon and especially thoron is high, contributing to the outdoor levels, with temporal variation affected by weather parameters like temperature and precipitation.

Comparing methods for high radon levels: a cross-dataset analysis

Antignani S

National Institute of Health, Italy (ISS)

This study aimed to explore statistical methods tailored to the prediction of high indoor radon concentrations. A literature review on such methods highlighted the lack of studies applying multiple methods to the same dataset, not enabling direct comparison and assessment of consistency across approaches. This motivated our work, in which four datasets were analysed, with different statistical methods applied to each. The analyses were shaped by dataset characteristics, including data type and available variables. Variations in model application—such as transformations of the response variable—were also considered and discussed.

Applying multiple methods to the same dataset consistently identified key predictors of indoor radon concentration (IRC), including building characteristics (type, age, floor level, ground contact) and environmental factors (geology, soil). The Italian dataset also highlighted occupant-related variables such as smoking, presence of young children, and duration of residence.

Model performance varied depending on how the target variable was defined—original, log-transformed, or categorised—emphasising the need to align methodological choices with specific prediction goals. IRC distributions were typically log-normal, with high values harder to predict. Analyses from Italy and Austria suggested that focusing on untransformed values or higher quantiles may enhance prediction of elevated IRC.

Machine learning models performed well but were comparable to traditional approaches. Applying multiple methods to the same dataset offered complementary insights, including variable effects at different IRC levels and the identification of interactions and nonlinearities, supporting the value of a multi-method approach.

A deeper understanding of the methodological aspects behind models predicting high indoor radon concentrations aids the identification of buildings and areas at greater risk, contributing to more accurate assessments of population exposure. Such insights can support the prioritisation and implementation of targeted mitigation strategies, thereby reducing radon-related health risks. Since long-term exposure to high radon levels is a leading cause of lung cancer after smoking, efforts to predict and prevent such exposures directly contribute to achieving Sustainable Development Goal 3: “Ensure healthy lives and promote well-being for all at all ages.”

Report on the capability of models to predict site-specific NOR K_d

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The dispersion of naturally occurring radionuclides (NOR), such as uranium (U), thorium (Th), radium (Ra), polonium (Po), radon (Rn), and lead (Pb), poses a risk to the environment and population, and must therefore be avoided. To better assess this potential risk, improved models are urgently needed to predict the sorption and subsequent mobility of NOR in soils. One objective of the RadoNorm project is to contribute to the improvement of these models.

This requires detailed knowledge of the chemical behaviour of NOR in the environment. To achieve this, complementary laboratory and in situ studies on a limited number of NORs were performed in Task 2.7, with the aim of generating new knowledge on the interaction behaviour of NOR in the environment and improving the models used to predict NOR mobility. The NORs of interest in our studies are U, Ra, Po and Pb.

Model improvement is partially based on expanding datasets with sorption and desorption parameters, which will eventually enable the development of thermodynamic, probabilistic, or parametric equations. These equations can be used to predict various parameters, including the solid-liquid distribution coefficient (K_d) of NOR. Within the radio-ecological community, the K_d value of a contaminant between the immobilised phase (mineral precipitation or sorption) and the aqueous phase is used as an indicator of mobility. It is possible to model the saturation of NOR mineral phases, as well as the sorption of NOR on the surfaces of naturally occurring mineral phases, using mechanistic models or probabilistic distribution functions. This allows the K_d value to be calculated using the model parameters.

This work aims to apply the smart- K_d method to predict the K_d values of some NORs in selected natural scenarios, and to compare the results obtained with measured field data. The wetland at the Rophin site was used as test site. For the whitish layer of the Rophin site, the predicted Kd value for U (K_d^{calc} = 66 to 98 L/kg) was in very good agreement with a experimentally determined value (K_d^{exp} = ~50 L/kg).

This report also presents an integrated approach to generating K_d (NOR) prediction models, particularly for Ra, Po and U. A dataset containing new experimental data is created that is supplemented by literature data and contains a large number of characteristic soil properties. In the next step, the most important properties determining the interaction of a particular NOR in soils are identified using chemometric tools such as principal component analyses and partial least squares regression analysis. These properties are then used to construct parametric equations derived from univariate or multivariate linear regressions. This allows as much of the K_d (NOR) variability as possible to be explained. Where detailed soil data is lacking, probabilistic distribution functions help estimate K_d (NOR) for similar soil groups. This is exemplified with Ra. The approach successfully predicts K_d (NOR), often explaining over 80% of its variance, and is suitable for use in radioecological risk assessment codes.

Furthermore, expected K_d values were predicted as a function of variable geochemical parameters in a blind prediction exercise. Despite the incomplete thermodynamic surface complexation data and input parameters required for thermodynamic modelling, partition coefficients for U, Ra, and Pb could be calculated using the smart- K_d approach, and compared with the available field data. There was good agreement between the calculated and measured K_d values, particularly for U. Similar good results were obtained using the approach of constructing parametric models and probabilistic distribution functions.

The reasons for the deviations observed in the case of Ra lie in the incomplete surface complexation modelling (SCM) data available for Ra in many mineral phases. This situation is improved by Viktor Dück's PhD thesis, in which the chemical analogues of Ra, barium (Ba) and strontium (Sr), are investigated for their sorption behaviour on gibbsite and quartz. The aim is to develop a generic sorption model for alkaline earth metal ions on feldspars. In his work a mechanistic understanding of Sr(II) and Ba(II) sorption on gibbsite, a representative mineral for aluminol surface sites, was provided and it was found that sorption is strongly pH-dependent and sensitive to ionic strength. Outer-sphere complexation that was confirmed by extended X-ray absorption spectroscopy was the dominant sorption process. Furthermore, an unexpected and pronounced influence of the background electrolyte (NaCl) on the sorption behaviour was observed, shifting sorption edges significantly. This is in contrast with previous studies and suggests electrolyte-specific interactions at the gibbsite surface.

In conclusion, in addition to a complete set of SCM parameters, the reliable prediction of K_d values requires comprehensive characterisation of the soil, which is rarely available. One critical parameter is the specific surface area of the mineral phases present in the soil. This is often given as a total surface area at best and is not broken down into the individual minerals. The inclusion of organic substances also poses a problem for prediction as they are often poorly characterised (or not characterised at all), and for many of them, especially those with a high molecular weight, e.g. humic and fulvic acids, there is often no thermodynamic data available for interaction with NOR.

Despite the above-mentioned uncertainties, there is a very good agreement between the predicted and measured K_d values for both approaches. Using the smart- K_d approach and the probabilistic distribution functions allows large parameter ranges to be captured quickly and helps to identify relevant sorption processes. Smart-K_d predictions can be further improved by extending the SCM dataset to fill existing data gaps.

Overview and impact of NORM in different exposure situations across Europe, including work on development of a holistic assessment methodology for multiple hazards

Mrdakovic Popic J

Norwegian radiation and nuclear safety authority (DSA)

An investigation of existing and planned NORM exposure situations across European countries was conducted in a systematic and harmonised way, using several approaches. The main outcomes regarding:

- overview of the different NORM sites across Europe,
- consideration of the main features of planned exposure situations – NORM involving industries and existing exposure situations – NORM affected legacy sites,
- improved data on NORM matrices per different exposure categories, updated quantitative data on NOR in different materials – raw materials, main and by-products, residues, discharges and wastes,
- overview of exposure scenarios and pathways considered in different countries for estimation of radiation dose magnitude for workers, public and environment, including non-human biota,

and their relationship to UN SDGs will be presented.

As NORM exposure situations are commonly multiple hazards exposure situations, it has been previously highlighted that the development of integrated risk/impact assessment (and thus management, control etc) would be beneficial for operators and regulators. First steps towards such assessment, which included a holistic site characterisation and analysis of hazards behaviour depending on environmental parameters are done on example of Fen Complex in Norway (enriched in Th-232, U-238, REE and heavy metals) and will be also presented.

Measures to Protect People

Block 1

Exploring spatial and temporal variability: new insights

Antignani S

National Institute of Health, Italy (ISS)

This work aims to advance the characterization of uncertainty in radon assessment by analysing indoor radon's spatial and temporal variability using new and existing data collected across several countries. While extensive literature exists on radon variability, this study addresses specific topics where knowledge gaps remain, focusing on quantifying variability rather than investigating its underlying causes.

Overall, the analysed datasets show significant temporal and spatial variability in radon concentrations, with important implications for measurement protocols. Year-to-year variability in Finland is moderate (16% CV), though greater fluctuations may result from shorter measurement durations. Short-term seasonal effects appear limited in some regions, such as Switzerland, likely due to mild winters, while in Norway, seasonal variability appears to be quite large, resulting in high variability in the calculated seasonal correction factors (CV = 56%). The Finnish study indicates that very short-term variability remains too high to justify changing the established measurement duration in existing protocols. Daily fluctuations in Italy show radon levels about 30% lower during daytime hours compared to night-time hours. In this regard, seasonal effects are somehow evident: in winter the indoor radon concentration appears less variable, likely due to more stable indoor conditions. On the spatial scale, within-dwelling variability in Norway reveals that room location (e.g., different floors) can influence radon levels, with less variability when rooms are on the same floor. Within-building variability is somewhat elevated (CV ~28–36%) and not always floor-dependent—Italian data show 15–25% of buildings with higher radon levels on upper floors. Between-building variability is even more pronounced, as low concentrations in one unit do not guarantee low levels nearby. In workplaces, spatial variability is particularly high: even with low average levels (e.g., 50 Bq/m³), there is a >20% chance of exceeding the reference level in at least one room when multiple measurements are taken.

Spatial and temporal variability can significantly impact the accurate assessment of annual indoor radon concentration, which forms the basis for exposure evaluation and compliance with regulatory reference levels (e.g., 300 Bq/m³ according to Directive 2013/59/Euratom). A thorough understanding and quantification of these variabilities is essential to improve measurement protocols for radiation protection. Accounting for variability helps reduce uncertainty and supports more reliable estimates for both public health and occupational safety purposes, thereby directly contributing to the achievement of Sustainable Development Goal 3: "Ensure healthy lives and promote well-being for all at all ages.".

Quality infrastructure and methods needed to answer a question: Is Thoron of concern or not?

Feige S

Federal Office for Radiation Protection, Germany (BfS)

According to Article 100, the Council directive 2013/59/EURATOM requires EU member states to take appropriate actions to identify and evaluate existing exposure situations taking into account exposure from Rn-220 (Thoron) and to determine the corresponding occupational and public exposures. Requirements from Article 103 equally apply to Thoron exposure and necessitate a strategic consideration of Rn-220 and Rn-220 progeny in national Radon Action Plans. For the first time, the exposure of the public caused by the two naturally occurring radon isotopes ^{222}Rn and ^{220}Rn had become part of legal metrology in Europe. The prerequisites for the identification, verification and calibration of appropriate radiation protection equipment for the determination of Thoron / Thoron decay exposure are, compared to vast experiences with Radon monitoring, less advanced. In order to prepare for national surveys of indoor Thoron / Thoron progeny concentrations at work or at home, metrological capabilities and prerequisites for the thoron / thoron decay product calibration had been discussed within the Task 2.1.2 by GIG and BfS.

Following theoretical considerations, BfS is already using experiences from the RadoNorm project work to establish a Thoron / Thoron Progeny Reference Calibration Chamber in the Radon calibration laboratory that is accredited to ISO / IEC 17025. This will ensure quality assured verification and calibration of instruments for the determination of thoron exposure in nearest future. The presentation will give an introduction into measurands and quality infrastructure needed to answer a question: is Thoron of concern or not? This research primarily addresses UN Sustainable Development Goals (SDGs) 3 (good health and wellbeing) and 9 (industry, innovation and infrastructure).

Potential use of continuous radon monitors for active radon control systems, current equipment quality, challenges for future research

Havelka M

National Radiation Protection Institute, Czech Republic (SURO)

The presented study, carried out as part of the RadoNorm project, was focused on testing the potential use of continuous radon sensors of indoor air quality for direct ventilation regulation to achieve the recommended radon reference level of 300 Bq/m^3. The ventilation of indoor air can be used as an alternative radon risk reduction measure, for example, when other radon protection technologies has failed or it can be used in low-risk areas. Three types of sensors with different detection efficiency and different detection methods were selected for this study. In addition to the tests to determine their key parameters in a reference radon atmosphere with a radon concentration less than 300 Bq/m^3, simulations were performed to estimate their dynamic behaviour during ventilation.

Air exchange rate measurement protocol, ventilation as a possible effective tool for improving indoor air quality (including radon

Jílek K

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Air exchange rate in a building is defined as a total volumetric air flow passing through investigated volume of the building to outdoor air per unit of time. That is why it plays the crucial role in the behaviour of all gaseous mixtures and aerosol particles in indoor environment and also mediates their transfer from the outside of buildings to their interiors and vice versa. So, the air exchange rate is thus directly responsible for both thermal comfort and indoor air quality including behaviour of radon gas levels in measured homes and workplaces.

A suitably performed simultaneous continuous or a passive integral measurement of volume radon activity and the air exchange rate in a measured building makes it possible to determine the temporal variability of a total radon entry rate into the internal volume of an investigated building or its average value over the measured period. The knowledge simultaneously measured of both the total radon entry rate and the air exchange rate in an investigated building or workplace can then significantly help to decide on the effectiveness of the radon protection measure implemented or on the non-exceedance of the recommended reference radon level of 300 Bq/m^3.

The presented report provides standardised methodological guidance for use of a passive integral tracer gas technique for determining average air exchange in a building or a workplace based on many years of experience with the use of the method in SURO and obtained during this Project, as well. The approach used involves the use of multiple tracer gases and thus allows not only the determination of average air exfiltration from individual zones of multi-storey buildings, but also the determination of average air flows between individual zones (floors).

The methodological procedure proposed is suitably supplemented by examples and procedures used in the SURO. An integral part of the validation and verification of the presented methodology were the results of a successful international comparison of the determination of average air exchange from 10 CZ buildings. The inter-comparison took place in March of this year and included results from both apartments and multi-storey family houses. The call for comparison was published on the official website of the RadoNorm project. Probably due to a uniqueness of direct and continuous measurement of the quantity air exchange rate in buildings on a larger scale, only a Swedish company PentIAQ applied to participate. Statistical evaluation of the comparison results showed that the mean difference between the SURO and PentIAQ results was not statistically significant for a significance level of α = 0.05 (95% confidence level).

The undeniable advantage of using this approach with passive integral tracer gas detectors is that they can be used on a large scale at a relatively affordable cost. The use of this technique is then also directly offered for validation and verification of numerical models of the air exchange rate calculation widely used especially in construction practice.

Dynamic range of measurement of indoor average air exchange rate using this methodology is ranging from 0.05 to 1.5 in units of (1/h) for the SURO equipment used. The overall uncertainties in the measurement of the average air change rate during a typical 1 – 4-week exposure in buildings are better than approximately 15% for an expansion factor of k=1.

Block 2

Radiological dose assessments due to effluents of NORM industries discharged in municipality sewers

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While the European Commission's guidelines outlined in Radiation Protection 135 (RP135) provide a general methodology for assessing doses due to effluents from NORM industries, they do not specifically consider the municipal sewer systems as disposal route. To address this shortcoming, this study is focused on the evaluation of the radiological impact, for both workers and members of the public, associated with the management of sludge contaminated by NORM effluents discharged into public sewer systems.

The primary relevance of this research to radiation protection lies in establishing both general and scenario-specific screening levels. These levels, defined in terms of annual activity discharged corresponding to a given dose criterion (e.g., 1 mSv/year), are intended as practical tools for the stakeholders, even those not experts in radiation protection. Importantly, these screening levels will be established with consideration for a range of end-of-life scenarios for the sludge, including disposal in landfills, application as agricultural fertilizer, and potential use as a fuel source through incineration.

The outcomes of this work are strongly connected to several UN Sustainable Development Goals (SDGs). Specifically, it contributes to SDG3 (Good Health and Well-being) by assessing and aiming to minimize radiological risks to human health. It supports SDG15 (Life on Land) by providing frameworks for the safe application of treated sludge to land, thereby protecting terrestrial ecosystems. Most significantly, this research directly aligns with SDG12 (Responsible Consumption and Production) by promoting the safe and sustainable reuse of materials like sewage sludge within a circular economy framework, thereby reducing waste and encouraging resource efficiency.

Scientific rationales for improving regulatory approaches of NORM treatment and management

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The main goal of WP5 (Mitigation) in RadoNorm was to improve and optimise radiation protection of workers, the general public and the environment against the harmful effects of ionising radiation related to Naturally Occurring Radioactive Materials (NORM) utilizing innovative mitigation techniques and improvement of radiation protection systems. Activities carried out were focused on the review, evaluation and improvement of overall mitigation of hazard caused by naturally occurring radionuclides (NOR) present at any level of industrial processes as well as environmental burden related to NORM residues release into environment as a result of intended waste treatment or uncontrolled, current and former discharge. One specific objective was aimed at the development of NORM residues/waste final treatment strategies based on preventive actions and mitigation methods with respect to existing circumstances corresponding to specific NORM involving industries, technological processes, legacy sites and environmental conditions.

Knowledge gathered allowed the formulation of reasonable and scientifically justified suggestions on possible modification of the existing radiation protection system, improving its effectiveness and efficiency towards overall NORM management based on radiation protection principles as hazard optimization and evaluation considered from features specific to a NORM perspective.

The presentation discusses the need for improved regulatory approaches to the treatment and management of NORM. It emphasizes the importance of optimizing radiation protection for workers, the public, and the environment by integrating NORM into existing waste management systems. It outlines the challenges posed by possible classifications of NORM as radioactive waste, which can hinder recovery and disposal efforts and provides the rationale how to avoid such situation.

Moreover, it points out the origin of existing exemption and clearance levels used for classification of NORM and related practices, expressed in terms decay series parent radionuclides activity concentration, considering their drawbacks and justifying necessary modifications based on effective dose evaluations.

From a pragmatic perspective, the presentation emphasises the potential of NORM residues for sourcing valuable elements, underlines the fact that most options are technically available and the proposals aim to align regulatory frameworks with practical solutions while fostering collaboration between radiation protection experts and industry operators.

Relevant SDG: 9 Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.

Block 3

European radon Behavioural Atlas and practical implementation of results in Radon Action Plans

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Before promoting radon protection behaviours, we must first understand what information needs to be conveyed to effectively influence people's actions. Additionally, it is essential to investigate the baseline—what people already know, do, and feel about radon. Without a theory-based and methodologically correct approach, efforts may lead to misguided priorities in radon mitigation interventions and ineffective communication strategies, ultimately resulting in low compliance with testing and mitigation in private homes.

The RadoNorm European Radon Behavioural Atlas, an open database and open results, represents the largest (N > 17,000) and most comprehensive study (average duration 17 minutes, >250 items) on people's behaviour, attitudes, and awareness related to radon. Conducted between 2021-2024, it encompasses representative populations across Austria, Belgium, Bulgaria, Czech Republic, Finland, Germany, Greece, Ireland, Norway, Portugal, Romania, Slovenia, Spain, Sweden, and specific regions such as Wallonia in Belgium and Galicia in Spain. The data were collected with the support and collaboration of national authorities responsible for radon action plans in each of the participating countries. This presentation will, for the first time, compare the results across the investigated countries and regions. Where possible, it will contrast the findings between residents in radon priority areas and those not exposed to radon, who are consequently not the primary target of communication interventions. Using scales that measure a wide range of theory-based socio-psychological concepts influencing protective behaviour against radon risk, this study provides researchers, authorities, and practitioners with a valuable and versatile survey tool. It explores the complexity of human behaviour in the context of radon, offering a foundation for assessing gaps and strategies to increase home testing and remediation.

Reflections on RadoNorm E&T activities and perspectives from ECRs

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As the RadoNorm project approaches its conclusion, this presentation offers a critical reflection on the Education and Training (E&T) activities from the perspective of Early Career Researchers (ECRs). It highlights the establishment of the RadoNorm ECR Council (ECRC) and its achievements, including networking initiatives, webinars, and regular online meetings where different work packages shared their work. Additionally, three training courses were organised that focused on science communication, career development, and the use of AI in research. Experiences from organising and participating in these training courses were generally positive and helped build transferable skills alongside disciplinary expertise. Travel grants and research stays played a key role in enabling participation in conferences, training courses, and research exchanges — opportunities that many ECRs found particularly valuable.

Drawing from experience, the presentation also addresses a few structural challenges such as the difficulty of sustaining engagement over time, especially when activities begin later in a project, and the need to balance diverse academic backgrounds in interdisciplinary settings. These reflections support global efforts to ensure inclusive and equitable quality education for all (UN SDG 4), while responding directly to the ICRP's Vancouver Call for Action to sustain expertise in radiation protection. The RadoNorm ECRC helped spark the formation of a broader, independent ECR network (ECRad), which aims to continue supporting young scientists in radiation protection even after the conclusion of the RadoNorm project.

Appendix C. Feedback Form

Please answer the questions on a scale of 1-5, with 1 indicating absolute disagreement and 5 indicating full agreement.

1. I was very satisfied with the overall experience of the RadoNorm Final Meeting.

	1	2	3	4	5	
Absolutely not	○	○	○	○	○	Fully agree

2. I could understand / comprehend the content of the scientific presentations.

	1	2	3	4	5	
Absolutely not	○	○	○	○	○	Fully agree

3. I could easily participate in the discussions.

	1	2	3	4	5	
Absolutely not	○	○	○	○	○	Fully agree

4. The scientific progress of the project lines up with the initial goals of the project.

	1	2	3	4	5	
Absolutely not	○	○	○	○	○	Fully agree

5. I was satisfied with the information passed along during the planning and organisation of the Final Meeting.

	1	2	3	4	5	
Absolutely not	○	○	○	○	○	Fully agree

6. Offering a hybrid meeting was a good way to organise the annual meeting.

	1	2	3	4	5	
Absolutely not	○	○	○	○	○	Fully agree

Please fill in your answers as sentences to the following questions.

7. Do you have any feedback about the venue, catering, email communications and general organisation?

8. What was the most useful part of this meeting?

9. What is your key takeaway from the meeting?

10. Would you like to give a final message / share your thoughts about the #5yearsofRadoNorm?

11. Any other comments:

12. I am a/an: (*mandatory)

- ☐ RadoNorm PhD/ECR
- ☐ RadoNorm Senior scientist / Task leader / Work package leader / Administrator
- ☐ Stakeholder / Advisory board member / External guest

13. I followed the meeting: (*mandatory)
    a. Online
    b. In-person

Appendix D. Group Photo

Figure A1: Photo of participants at RadoNorm Final Meeting