STUK-A262 / DECEMBER 2018

Sisko Salomaa (Ed.)

National Programme for Radiation Safety Research

2018-2022

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ISBN 978-952-309-429-1
ISSN 2243-1888 (pdf)

SALOMAA Sisko (Ed.). National Programme for Radiation Safety Research. STUK-A262, Helsinki 2018, 99 pp.

KEYWORDS: radiation protection, ionising radiation, non-ionising radiation, dosimetry, metrology, environment, biological effects, health risks, Cores

Abstract

This report provides an update on the national radiation safety research programme and the activities of the Consortium for Radiation Safety Research (Cores), giving more detail on radiation safety research carried out by the consortium members. While there has been long-standing cooperation between STUK and universities, such ties were further strengthened and formalised after the government decided to introduce a comprehensive reform of the Finnish research and innovation system in 2013. This subsequently led to the setting up of the national Consortium for Radiation Safety Research (Cores) and the formulation of a national programme on radiation safety research in Finland. The main goal of the government reform was to strengthen multidisciplinary, high-level research of social significance. One line of action was to deepen cooperation between research institutes and universities. To achieve this goal, the Resolution envisaged a step-by-step integration process leading to centres of competence (agreement-based consortia). According to the government policy, such agreement-based consortia must have common research equipment, laboratories and information resources (e.g. follow-up material, sample material, statistical and register material) as well as engage in close cooperation in research and education (e.g. sharing of mutually complementary competencies, joint professorships and duties, and shared staff). Based on the Government Resolution, a process was initiated to strengthen the cooperation between STUK and universities and to create a national research consortium that would carry out research on various aspects of ionising and non-ionising radiation safety. The agreement to set up the Consortium was signed between STUK and nine universities by 2015. In addition to STUK, the following universities signed the Consortium Agreement forming the Finnish Consortium for Radiation Safety Research (Cores), and contributed to the national programme: Aalto University, Lappeenranta University of Technology, Tampere University of Technology, the University of Helsinki, the University of Eastern Finland, the University of Jyväskylä, the University of Oulu, the University of Tampere and the University of Turku. More recently, Åbo Akademi University and Technology Research Centre VTT Oy also joined Cores.

The first version of a National Programme for Radiation Safety Research was published in parallel (Salomaa et al., 2015). After publishing the national programme in 2015, a stakeholder consultation on the national programme was carried out in 2016. The programme was sent to almost 80 stakeholders and statements were received from about half of them. The feedback from stakeholders was analysed by the Cores Board and taken into account in the new version of the programme, along with emerging research needs. A new strategy and a roadmap for 2018–2022 has now been set up and the national programme has been updated accordingly, providing more detail on the research plans of each consortium member. The roadmap involves engaging new partners, universities and research institutes, and organising activities fostering the cooperation, such as joint symposia and working groups. Dissemination of Cores aims and achievements is supported by newsletters and the Cores website. Fostering the education and training and promoting the joint use of infrastructure and databases (open science) are important lines of action. Cores also promotes national and international funding for radiation sciences and links with the European radiation protection research platforms. In the longer term, the objective is to actively participate in international collaboration, in particular the Horizon Europe programme. Cores research activities are well in line with the objectives of European radiation protection research. A long-term funding plan is among the key objectives for the next strategy period.

SALOMAA Sisko (toim.). Kansallinen säteilyturvallisuustutkimuksen ohjelma 2018 - 2022. STUK-A262. Helsinki 2018, 99 s.

AVAINSANAT: säteilysuojelu, ionisoiva säteily, ionisoimaton säteily, dosimetria, metrologia, ympäristö, biologiset vaikutukset, terveysriskit, Cores

Tiivistelmä

Tämä raportti antaa päivitettyä tietoa kansallisen säteilyturvallisuustutkimuksen ohjelmasta ja kansallisen säteilyturvallisuustutkimuksen yhteenliittymän (Cores) toiminnasta, erityisesti kuvaten tarkemmin eri osapuolien tekemää tutkimusta. Vaikka STUKin ja yliopistojen välillä on ollut pitkäaikaista yhteistyötä, näitä yhteyksiä edelleen vahvistet-

tiin sen jälkeen kun hallitus teki periaatepäätöksen valtion tutkimuslaitosuudistuksesta vuonna 2013. TULA-päätöksen seurauksena perustettiin kansallinen säteilyturvallisuustutkimuksen yhteenliittymä ja laadittiin kansallinen säteilyturvallisuustutkimuksen ohjelma. TULA-uudistuksen päämääränä oli tukea monitieteistä, korkeatasoista ja yhteiskunnallisesti merkittävää tutkimusta. Yhtenä tavoitteena oli syventää tutkimuslaitosten ja yliopistojen tutkimusyhteistyötä. TULA-päätöksessä edelleen linjataan, että tutkimuslaitosten ja korkeakoulujen yhteistyön syventämiseksi synnytetään valtakunnallisesti ohjattu useampivuotinen kehittämisprosessi, jossa tutkimuslaitokset ja korkeakoulut muodostavat asteittain aitoja osaamisen keskittymiä (sopimusperusteiset yhteenliittymät). Valtioneuvoston periaatepäätöksen mukaan tutkimuslaitosten ja korkeakoulujen sopimusperusteisilla yhteenliittymillä tulee olla yhteisiä tutkimuslaitteita, laboratorioita ja tietovarantoja (mm. seurantaaineistot, näyteaineistot, tilasto-ja rekisteriaineistot), ja tiivis yhteistyö tutkimuksessa ja opetuksessa (mm. toisiaan täydentävien osaamisten yhdistäminen, yhteiset professuurit, tehtävät ja yhteistä henkilökuntaa). Valtioneuvoston periaatepäätöksen pohjalta lähdettiin tiivistämään STUKin ja yliopistojen yhteistyötä ja perustettiin STUKin ja yhdeksän yliopiston keskeinen yhteenliittymä, jonka tavoitteena on tehdä ionisoivaan ja ionisoimattomaan säteilyn turvallisuuskysymyksiin liittyvää tutkimusta. STUKin lisäksi sopimusosapuolina olivat: Aalto yliopisto, Helsingin yliopisto, Itä-Suomen yliopisto, Jyväskylän yliopisto, Lappeenrannan teknillinen yliopisto, Oulun yliopisto, Tampereen teknillinen yliopisto, Tampereen yliopisto, ja Turun yliopisto. Sittemmin myös Åbo Akademi ja Teknologian tutkimuskeskus VTT Oy ovat liittyneet Coresin jäseniksi.

Kansallisen ohjelman ensimmäinen versio julkaistiin 2015 (Salomaa ym. 2015). Kansallisen ohjelman julkaisemisen jälkeen pyydettiin sidosryhmien kommentteja kansalliseen ohjelmaan vuonna 2016. Raportti lähetettiin lähes 80 sidosryhmälle ja näistä lähes puolet toimittivat lausuntonsa. Coresin johtoryhmä analysoi palautteen ja kommentit otettiin huomioon ohjelman päivityksessä, uusien tutkimustarpeiden ohella. Uusi strategia ja tiekartta vuosille 2018-2022 on sittemmin valmisteltu ja tutkimussuunnitelmiin on päivitetty aiempaa tarkempaa tietoa kunkin konsortion jäsenen osalta. Tiekartan toimintalinjoihin kuuluu uusien osapuolien, niin yliopistojen kuin tutkimuslaitostenkin, ottaminen mukaan toimintaan sekä yhteistyötapojen kehittäminen, kuten yhteisten symposiumien ja työpajojen järjestäminen. Viestintää Coresin tavoitteista edistetään verkkosivun ja uutiskirjeiden avulla. Myös koulutuksen ja infrastruktuurien ja tietoaineistojen käytön edistäminen (avoin tiede) on keskeinen toimintalinja. Cores myös edistää kansallisen ja kansainvälisen rahoituksen saamista säteilyturvallisuustutkimukseen yhteistyössä eurooppalaisten tutkimusyhteenliittymien kanssa. Pitemmällä tähtäimellä tavoitteena on aktiivisesti osallistua kansainväliseen tutkimusyhteistyöhän, erityisesti Horizon Europe –ohjelmassa. Cores-yhteenliittymän tutkimus on hyvin linjassa eurooppalaisen säteilysuojelututkimuksen tavoitteiden kanssa. Pitkän aikavälin rahoitussuunnitelma on keskeinen tavoite seuraavalla strategiakaudella.

Contents

1. Introduction

While there has been long-standing cooperation between STUK and universities, such ties were further strengthened and formalised when the government decided to introduce a comprehensive reform of the Finnish research and innovation system in 2013. This subsequently led to the setting up of the national Consortium for Radiation Safety Research (Cores) and the formulation of a national programme on radiation safety research in Finland. The Finnish Government Resolution on Comprehensive Reform of State Research Institutes and Research Funding took place in September 2013. The main goal of the reform was to strengthen multidisciplinary, high-level research of social significance. One line of action was to deepen cooperation between research institutes and universities. To achieve this goal, the resolution envisaged a step-by-step integration process leading to centres of competence (agreement-based consortia). According to government policy, such agreement-based consortia must have common research equipment, laboratories and information resources (e.g. follow-up material, sample material, statistical and register material) as well as engage in close cooperation in research and education (e.g. sharing of mutually complementary competencies, joint professorships and duties, and shared staff). Furthermore, it was envisaged that, within the consortia, the research institutes and universities form joint campus areas with common functions on a regional basis.

2. Cores – Consortium for Radiation Safety Research

2.1 National strategy

A roadmap for the integration of radiation safety research during the period 2013¬–2017 was prepared. As a first step, a national strategy was formed during 2013–2014, evaluating the impact of the Government Resolution and setting the objectives for the national programme and consortium. STUK surveyed potential national cooperators, made initial contact and organised seminars. Stakeholder consultations were carried out by STUK, in particular with the universities and at the ministerial level. Radiation safety research was identified as one of the priority programmes in the national research strategy of nuclear sector (Työ- ja elinkeinoministeriö, 2014), along with current research programmes for nuclear safety and waste management and the research programme for future nuclear energy (fission and fusion). It was envisaged that the national radiation safety programme will ensure the national competence and scientific base in radiation safety, secure the needs for knowledge of the national authorities, and integrate research with education and innovation. The strategy envisaged the setting up of a national research consortium along the lines of the Government Resolution. Furthermore, the national programme would be linked with the European radiation protection research area (Euratom/Fission).

2.2 Establishment of consortium

Based on the Government Resolution, a process was initiated to strengthen the cooperation between STUK and universities and to create a national research consortium that would carry out research on various aspects of ionising and non-ionising radiation safety. This process has involved an analysis of scientific disciplines required for radiation protection and surveying the profiles of Finnish universities. Existing collaborations were formalised and additional competencies were identified. As part of the Euratom-funded OPERRA project (Open Project for European Radiation Research Area), a research seminar was organised at STUK in June 2014, highlighting European research agendas and STUK research activities. Another workshop presenting relevant research activities in the universities and discussing the national programme was organised in November 2014. To state the joint intention for forming a long-term consortium, Letters of Intent were signed between STUK and universities during 2013–2014.

The actual agreement to set up the consortium was signed by STUK and nine universities by 2015. In addition to STUK, the following universities signed the Consortium Agreement forming the Finnish Consortium for Radiation Safety Research (Cores), and contributed to the national programme: Aalto University, Lappeenranta University of Technology, Tampere University of Technology, the University of Helsinki, the University of Eastern Finland, the University of Jyväskylä, the University of Oulu, the University of Tampere and the University of Turku. The first version of a National Programme for Radiation Safety Research was published in parallel (Salomaa et al., 2015). More detailed plans for the use of infrastructures and information resources were made for specific areas, and bilateral agreements were prepared between STUK and the University of Eastern Finland, between STUK and the University of Tampere, and between STUK and the University of Jyväskylä. The first meeting of the board was held on 3 December 2015 and the rules for operation of the consortium were approved. Cores was adopted as an acronym for the Consortium of Radiation Safety Research.

2.3 Implementing the programme

The Cores consortium established a website available at http://www.stuk.fi/web/en/about-us/cooperation/cores-finnish-consortium-for-radiation-safety-research. Research areas for the national programme include health (low dose risk as well as medical use of radiation), environment (radioecology) and emergencies (emergency preparedness and response, security of sources). The cross-cutting themes of risk assessment, risk management and technological development (metrology and dosimetry) are addressed. Overall, the programme is well aligned with the objectives of European radiation protection research platforms (MELODI, ALLIANCE, NERIS, EURADOS and EURAMED), with additional elements relevant for non-ionising radiation safety, security research and metrology research. While the European SRAs also include a research agenda for Social Sciences and Humanities (SSH), this area is so far not covered in the national programme.

Based on the Government Resolution, the Agreement on National Consortium for Radiation Safety Research is expected to establish the necessary legal link for the beneficiary-Linked Third Party-relationship between the members of the Consortium in the framework of Horizon 2020 programme and beyond, including CONCERT EJP. STUK was not involving any Linked Third Parties at the beginning of the CONCERT project, but reserved this possibility in the later stages of CONCERT, in calls organised by CONCERT, or other H2020 projects. The University of Tampere subsequently joined CONCERT as a Linked Third Party to STUK.

During the preparation of the Euratom Joint Programme co-funded action in 2014, the Ministry of Social Affairs and Health (programme owner) mandated STUK to participate as programme manager and participant in the EJP Consortium. Since then, the role of Finnish universities in radiation safety research has been increasing. This development is in line with the national KOTUMO roadmap for cooperation between universities and research institutes (KOTUMO), outlined by the Ministry of Education and Culture. In 2016, the Ministry of Education and Culture named the University of Eastern Finland as programme manager and the University of Eastern Finland joined CONCERT as of June 2016.

3. Stakeholder feedback

After publishing the national programme, a stakeholder consultation on the national programme was carried out in 2016. The report was sent to almost 80 stakeholders, and statements were received from about half of them. The feedback from stakeholders was analysed by the Cores Board and taken into account in the new version of the programme (this report).

3.1 Summary of statements by the stakeholders

Overall, the stakeholders considered the programme to be well structured and necessary in order to maintain and develop national competence in radiation safety. However, more concrete plans were requested in many statements. Furthermore, the importance of international research was emphasised, to complement the national programme. The first version of the national programme was seen as a well justified list of research needs and what each consortium partner is doing. The roadmap describing the development of activities was regarded positively. The statements also emphasised that arrangements for long-term stable funding were necessary. However, there was no practical solution to point out possible funding sources. In its statement, the Academy of Finland reminded us that they are providing national co-funding for Horizon2020 EU projects. A major drawback for Cores was, however, that the major funder of radiation protection research, the Euratom H2020 programme, was excluded from this co-funding by the Academy of Finland.

Many stakeholders also noted that the programme is focused on collaboration between STUK and universities only, and the research carried out by other institutes should also be mentioned. A major issue was raised by stakeholders: who is taking general responsibility for the maintenance of knowledge and competence in Finland? This question is of course very much linked to the funding of research.

3.2 Subsequent actions by Cores and STUK

Based on the stakeholder feedback, three main actions were identified by Cores:

- the national programme should be updated and made more concrete
- the operational modes of the consortium should be further developed
- long-term funding must be ensured

It was decided to update the national research programme so that each partner would describe their 3–5 year plans for research addressing radiation safety. This enables the partners to better identify joint research interests and find complementary expertise. The national programme description should also include a summary of the stakeholder feedback and actions based on it, as well as description of research activities and cooperation carried out with the government research institutes in the field of radiation safety.

As for the modes of action, it was decided to bring together researchers interested in specific topics like medical use of radiation, environmental radiation and technological development. Such working groups could be open to other interested parties as well. The board also welcomes other organisations interested in radiation safety research to join Cores. To bring together researchers, Cores organises open symposia. Three major symposia were organised in 2018. The Cores symposium Radiation in the Environment – Scientific Achievements and Societal Challenges brought together more than 100 participants in Helsinki in April 2018. Another Cores symposium took place in Tampere, addressing applications of big data, sensor networks, robotics and artificial intelligence, and covering sessions on medical radiation and nuclear emergency preparedness and response. The topic for the third symposium in Kuopio, held on 21–22 November 2018, is non-ionising radiation research and safety.

The ultimate objective for the funding arrangements is to ensure long-term competence in Finland. The new instrument, the Strategic Research Council (STN), has not provided the anticipated funding source for societally relevant radiation safety research. Furthermore, the STN excluded the Euratom H2020 programme from the co-funding provided for projects that were successfully evaluated in H2020. Overall, external project funding does not compensate for the long-term basic funding that is necessary for maintaining national competence.

In STUK's strategy for 2018–2022, an effective national radiation safety programme is highlighted as one of the main targets. Radiation safety research generates experts, tools and knowledge for authority supervision and emergency preparedness. Via cooperation with universities and the Tulanet network, STUK aims to set radiation safety research as one of the key areas for the universities and research centres and to make sure that STUK is a central part of national and international networks carrying out research that is relevant for STUK. For its own part, STUK also assures that funding of research is kept on a sustainable basis, ensuring participation in national and international projects. To achieve these goals, several lines of action are planned. The networks with universities and research centres are further advanced via exchange of researchers, supervision of theses, joint seminars and collaborative projects. Acquiring funding for research of relevance for STUK is achieved, for example, by allocating income from expert services. STUK also plans to influence research funding agencies and ministries to ensure sustainable funding for radiation safety research and participation in national and international projects. Collaboration in undertakings where STUK has significant radiation safety research projects with universities will be strengthened, and the objective to establish radiation safety research will be a key research area among universities and research centres.

4. Research plans of Cores members 2018–2022

4.1 STUK – Radiation and Nuclear Safety Authority

DR TEEMU SIISKONEN, DR MAARIT MUIKKU, DR KARI PERÄJÄRVI

In the main, the European Union radiation research programmes are currently carried out in consortia and calls organised by large research platforms. Participation in the planning of research programmes and calls is important as it provides an opportunity to have impact on the priorities and contents. STUK participates in the Working Groups on Strategic Research Agendas of NERIS, ALLIANCE, EURADOS and MELODI platforms.

STUK also participates in the strategic working group of the metrology research programme (EMPIR).

4.1.1 Medical use of radiation

New radiation therapy techniques challenge the conventional measurement methods used for the verification of radiation beams and dose planning for patients. Narrow beams, the simultaneous use of several radiation qualities and the use of particle radiation call for new approaches in the whole measurement chain. New detector types call for the development of methods for calibration and quality assurance. Securing complicated treatment plans call for measurements in anthropomorphic phantoms that are more realistic than those currently used. STUK participates in metrology research programme (EMPIR) projects that develop external beam radiotherapy dosimetry, such as the use of measurements and Monte Carlo simulations to assess perturbation correction factors of ionisation chambers, which are used in the dosimetry of radiotherapy. In collaboration with Helsinki Institute of Physics, STUK develops detectors suitable for measuring 3D dose distributions.

In cooperation with EURADOS, STUK carries out research on patient exposures in interventional radiology and cardiology. The study focuses on diagnostics and procedures with high exposure, potentially causing deterministic effects. EURADOS cooperation also encompasses research on radiation doses on tissues and organs outside the radiotherapy target area.

In the metrology research programme, STUK collaborates with Helsinki University Hospital on patient-specific dosimetry for decision support on optimisation. By combining information from patient models (phantoms) and simulations, it is possible to validate computational methods and to produce material for image quality assessments. The assessments focus in particular on computed tomography (CT).

4.1.1.1 Ongoing projects

Radiation Metrology for Applications (Helsinki Institute of Physics, Technology Programme), 2017-2019

PerfusImaging (Metrology for multi-modality imaging of impaired tissue perfusion, EMPIR), 2016-2019

RTNORM (kQ factors in modern external beam radiotherapy applications to update IAEA TRS-398, EMPIR), 2017-2019

EU CARDIO (Diagnostic Reference Levels in interventional cardiology – Europe-wide analysis, EURADOS), 2016-2018

MPMIB (Multispectral photon counting for medical imaging and beam characterisation, Academy of Finland), 2018 - 2021

Contact person at STUK: Teemu Siiskonen

4.1.2 Non-ionising radiation

New applications of non-ionising radiation in services for cosmetic body shaping set new demands for supervision and exposure assessments. The intentional exposure of skin to radiofrequency radiation and ultrasound that are close to levels that can cause damage are new applications that call for the development of new measurement methods in order to ensure safety and proper supervision. During the strategy period, STUK will improve its capabilities on exposure assessment to foster supervision.

During the strategy period, STUK also participates in long-term cooperation with the University of Tampere in order to clarify the health effects of UV radiation. In particular, STUK will provide expertise in UV dosimetry.

It is possible that the reform of the Radiation Act may bring new technologies and applications under the supervision of STUK. STUK will develop necessary methods for measurements and exposure assessments and maintain and develop measurement standards required.

4.1.2.1 Ongoing projects

Measurements and exposure assessments of non-ionising radiations:

Measurements in cosmetic applications of radiofrequency radiations.
Supervisor Pasi Orreveteläinen

Improving the radiofrequency dosimetry in cosmetic applications.
Contact person at STUK: Sami Kännälä

Clarifications supporting supervision:

Reform of the Radiation Act and magnetic field exposure on railways.
Contact person at STUK: Lauri Puranen

Safety of amateur radio stations. Contact person at STUK: Lauri Puranen

UV radiation (Prof. Erna Snellman, Tampere University Hospital):

UV radiation and vitamin D; perceived pleasure and addiction due to UV radiation.
Contact person at STUK: Lasse Ylianttila

4.1.3 Radiation in the environment

The general aim for the research and development supporting the environmental surveillance of radiation is to improve knowledge and expertise on the occurrence and environmental transfer of both natural and anthropogenic radionuclides and their effects on man and the biota. Research and clarifications related to metrology aim at enabling and ensuring reliable and accurate radiation measurements.

Finns obtain the majority of their annual radiation dose from indoor radon. STUK actively participates in the preparation and implementation of the national Radon Action Plan that aims for the prevention of radon risks. The reference level for indoor radon is the annual average of radon concentration. It is estimated on the basis of a shorter measurement period (2–3 months) using a generalised correction factor. Uncertainties in the measurements are brought about by differences in radon concentrations between rooms as well as annual variations. On the basis of the samples taken in 1996 and 2006, the correction factor values deviate and there is no reliable data on annual variation in radon concentrations. These shortcomings will be addressed in studies assessing uncertainties in measurements.

Information on the behaviour of radionuclides in the Finnish environment is needed in the environmental surveillance of mines and nuclear power plants, as well as in the assessment and remediation of old mining and mine tailing areas (NORM). In radiological and nuclear emergencies, it is necessary to apply radionuclide dispersion and dosimetric models in Finnish circumstances. STUK participates in Horizon 2020 projects and Nordic projects that aim at developing tools for decision support in case of various radiological emergencies (e.g. nuclear power plant accident or NORM releases related to mining) in order to help in the remediation and management of contaminated areas. STUK also conducts various clarifications related to the Finnish environment and foodstuffs. These clarifications may give rise to further research.

The development of radiation protection of biota is also needed by STUK as authority. The authority needs knowledge on the exposure of biota after releases related to mining or nuclear installations. However, research and development on the radiation protection of biota is not among the key priorities at STUK.

4.1.3.1 Ongoing projects

KATORRE (National Radon Action Plan, 2015-2018, STUK, Ministry of Social Affairs and Health). Contact person at STUK: Päivi Kurttio

TERRITORIES (To enhance uncertainties reduction and stakeholders involvement towards integrated and graded management of human and wildlife in long-lasting radiological exposure situations, 2017-2019, EU H2020). Contact person at STUK: Pia Vesterbacka

NANOD (Natural radioactivity in the Nordic diet, 2018, NKS). Contact person at STUK: Sinikka Virtanen

4.1.4 Measurement of radiation (activity)

The EU MetroRADON project, aimed at the development and harmonisation of calibration practices for radon (220Rn) monitoring equipment is part of the EMPIR research programme, which STUK is participating in during the period 2017–2020. The project also examines the effect of 220Rn on radon measurement results and methods for identifying radon risk areas.

The development of national measurement standard for activity and activity concentration is in progress.

4.1.4.1 Ongoing projects

MetroRADON (Metrology for radon monitoring, 2017-2020, EU H2020).
Contact person at STUK: Tuukka Turtiainen

DIGITALSTD (Standard for Digital Data Format for Nuclear Instrumentation, 2015-2018, EU EMPIR). Contact person at STUK: Tarja Ilander

RADICAL (RAdiation Detection In Coincidence And List mode, 2018-2021, STUK, JY).
Contact person at STUK: Jani Turunen

4.1.5 Emergency Management and Nuclear Security Arrangements

Despite all the preventive radiation and nuclear safety activity, the possibility of an emergency radiation situation cannot be discounted. For example, a severe emergency affecting a wide area in Finland may be caused by a serious nuclear power plant accident at a domestic or foreign plant nearby. In addition to preparing for nuclear and radiological accidents, efforts are also needed to prevent the malevolent use of radiation. Measurements and technology in general are an essential part of both emergency management and nuclear security activities.

STUK is participating in undertakings such as HORIZON2020 (e.g. CONFIDENCE) and joint Nordic projects aimed at reducing uncertainties in risk assessment and the management of various radiation hazard situations, starting from the release of radioactivity into the environment and ending in plans for the long-term recovery of society. Within the framework of the projects STUK, among others, is developing its prediction and situational awareness software (e.g. the TIUKU system). The projects will improve STUK's capability to prepare for and manage various radiation emergency situations. These projects will also harmonise the activities of different countries. STUK also participates in the development of a national monitoring strategy that will be employed during nuclear or radiological emergencies.

Nuclear security is part of national security. It is a genuine 24/7 multi-authority activity. Nuclear security is linked to national security, for example, through the national CBRNE strategy. There are several groups under the CBRNE Coordinating Body. One of the groups focuses on research, development and education. STUK participates the work of the coordinating body and its sub-groups. The Finnish nuclear security detection architecture (NSDA) for nuclear and other radioactive materials out of regulatory control is currently being updated. The NSDA materialises the CBRNE strategy on a general and public level. The NSDA covers all national technical and non-technical detection systems for nuclear security.

The key cross-cutting theme of our NSDA is reachback: the remote expert support of field teams. This mode of operation requires that the measuring devices are able to store their measurement data to a remote database that is accessible for radiation detection specialists. This approach was selected since nuclear security measurements involve several different authorities across Finland and not all of them have their own radiation specialists to adjudicate the instrument alarms. In addition, spectrometric instruments are becoming more frequently used in nuclear security.

Interesting research projects related to emergency management and nuclear security can be initiated from the following topics, among others: new detector materials and detection concepts, digitisation and the internet of things, automation, large data sets, and data mining. The most significant self-funded ongoing research and development projects on emergency management and nuclear security are:

1. Research and development related to the renewal of the national radiation monitoring network
2. Research and development related to the radiation detection equipment used by customs
3. General development of data transfer, management and reachback functions

4.1.5.1 Ongoing projects

CONFIDENCE (COping with uNcertainties For Improved modelling and DEcision making in Nuclear emergenCiEs, 2017-2019, EU H2020). Contact person at STUK: Juhani Lahtinen

EUNADICS-AV (European natural airborne disaster information and coordination system for aviation, 2016-2019, EU H2020). Contact person at STUK: Juhani Lahtinen

DEFACTO (Detector for fallout and air concentration monitoring, 2018-2021, STUK, HIP, CSIC). Contact person at STUK: Sakari Ihantola

AUTOMORC (Detection limits for mobile search of material outside of regulatory control (MORC) - experimentally assessed in field trials, 2018, NKS).
Contact person at STUK: Petri Smolander

4.1.6 Health effects of radiation

The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) will make a new assessment of the risk of radon-induced lung cancer based on the recent scientific evidence, as well as an assessment on the risk and dose response of lung cancer due to external gamma radiation. The objective is also to re-evaluate the dosimetric models for the calculation of dosage from radon exposure.

The understanding of the impact of radiation on lens opacities has changed in recent years. Therefore, the dose limit for the lens of the eye has been reduced. The EURALOC study of the OPERRA consortium has assessed the association of occupational radiation exposure with the risk of lens opacities. The aim is to obtain a more accurate estimate of the risk and information on the dose response.

Leukaemia is one of the most sensitive indicators of cancer risk from radiation, with an elevated incidence in several radiation-exposed populations. Increased childhood cancer incidences have also been reported around several nuclear installations, which is difficult to explain on the basis of the low radiation doses. Better knowledge of other leukaemia risk factors helps to define radiation-induced risk. STUK participates in a case-control study investigating the risk factors for childhood leukaemia together with the University of Tampere and the Cancer Registry.

Knowledge of the health effects of radiofrequency electromagnetic fields is still poor. The international COSMOS study clarifies the association between the use of mobile phones with symptoms as well as the incidence of cancer, neurological diseases and disturbances of cerebrovascular circulation. The RF-Astro study coordinated by the WHO International Agency for Cancer Research (IARC) and based on the Interphone data investigates the association between the use of mobile phones with the prognosis of glioma.

4.1.6.1 Ongoing projects

CONCERT (European Joint Programme for the Integration of Radiation Protection Research, 2015–2020, EU H2020). Contact person at STUK: Pia Vesterbacka

EURALOC (European epidemiological study on radiation-induced lens opacities for interventional cardiologists, 2014–2017, EU FP7). Contact person at STUK: Anssi Auvinen

Case-control study of childhood leukaemia, predictive model on radon (2012-2017, Cancer Registry). Contact person at STUK: Anssi Auvinen

4.1.7 Recent publications

Garnier-Laplace J, Vandenhove H, Beresford NA, Muikku M, Real A. COMET strongly supported the development and implementation of medium-term topical research roadmaps consistent with the ALLIANCE Strategic Research Agenda. Journal of Radiological Protection 2018; 38: 164–174. https://doi.org/10.1088/1361-6498/aa9c0a

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Michelson D, Henja A, Ernes S, Haase G, Koistinen J, Ośródka K, Peltonen T, Szewczykowski M, Szturc J. BALTRAD Advanced Weather Radar Networking. Journal of Open Research Software 2018; 6(1): p.12. DOI: 10.5334/jors.193

Muikku M, Sirkka L, Beresford N A, Garnier-Laplace J, Real A, Thorne M, Vandenhove H, Willrodt C. Sustainability and integration of radioecology—position paper. Journal of Radiological Protection 2018; 38: 152–163. https://doi.org/10.1088/1361-6498/aa9c0b

Suran J, Kovar P, Smoldasova J, Solc J, Van Ammel R, Garcia Miranda M, Russell B, Arnold D, Zapata-García D, Boden S, Rogiers B, Sand J, Peräjärvi K, Holm P, Hay B, Failleau G, Plumeri S, Laurent Beck Y, Grisa T. Metrology for decommissioning nuclear facilities: Partial outcomes of joint research project within the European Metrology Research Programme. Applied Radiation and Isotopes 2018; 134: 351–357. http://dx.doi.org/10.1016/j

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Madekivi V, Boström P, Aaltonen R, Vahlberg T, Salminen E. The Sentinel Node with Isolated Breast Tumor Cells or Micrometastases. Benefits and Risks of Axillary Dissection. Anticancer Research 2017; 37(7): 3757-3762.

Niiniviita H, Kulmala J, Pölönen T, Määttänen H, Järvinen H, Salminen E. Excess of radiation burden for young testicular cancer patients using automatic exposure control and contrast agent on whole body computed tomography imaging. Radiology and Oncology 2017; 51 (2): 235 – 240. doi:10.1515/raon-2017-0012

Salminen E, Niiniviita H, Järvinen H, Heinävaara S.Cancer Death Risk Related to Radiation Exposure from Computed Tomography Scanning Among Testicular Cancer Patients. Anticancer Research 2017; 37 (2): 831-834. DOI: 10.21873/anticanres.11385

Talibov M, Salmelin R, Lehtinen-Jacks S, Auvinen A. Estimation of Occupational Cosmic Radiation Exposure Among Airline Personnel: Agreement Between a Job-Exposure Matrix, Aggregate, and Individual Dose Estimates. American Journal of Industrial Medicine 2017: 60: 386-393.

Toledano MB, Auvinen A, Tettamanti G, Cao Y, Feychting M, Ahlbom A, Fremling K, Heinävaara S, Kojo K, Knowles G, Smith RB, Schüz J, Johansen C, Harbo Poulsen A, Deltour I, Vermeulen R, Kromhout H, Elliott P, Hillert L. An international prospective cohort study of mobile phone users and health (COSMOS): factors affecting validity of self-reported mobile phone use. International Journal of Hygiene and Environmental Health 2017. Online 20 Sept 2017. https://doi.org/10.1016/j.ijheh.2017.09.008

4.2 Aalto University

PROFESSOR FILIP TUOMISTO, ANTIMATTER AND NUCLEAR ENGINEERING

4.2.1 General

Aalto University has seven key research areas that particularly relate to promoting and maintaining Finnish competitiveness and welfare through renewal and entrepreneurship. The cornerstones of Aalto University research are the following four fundamental competence areas:

1. ICT and digitalisation
2. Materials and sustainable use of natural resources
3. Art and design knowledge building
4. Global business dynamics.

In addition to these areas, the university invests in three integrative multidisciplinary themes that focus on solving challenges that are important globally and for the Finnish economy.

5. Advanced energy solutions
6. Human-centred living environments
7. Health and well-being.

The key research areas particularly relate to promoting and maintaining Finnish competitiveness and welfare through renewal and entrepreneurship. They define Aalto University's academic profile by guiding its tenure track allocations, major university-level research initiatives, infrastructure investments, educational activities and other investments.

Two of the above-listed fundamental competence areas are relevant from the point of view of radiation safety research: "ICT and digitalisation" and "Materials and sustainable use of natural resources". ICT and digitalisation research relates to both theory and practice, computational and mathematical sciences, software and hardware technologies, secure communications, digital media, digital services, and digital engineering and management across technologies and industrial sectors. This combination provides an excellent launch pad for interdisciplinary innovations. Aalto University's expertise in the area of materials covers a wide range of fields: from condensed matter and materials physics, nanoscience and nanotechnology, mechanics and materials to the sustainable use and processing of natural resources.

All of the multidisciplinary themes have links to radiation safety: advanced energy solutions in terms of nuclear power production, human-centred living environments in terms of radon safety, and health and well-being in terms of nuclear medical imaging.

4.2.2 Radiation safety

Research related to radiation safety at Aalto University is focused around two main themes: materials for radiation detectors (applied physics, materials science, electrical engineering) and detection technologies (applied physics, applied mathematics, computer science and electrical engineering).

Novel semiconductor materials for photodetectors, with wavelengths ranging from infrared to visible and ultraviolet (hence extending to ionising radiation) are developed in several research projects. These materials and device structures typically belong to the "traditional" families of Si-based and III-V semiconductors, including III-nitride semiconductors.

Innovative detector designs and novel materials are also explored and developed for shorter-wavelength electromagnetic radiation, namely X-rays. Extending the materials space from CdTe-based to III-V semiconductors is an active research area.

Novel materials are explored and new detector concepts developed for neutron detection. Scientifically challenging research projects focus on emerging electronic materials such as SiC and semiconducting oxides. The detector concepts rely on innovative approaches and neutron-sensitive isotopes directly integrated into the semiconductor matrix, allowing for designs that allow simple, robust and autonomous operation.

Gamma-ray detection technologies are developed both for radioactive materials analysis and medical imaging applications such as positron emission tomography or spectral computer tomography. The research is focused on detector systems, data acquisition and signal analysis.

Detection systems for non-ionising radiation – namely magnetic fields and THz signals (mm-waves) – are also developed. The detection and analysis of propagation of radiofrequency signals is an important direction for research activities.

4.3 Tampere University of Technology

PROFESSOR JUHA TOIVONEN, APPLIED OPTICS, PROFESSOR MIKA VALDEN, SURFACE SCIENCE, AND PROFESSOR TARMO LIPPING, DATA ANALYTICS AND OPTIMISATION

4.3.1 Optics and photonics: development of novel radiation detection methods

4.3.1.1 Introduction

The detection methods for ionising radiation have been fairly well established for decades. Now, however, methods are changing due to the prevalence of X-ray and gamma camera technologies, for instance. Corresponding imaging methods for alpha and beta radiation are not yet available. One limiting factor is that alpha particles travel only a few centimetres in air, and beta particles, correspondingly, travel several metres. Therefore, in the case of alpha radiation, a radiation detector should be only a few centimetres from the source of radiation, which makes imaging detection impossible. However, alpha and beta radiation strongly ionise the surrounding air, and as a result, the excited air molecules around the source become luminescent. This radioluminescence can be utilised for locating a radioactive source by optical imaging means.

The localisation and cleaning of alpha contamination is an extremely time-consuming operation, for example when cleaning workspaces and decommissioning a nuclear plant. Optical detection is ideally suited for mapping out medium and highly active sources of alpha radiation, such as for imaging a fixed workspace or by using environment-mapping robots. More effective processes are needed for the field of radiation measurement, since in Europe alone 150 nuclear reactors will reach the end of their operational life by 2030. The total costs incurred for their decommissioning are estimated to be approximately 80 billion euros. In addition, it will be extremely challenging to demolish nuclear material research and recycling centres, where the spent fuel undergoes chemical processing.

Besides the remote detection of alpha radiation, air scintillations can be utilised when measuring radon concentrations. Radon gas is generated as a decay product of natural uranium in the ground. It accounts for about half of the population's annual radiation dose in Finland. By examining the flashes in the air caused by radon instead of the actual alpha particles, the response of the measuring device can be speeded up significantly, even by minutes. Fast-response measuring devices are required in workplace radon monitoring, during radon remediation work, and in plants that process nuclear materials.

4.3.1.2 Objectives

The objective is to develop novel imaging radiation detection methods, particularly for alpha radiation, which is difficult to detect using conventional methods and at the same time significant, in the case of e.g. radon, plutonium, polonium, americium and many other radioactive materials. To date, we have been able to indicate that the method can be utilised in locating radiation sources, but one obstacle to its widespread use remains the problems caused by background light. In addition, the sensitivity of the detection needs improvement so that weaker radiation sources can also be detected.

With the current state of the art, we are able to image alpha radiation sources of over 10 kBq in the dark or in artificial light. However, it is not often possible to dim the background light of the surroundings, so in the near future our research will focus on the utilisation of a background-free wavelength range of 200 – 300 nm. The ozone in the atmosphere absorbs light coming from the sun in this range, and lighting barely affects the background at all in such a deep ultraviolet range, thus eliminating the background problem to a major extent. We are aiming for a detection distance of at least several metres rather than the few centimetres demanded by conventional methods.

4.3.1.3 Methods

The latest detector, camera and filter technologies plus spectrometers are used for optical detection and imaging. We study signal intensification using active methods, such as laser excitation and gas exchange. As well as camera technologies, we are developing improved performance for single-point measurement, which is then moved with the scanning unit. The measurement distances in our tests are between 0.5 and 4 m. In addition to the application, there is also plenty to research in the dynamics of excited molecules, their interaction, and modelling. The aim is to improve the performance of the applications via more rigorous research into their parts.

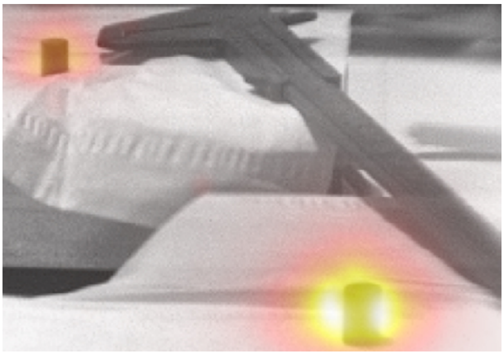

FIGURE 1. MOX pellets used as nuclear fuel captured in the deep UV range and combined with an ordinary photograph of the object. The narrow fluorescence lines of nitrogen excited by alpha radiation are separated with optical filters to improve the selectivity of the method.

The optical detection of radiation has been developed by TUT and the Radiation and Nuclear Safety Authority of Finland as a result of long-standing cooperation, and techniques relating to the remote detection of alpha radiation are tested in real environments, for example at the European Commission's Joint Research Centre for nuclear material in Karlsruhe, Germany (Figure 1).

4.3.1.4 Funding

For the period 2009–2016, this research was financed via EU-funded projects, Matine (the scientific advisory board for defence), Tekes *(the Finnish Funding Agency for Technology and Innovation)*, and STUK *(the Finnish Radiation and Nuclear Safety Authority)*. The current four-year FiDiPro project (2015–2019) together with the Helsinki Institute of Physics (HIP) at the University of Helsinki is funded by Tekes. Also, the international EMPIR project, funded by the EU, has just commenced for the period 2017-2019.

4.3.1.5 Publications

Sand J, Nicholl A, Hrnecek E, Toivonen H, Toivonen J, and Peräjärvi K, Stand-Off Radioluminescence Mapping of Alpha Emitters under Bright Lighting, IEEE Transactions on Nuclear Science 2016; 63, 1777-1783.

Sand J, Ihantola S, Peräjärvi K, Toivonen H, Toivonen J. Optical detection of radon decay in air, Scientific Reports 2016; 6, 21532.

Sand J, Ihantola S, Peräjärvi K, Nicholl A, Hrnecek E, Toivonen H, Toivonen J, Imaging of alpha emitters in a field environment, Nuclear Instruments and Methods in Physics Research A 2015; 782, 13–19.

Sand J, Ihantola S, Peräjärvi K, Toivonen H, Toivonen J. Radioluminescence yield of alpha particles in air, New Journal of Physics 2014; 16, 053022.

4.3.2 Physicochemical phenomena on material surfaces: Corrosion studies on the copper capsules used for final disposal of spent nuclear fuel

4.3.2.1 Introduction

The spent nuclear fuel generated by Finnish nuclear power plants is stored underground in capsules, where the innermost part is made of copper. The corrosion resistance of the capsules over the millennia, as the corrosion factors of temperature, radiation and the environment change, is one of the most critical properties of the capsules. It has been estimated earlier that, within a million years, the copper capsules will corrode to a maximum depth of 2 mm. Only recently, however, by relying on empirical observations, it has been posited that copper corrosion would penetrate considerably deeper. The reason put forward for this is the currently unknown corrosion mechanism between oxygen-free water and copper found in the storage conditions (Szakálos et al., 2007). It has not yet been possible to rule out the presumption that copper corrosion occurs in oxygen-free water, so the mere suspicion of a new significant copper corrosion mechanism has given rise to further research into capsule materials. As regards proving or ruling out the corrosion phenomenon, it is essential to identify the surface reactions between the copper surface and oxygen-free water at molecular level and to map out their link to potential corrosion.

4.3.2.2 Objectives

Our group determines the interaction mechanisms between oxygen-free water and various copper surfaces in well-defined conditions using surface science methodology. The objective is to understand the binding mechanisms and reactions of water molecules (e.g. the dissociation of water into hydrogen and oxygen) on the copper surface, detect any surface compounds that may form (e.g. oxides or hydroxides), the influence of environmental conditions (e.g. partial pressure or temperature of the water), as well as the effect of material properties (e.g. surface structure, composition or impurities) on the interaction of water with the copper surface. In our well-defined testing conditions, it is possible to determine the effect of various factors such as temperature on the interaction between water and the surface in a controlled way.

The aim of the experiments is to detect the early stages of corrosion that may potentially occur on the surface and to understand the effect of various factors (e.g. the composition, temperature or structure of the material) on the corrosion (Lahtonen et al. 2008a, 2008b, Lampimäki et al. 2007). Based on detailed physicochemical data, it can be estimated better whether the corrosion mechanism presented on the basis of the previous tests exists, and to make material selections for the capsule materials deriving from research data in order to optimise their corrosion resistance. The data obtained will also be useful when developing computational models for the properties of copper capsules.

4.3.2.3 Methods

Our research is carried out using surface science methodology with vacuum equipment under varying conditions. The vacuum creates a controlled starting point for the test conditions: the composition of the copper surface is determined exactly at the start of the tests and no impurities can be transferred to it from the atmosphere, which might hinder the interpretation of the results. The sample is exposed to water and studied using analytical methods in varying conditions. The magnitude of the water exposure (pressure and exposure time) as well as the temperature of the sample can be controlled precisely.

The main research method is X-ray photoelectron spectroscopy (XPS). This is a research method which enables the quantitative determination of surface composition, surface compounds (e.g. oxides and hydroxides), the molecules on the surface and their molecule bonds, and partially also the structure of the surface. XPS is a surface-sensitive research method, i.e. all the information generated comes from a depth of just a few nanometres.

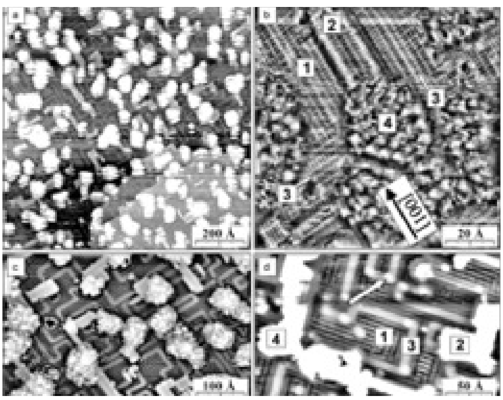

FIGURE 2. Nano oxide islands formed on the copper surface during oxidation (20 Å = 2 nanometres) (Lahtonen et al. 2008a).

By utilising international synchrotron radiation centres such as the MAX IV laboratory (Lund, Sweden), XPS measurements can also be carried out during water exposure. In this way, metastable surface compounds can be detected, which may play a significant role in surface reactions. Synchrotron radiation also increases the sensitivity of the method to small concentrations, whereby the significance of small impurities in potential corrosion can be studied in more detail.

4.3.2.4 Funding

Research was funded in 2017 by Posiva Oy, the organisation responsible for the final disposal of spent nuclear waste in Finland.

4.3.2.5 Publications

Szakálos P, Hultquist G, Wikmark G. Electrochemical and Solid-State Letters 2007; 10 C63-C67.

Lahtonen K, Hirsimäki M, Lampimäki M, Valden M, Journal of Chemical Physics 2008a; 129 124703.

Lahtonen K, Lampimäki M, Hirsimäki M, Valden M, Journal of Chemical Physics 2008b; 129 194707.

Lampimäki M, Lahtonen K, Hirsimäki M, Valden M. Journal of Chemical Physics 2007; 126 034703.

4.3.3 Biosphere modelling: modelling of radionuclide transport in the biosphere

4.3.3.1 Introduction

The transport of radionuclides in the biosphere is usually modelled using the compartment model, whereby the biosphere is described in compartments (such as lake, plants, fields, etc.), and the transport of radionuclides between compartments is described using concentration ratios (CR). The behaviour of radionuclides inside the compartment is described by distribution coefficients (Kd). The values of the coefficients are based on research results and information can be found on them in the literature. Although there is an abundance of research results, the knowledge base for modelling is nevertheless incomplete, since the coefficients have to be determined separately for different radionuclides. The greater detail the model goes into, the greater the number of different types of compartments and interfaces between them there are. In addition, the coefficient values are often extrapolated linearly in relation to radionuclide concentrations, which does not necessarily correspond to their actual behaviour on the basis of more recent research results.

Although detailed models of the transport of radionuclides in the biosphere exist, these models are generally deterministic and do not enable sensitivity analysis. Sensitivity analysis can be used to obtain further information on which kinds of input parameters have the greatest effect in terms of the radiation dose ending up in humans and, on the other hand, which kinds of ecosystems are the most critical. In addition, compartment models are not capable of adequately addressing all questions arising in the study of radionuclide transport and therefore, FEM (finite element method) type models are required. Such questions include the effect of lake bottom sediments on transport from the bedrock to the water system or in the land-water interface in mire areas.

4.3.3.2 Objectives and methods

The objective of our group is to continue the research carried out in recent years on simplified ecosystem models as far as sensitivity analysis is concerned. The results to date of the sensitivity analysis of the lake-farm model have been published in the Journal of Environmental Radioactivity (Pohjola et al. 2016a). Modelling is based partially on previously conducted work related to the statistical modelling of land uplift and terrain in the Olkiluoto area (Pohjola et al. 2014). In addition, research has been carried out on the influence of foodstuff grouping on the radionuclide dose conversion factors in relation to lake properties (Pohjola et al. 2016b).

During the next few years, the intention is to continue the development of simplified compartment models and to perform sensitivity analysis related to different ecosystems. Some ecosystems of interest are presented in Figure 3, in which the radionuclides are assumed to be released from the bedrock into the lake, as in the lake-farm model, but the lake is part of different ecosystems, such as forest (scenario 1A), mire/dried mire (scenario 2A), or floodplain used for pasture. Regarding ecosystems, the effect of variation in the model parameters on the radiation dose received by humans will be studied.

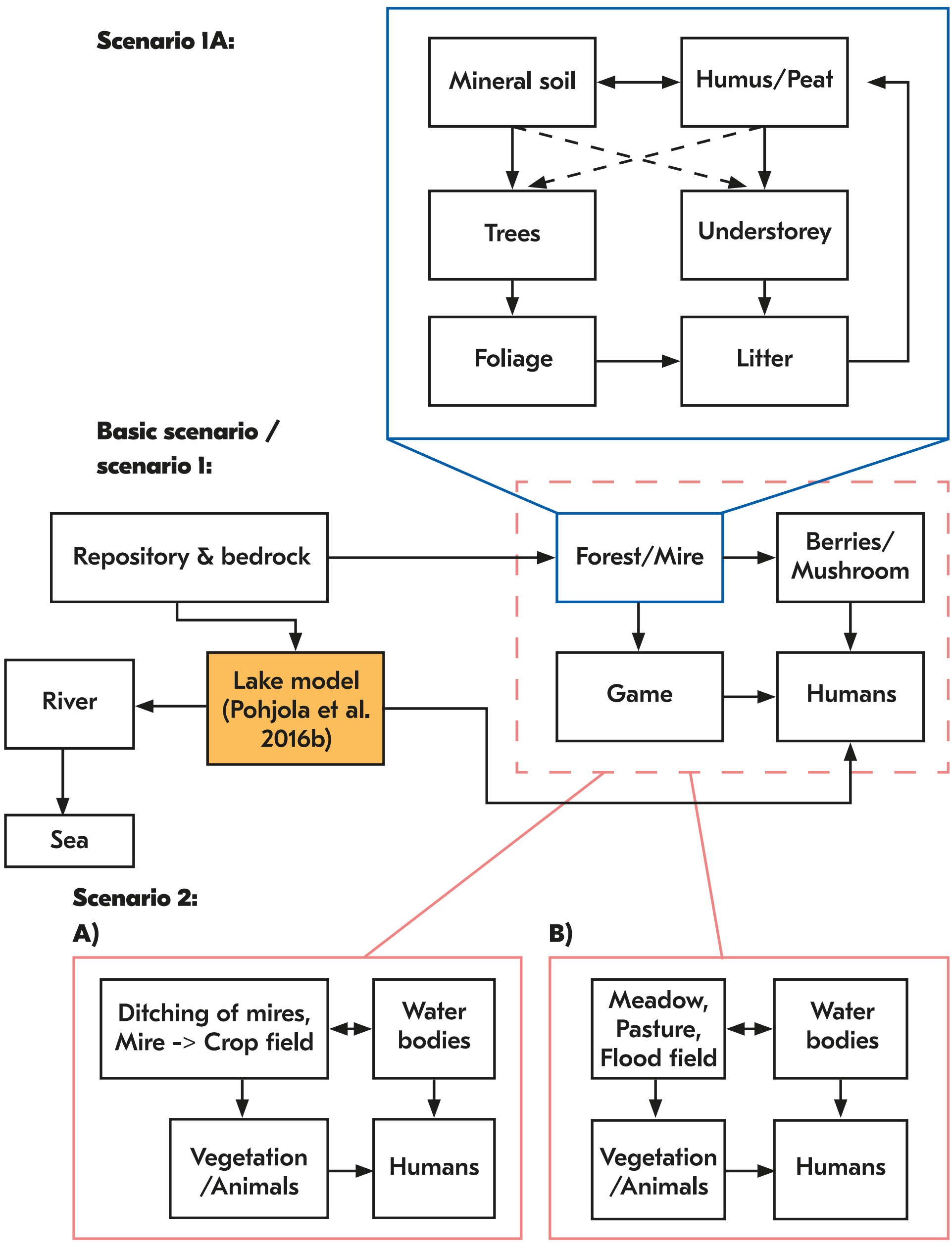

FIGURE 3. Ecosystems for investigation in future research

Facilia AB's Ecolego tool has been used in the design and implementation of the compartment models and in sensitivity analysis. The tool has been developed specifically for the modelling of radionuclide transport and is also used by Posiva and its Swedish counterpart, SKB. The tool is described in (R. Avila et al., 2003. Ecolego – a toolbox for radiological risk assessment. Proc. International Conference on the Protection from the Effects of Ionising Radiation, Stockholm, Sweden, IAEA- CN-109/80, IAEA, 2003, pp. 229–232). From the viewpoint of radionuclide transport, the hydrology is crucial. Therefore, in future it is intended to examine in particular the influence of lake bottom sediments and the land-water interface in various ecosystems (mires, floodplains) using FEM-type modelling tools such as GSFlow by USGS, for example.

In recent years, the research group at the University of Eastern Finland led by Prof. Jukka Juutilainen has studied concentration ratios and observed that a linear model does not adequately describe the behaviour of radionuclides in the biosphere (T. Tuovinen, 2016. Transfer of elements related to the nuclear fuel cycle – Evaluation of linearity in boreal ecosystems. Thesis, University of Eastern Finland). One of the research aims of our group is to ascertain what kinds of effects nonlinear transport coefficients have on the radiation dose received by humans in relation to the set of ecosystem models presented above.

4.3.3.3 Funding

The research was funded in 2015-2016 by the national programme for the Safety of Nuclear Waste Management (KYT). The modelling of terrain development in relation to the topic was earlier funded by Posiva Oy, among others.

4.3.3.4 Publications

Pohjola J, Turunen J, Lipping T, Ikonen A. Probabilistic assessment of the influence of lake properties in long-term radiation doses to humans. Journal of Environmental Radioactivity 2016a; 164, 258-267.

Pohjola J, Turunen J, Lipping T, Ikonen A, Landscape development modeling based on statistical framework. Computers & Geosciences 2014; 62, 43-52.

Pohjola J, Turunen J, Lipping T, Ikonen A. The influence of foodstuff grouping on doses in safety assessments. Proc. Ninth International Conference on Nuclear and Radiochemistry - NRC9 2016b; P2-118.

4.4 University of Helsinki

The University of Helsinki addresses a wide range of research on radiation and nuclear safety. The main units contributing to this field are the radiochemistry laboratory of the Department of Chemistry, the medical physics team of the Department of Physics (jointly with HUS, the Hospital District of Helsinki and Uusimaa) and the accelerator laboratory, and Helsinki Institute of Physics (HIP). A summary of ongoing and planned research is provided in the following chapters.

4.4.1 Environmental radioactivity research at the University of Helsinki

PROFESSOR JUKKA LEHTO, RADIOCHEMISTRY

The Radiochemistry unit at the University of Helsinki has studied environmental radioactivity for more than fifty years. The behaviour of natural radionuclides and those from the fallouts of atmospheric nuclear weapons tests and the Chernobyl accident has been studied in the environment and food chains. The studied artificial radionuclides are primarily the radiocesium, radiostrontium and transuranium elements Np, Pu, Am and Cm. The most important studied natural radionuclides are isotopes of uranium and thorium as well as 226Ra, 210Po and 210Pb. The spectrum of studied samples is wide, covering soil, natural waters, air, vegetation, animals, mining wastes and human samples.

At the moment the radiochemistry unit is focusing on transuranium elements in food chains, natural radionuclides in mining wastes, and the behaviour of long-lived fission products in the biosphere. The transuranium element studies utilise a large sample collection from the past fifty years, the study of which using present modern analytical techniques brings new understanding of their behaviour. The mining industry in Finland is still growing, but studies on the waste left on-site after closure of the mines has not been sufficient. Studies on a number of mining sites by the radiochemistry unit have been pioneering in Finland, and these studies continue. The behaviour of very long-lived radionuclides typical for spent nuclear fuel, such as 79Se and 129I, has been studied in overburden, including mineral soils, peat lands and sediments from lakes and the sea. An essential part in this research has been the study of the effects of microbes on radionuclide behaviour: how they affect the physico-chemical forms of radionuclides and how they retain radionuclides via biosorption and bioaccumulation. These three research lines, transuranium elements, natural radionuclides in mining wastes as well as long-lived fission products in overburden, and the effect on microbes on their behaviour, will be the main research fields in the radiochemistry unit in the coming years. A special emphasis will be on radionuclide transfer and retardation processes and mechanisms in which research in laboratory-scale model experiments play an essential role. Furthermore, novel advanced analytical techniques will be increasingly introduced, and not only to measure radionuclide concentrations but also to determine their chemical forms, or speciation.

The most important partners in environmental radioactivity studies in Finland are STUK, the Finnish Meteorological Institute and the University of Eastern Finland. International cooperation is also an important tool, particularly via the EU CONCERT programme and mutual collaboration with individual institutes, of which active collaboration is ongoing with the Helmholtz Zentrum Dresden-Rossendorf in Germany.

4.4.1.1 Publications

Lusa M, Bomberg M, Aromaa H, Knuutinen J, Lehto J. The microbial impact on the sorption behaviour of selenite in an acidic, nutrient-poor boreal bog. Journal of Environmental Radioactivity 2015; 147, 85-96.

Tuovinen H, Pohjolainen E, Lempinen J, Vesterbacka P, Read D, Solatie D, Lehto J, Behaviour of Radionuclides During Microbially-induced Mining of Nickel at Talvivaara, Eastern Finland. Journal of Environmental Radioactivity 2016; 151, 105-113.

4.4.2. University of Helsinki and Helsinki University Central Hospital Radiation

PROFESSOR SAULI SAVOLAINEN AND ADJUNCT PROFESSOR MIKA KORTESNIEMI, DEPARTMENT OF PHYSICS AND HUS

4.4.2.1 Medical physics in clinical and preclinical research

Molecular radiotherapy (MRT) applies multiple cell-level mechanisms (e.g. receptor binding) to deliver lethal radiation doses selectively to malignant cells. Despite the large number of treated patients and successful clinical trials in recent decades, considerable uncertainties still remain regarding the optimisation of MRT. The dosimetry of MRT is still developing. The key issues to establish are the relationship between administered activity, absorbed radiation dose distribution, clinical response and side effects, and the application of this knowledge to plan more individualised treatments.

We have developed a schema for radiopharmaceutical dosimetry. The schema utilises a partially supervised segmentation method for cell-level image data together with a novel main programme for voxel-based radiation dose simulations. We observed that for 177Lu, radiation crossfire enabled full dose coverage, even if the radiopharmaceutical had accumulated to only 60 per cent of the spheroid cells. This effect was not found with 111In and 125I. Use of these Auger emitters seemed to guarantee that only the cells with high activity uptake will accumulate a lethal amount of dose, while neighbouring cells are spared.

We have computed absorbed radiation dose distributions in a 3D-cultured cell spheroid. The novel cellular-level dosimetric calculation method together with pharmacological studies in different tissue models may enhance the prediction and understanding of dose-response relationships for radiopharmaceuticals used in MRT.

4.4.2.2 Optimisation research combining radiological image quality and radiation dosimetry

Ionising radiation is potentially harmful to health. Accordingly, the fundamental objective of radiation protection is to avoid unnecessary radiation exposure. Currently, more than 50 per cent of the cumulative radiation exposure to patients in diagnostic radiology is contributed by computed tomography (CT). Due to the rapid evolution of multislice CT technology, the increasing performance of CT scanners by improved resolution, speed and coverage has driven clinical applications of CT. As a result, the number and relative contribution of CT examinations in radiology has increased considerably over the past 15 years. Fortunately, from a radiation protection perspective, the methods for dose reduction have also improved along with the overall development of digitalised radiology with X-rays.

Optimisation in diagnostic radiology involves a carefully set balance between diagnostically reliable image quality and coverage in connection with the lowest applicable radiation exposure. The optimisation principle is emphasised in the updated recommendations of the International Commission on Radiological Protection (ICRP). Children are considered a special group in radiological optimisation, due to their longer remaining lifetime and increased sensitivity to ionising radiation.

Recent research is focused on paediatric image quality optimisation and organ dosimetry in digital radiology, with special emphasis on CT imaging. The aspects of image quality and organ dosimetry are approached by both computational and experimental methods, relevant to the actual clinical imaging applications used at Helsinki University Central Hospital in the HUS Medical Imaging Centre, Finland. In addition to the main X-ray modalities of digital radiography, multislice CT, angiography and mammography, emerging applications such as new cone-beam CT scanners are also considered vital parts of the research sub-topics.

The computational methods involve mainly Monte Carlo-based simulations of radiation dose and image quality. The simulations require modelling of X-ray sources, different exposure geometry used in the diagnostic applications, varying and personalised patient anatomy and geometry. Experimental methods utilise medical imaging equipment used with radiation dosimeters (e.g. MOSFET) in connection with human-like (anthropomorphic) test objects (newborn, paediatric and adult models). Such anthropomorphic objects provide realistic yet objective and constant targets for optimisation studies with different imaging equipment – without exposing real patients unnecessarily.

The research methodology can be applied for a vast amount of existing and prospective imaging applications, providing valuable results and effectiveness for optimisation in clinical radiology. The research is driven by true clinical problems in a multiprofessional university hospital environment. The research group includes PhD students within the MATRENA Doctoral Programme of the University of Helsinki, senior scientists, supervisors and professors in medical physics. The research network, consisting of medical physicists, radiation physicists, image processing and modelling scientists, clinical doctors, radiologists, technologists, engineers and industry scientists, ensure the required crossscientific expertise and reinforce the costeffective and influential direction of the research projects. Most research subprojects are carried out in partnership with the Finnish Radiation and Nuclear Safety Authority (STUK).

4.4.2.3 Optimisation-related European- and international-level research activities during the period 2017–2020

Physical dosimetry and anthropomorphic dosimetry are used in cardiac perfusion diagnostics with CT in an ongoing EURAMET Empir project "Metrology for multimodality imaging of impaired tissue perfusion (Grant: PerfusImaging -15HLT05). The project is coordinated by PhysikalischTechnische Bundesanstalt (PTB), in partnership with Laboratoire national de métrologie et d'essais (LNE), NPL Management Limited, Radiation and Nuclear Safety Authority of Finland (STUK), VSL B.V., University of Helsinki and Helsinki University Hospital, King's College London (KCL), Technische Universiteit Delft, VarsinaisSuomen Sairaanhoitopiirin Kuntayhtyma (TUCH) and ZMT Zurich MedTech AG.

Additional H2020 activities include ISADORAINFRAIA "European infrastructure for assessment and optimisation of radiation dose in personalised medicine" which is currently in the second evaluation phase. The project will be coordinated by Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA), in partnership with Elekta Limited, Fundacion para la investigacion del hospital universitario La Fe de la comunidad Valenciana (HULAFE), IBA Dosimetry GMBH, Helsinki University Central Hospital, Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences (IFJ), Fundacion para el fomento de la investigacion sanitaria y biomedica de la comunitat Valenciana (FISABIO), Radiation and Nuclear Safety Authority of Finland (STUK), Institut Curie, Centre Hospitalier Universitaire de Vaud (CHUV) and supported by administrational consultation by AYMING.

A recent international collaboration call is "CT Maestro", which is part of the transnational call for proposals (2017) for "Radiation Protection Research in Europe", coordinated by the University of Vienna in partnership with Katholieke Universiteit Leuven, University Hospital of Lausanne, Helsinki, University Hospital, Karolinska University Hospital and Institut de Radioprotection et de Sûreté Nucléaire.

Further activities to extend optimisation research to deep learning and big data methodology for comprehensive optimisation and risk/benefit quantitation in healthcare has been initiated by the most recent Academy of Finland intent call (RADDESS). This research branch includes collaboration with worldłeading scientists from the US (Duke University) and Switzerland (University of Lausanne).

4.4.2.4 Publications

Sundell V-M, Mäkelä TO, Meaney AJB, Kaasalainen TT, Savolainen SE. Automated daily quality control analysis for mammography in a multi-unit imaging center. Acta Radiologica 2018; (Accepted/In press).

Pekkarinen AJ, Siiskonen T, Lehtinen M, Savolainen SE, Kortesniemi M, Potential occupational exposures in diagnostic and interventional radiology: statistical modelling based on Finnish national dose registry data. Acta Radiologica 2018; (Accepted/In press).

4.4.3 Novel radiation instrumentation for applications

PROFESSOR PETER DENDOOVEN, HELSINKI INSTITUTE OF PHYSICS
DR. TEEMU SIISKONEN, STUK

4.4.3.1 Medical applications

Accurate and reliable radiation measurements are a cornerstone of medical applications that use ionising radiation. In particular in external beam radiotherapy, technical advances in treatment equipment have led to a situation where the traditional measurement methods are no longer capable of providing reliable and accurate dose information. This may, and has, led to a situation where the dose delivery to the tumour can be in error by such a large amount that it threatens the tumour control or may lead to life-threatening complications if healthy tissues surrounding the target volume receive overly large doses.

Accurate, reliable and fast methods that can be applied especially at radiotherapy clinics as well as in laboratory conditions to measure the absolute dose and three-dimensional dose distributions are needed. In the project, new measurement methods are developed, focusing on:

- Real-time position-sensitive detectors for 3D measurements
- Combining absolute dosimetry methods with 3D measurements

4.4.3.2 Safety, Security and Safeguards applications

Good stewardship of nuclear materials and an adequate response to threats that potentially involve nuclear materials are essential to protect people, society and the environment now and far into the future. In order to perform these nuclear safety, security and safeguards (3S) tasks, suitable instrumentation is needed. Finland has a long tradition and high competence in relevant research as well as in understanding the needs of the end-users of this research. Radiation measurements, either done in the field or in the laboratory, are essential in all 3S domains and require continuous research and development. Improvements in detection technology can have big impacts on operational processes. Novel detection solutions are required, for example, due to diminishing personnel resources, ever-changing operational environments and emerging measurement needs. It is foreseen that various operational measurement activities will continue far into the future.

Low-background laboratory measurement techniques are developed to improve environmental surveillance and measurement capabilities for emergency situations.

These include:

- Imaging and coincidence measurement techniques
- Conversion electron and alpha spectrometry with novel detectors
- Compton suppression techniques and anti-cosmic veto detectors

In-field measurements are improved by:

- Novel detector materials and detection concepts
- Internet of Things (IoT)
- Digitalisation
- Automatisation
- Big Data and Data Mining

The following novel instrumentation is being developed for 3S applications:

- passive gamma ray tomography and neutron measurements for the characterization of spent nuclear fuel in the context of the Finnish geological spent fuel repository. As an example of previous developments, passive gamma emission tomography im ages of spent nuclear fuel assemblies at the Finnish nuclear power plants are illustrated in Figure 4.
- improved concepts for alpha radiation threat detection and imaging from a distance via optical means
- integration of gamma ray imaging with active neutron interrogation of unknown objects, promising better detection capabilities of CBRNE threats.

Finnish industry will be strengthened by transferring the knowledge gained to companies for implementation in new commercial products and services.

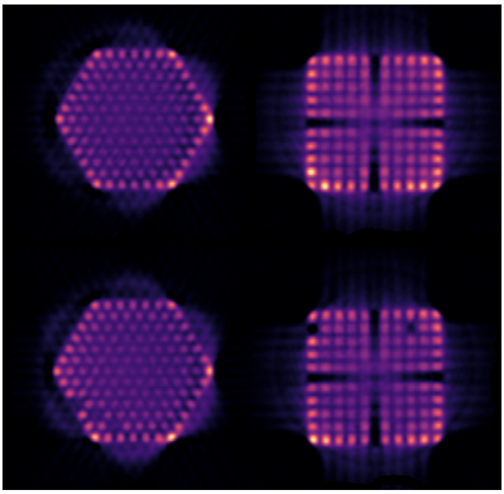

FIGURE 4. Passive gamma emission tomography images of spent nuclear fuel assemblies at the Finnish nuclear power plants. In the bottom row, missing fuel pins can clearly be identified.

4.4.3.3 Publications

Bélanger-Champagne C, Peura P, Eerola P, Honkamaa T, White T, Mayorov M, Dendooven P. Effect of Gamma-Ray Energy on Image Quality in Passive Gamma Emission Tomography of Spent Nuclear Fuel. IEEE Transactions on Nuclear Science 2018.

Tobin SJ, Peura P, Bélanger-Champagne C, Moring M, Dendooven P, Honkamaa T. Measuring spent fuel assembly multiplication in borated water with a passive neutron albedo reactivity instrument. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 2018; 897, 32-37.

Peura P, Bélanger-Champagne C, Eerola P, Dendooven P, Huhtalo E. Thin NaI (Tl) crystals to enhance the detection sensitivity for molten 241Am sources. Applied Radiation and Isotopes 2018; 139, 121-126.

Tobin SJ, Peura P, Bélanger-Champagne C, Moring M, Dendooven P, Honkamaa T. Utility of Including Passive Neutron Albedo Reactivity in an Integrated NDA System for Encapsulation Safeguards. ESARDA Bulletin 2018; 56, 12.

Gädda A, Winkler A, Ott J, Härkönen J, Karadzhinonva-Ferrer A, Koponen P, Luukka P, Tikkanen J, Vähänen S. Advanced processing of CdTe pixel radiation detectors. Journal of Instrumentation 2017; 12, C12031.

4.4.4. Fundamental studies of radiation effects in materials

PROFESSOR KAI NORDLUND, DEPARTMENT OF PHYSICS

The closely collaborating simulation groups of Prof. Kai Nordlund and Doc. Flyura Djurabekova simulate ion, electron, neutron and plasma irradiation effects, electrical arcing and other non-equilibrium effects in all classes of materials. The work is done in close collaboration with experimental groups in the same department and worldwide. Much of the work is done as part of the international collaboration networks associated with the big science facilities ITER, CERN and FAIR. In recent years, the work has resulted on average in about 30 international refereed publications and three PhD theses annually.

A particular focus area of the groups is damage in nuclear reactor (both fission and fusion) materials. This includes gaining insights, starting from the atomic level into the fundamental mechanisms by which neutrons initially create damage in the materials in picosecond time scales, and how this damage evolves over longer timescales to eventually affect the macroscopic property changes of the materials. This work is done as part of the EUROFusion consortium and the Euratom project M4F. Examples of recent results are illustrated in Fig. 5.

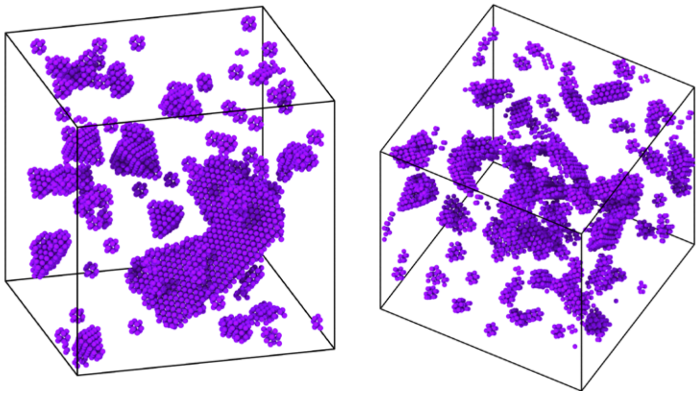

FIGURE 5. Left: radiation damage in a conventional metal, Ni. Right: radiation damage for exactly the same dose in NiFe equiatomic alloys. Due to the random arrangement of atoms in NiFe, the defect structures are smaller in these alloys. Figure Fredric Granberg (University of Helsinki). Reference: Granberg et al., Phys. Rev. Lett. 116, 135504 (2016)

4.4.4.1 Publications

Nordlund K, Zinkle SJ, Sand AE, Granberg F, Averback RS, Stoller R, Suzudo T, Malerba L, Banhart F, Weber WJ, Willaime F, Dudarev S, Simeone D. Improving atomic displacement and replacement calculations with physically realistic damage models, Nature communications 2018; 9, 1084.

Granberg F, Nordlund K, Ullah MW, Jin K, Lu C, Bei H, Wang LM, Djurabekova F, Weber WJ, Zhang Y. Mechanism of radiation damage reduction in equiatomic multicomponent single phase alloys. Phys. Rev. Lett. 2016; 116, 135504.

Nordlund K, Zinkle SJ, Sand AE, Granberg F, Averback RS, Stoller R, Suzudo T, Malerba L, Banhart F, Weber WJ, Willaime F, Dudarev S, Simeone D. Primary radiation damage: a review of current understanding and models, J. Nucl. Mater. 2018; 512, 450.

4.5 University of Eastern Finland

PROFESSOR JUKKA JUUTILAINEN, ASSOCIATE PROFESSOR JONNE NAARALA, PROFESSOR SISKO SALOMAA, DEPARTMENT OF ENVIRONMENTAL AND BIOLOGICAL SCIENCES

Research on the health effects of non-ionising radiation started in the 1980s with studies on the possible health risks of ELF magnetic fields (biological experiments, assessment of human exposure). Concerning ionising radiation, the assessment of environmental radioactivity and experiments on the biological effects of "hot particles" started after the Chernobyl accident. A total of 15 PhD degrees on risks of non-ionising and ionising radiation were completed at UEF between 1990 and 2016.

We use all approaches of environmental health research from exposure assessment and epidemiology to cellular and molecular biology to study the human health risks of radiation. Our research also covers the ecological risks of radiation. Our interests include low-level effects, "non-targeted" effects such as induced genomic instability, the joint effects of multiple environmental agents, and risk assessment.

Our current sources of major funding include the EU Framework Programmes, the Academy of Finland, and the Finnish Research Programme on Nuclear Waste Management. Minor funding has been received from other international and national funding bodies and foundations. The structure of our funding is believed to continue in a similar vein in the near future. We will particularly emphasise the continuation of European collaboration. In the CONCERT European Joint Programme, UEF has been nominated as the national programme manager by the Ministry of Education and Culture, leading the strategic research agenda's development and the integration of European research.

The Agreement on the Consortium on Radiation Safety Research (Cores, www.cores.fi) was signed in 2015. To complement this, STUK and the University of Eastern Finland signed a bilateral agreement on cooperation in 2015. The main joint research areas between STUK and UEF are the health effects of ionising and non-ionising radiations, radiation biology, epidemiology, use of radiation in medicine, radioecology and environmental research. The objective is to bring together multidisciplinary expertise via a joint strategy, joint projects and shared infrastructures, and to use the expertise in education and training to ensure the training of qualified experts in radiation safety. After the phasing out of radiobiology in STUK, radiobiological laboratory equipment was transferred from STUK to UEF. State-of-the-art facilities for cell culture and cell and molecular biology are available as well as access to the animal facilities of UEF. We have a collaborative Radiation Biology Unit at the Cancer Centre of Kuopio University Hospital (KUH), involving a cell biology laboratory next to a linear accelerator. The collaboration with KUH also offers the possibility to obtain samples from radiotherapy or diagnostic radiology patients. We also have measuring instruments covering a wide range of frequencies and wavelengths of non-ionising radiation.

The University of Eastern Finland's Department of Environmental and Biological Sciences is the main educator of experts on environmental health in Finland. Radiation safety (of ionising and non-ionising radiation) is an important part of environmental health. Another important dimension is the education of radiation protection experts as required by the European radiation protection directive. The transposition of BSS (Basic Safety Standards) into national legislation must be done by February 2018. The BSS sets requirements for radiation protection experts acting in different occupations using radiation, such as medical physics. Again, UEF has an important national role in this field of education.

Based on long-term research on non-ionising radiation, UEF has developed high-level expertise in this field, and will utilise this expertise by offering a 20 credit point training programme in non-ionising radiation as part of the Master's Programme in Environmental Health and Technology. The Master's Programme includes a wide selection of courses on exposure assessment, risk assessment, and so on, and is an optimal training framework for students who wish to specialise in risks related to non-ionising radiation. Combined with the 20 credit point course package, it forms an internationally unique opportunity to become an expert in non-ionising radiation.

4.5.1 Non-ionising radiation

4.5.1.1 Extremely low frequency (ELF) magnetic fields (MF)

Research on ELF MFs focuses on biological studies aiming at a breakthrough in understanding the mechanistic basis of the reported health effects of ELF MFs, such as childhood leukaemia, adverse reproductive outcomes and Alzheimer's disease, as well as epidemiological studies with a novel approach for minimal bias and confounding. The biological studies focus on the radical pair mechanism and plausible biological sensors of weak magnetic fields, such as cryptochrome proteins. Interactions with other physical and chemical environmental agents continue to be of major interest. The registry of residential buildings with indoor transformer stations (which we have compiled over the last few years) is an excellent basis for high-quality epidemiological studies on health risks of ELF MFs.

4.5.1.2 Intermediate frequency (IF) electromagnetic fields

Human exposure to IF fields is increasing due to new technologies, but possible health effects are less well known than those of ELF and RF fields. To address the gaps in knowledge, we conduct experimental and epidemiological studies on cancer-related, reproductive, developmental and behavioural/cognitive effects. An important perspective in these studies is the investigation into the frequency dependence of the effects reported/mechanisms found to be valid in the ELF range.

4.5.1.3 Radiofrequency (RF) electromagnetic fields

During this period, RF radiation has lower priority in our research than ELF and IF electromagnetic fields. Based on previous research, our primary focus in the RF range is on nervous system effects and mechanisms, although some research related to cancer risk can still be continued.

4.5.1.4 Static magnetic fields and MRI

The increasing use of magnetic resonance imaging (MRI) has stimulated discussion on the possible health risks of static magnetic fields. MRI exposes patients and medical personnel to a complex mixture of static, low frequency and RF fields. It is generally believed to be safer than X-ray based imaging, but some research findings (e.g. on genotoxicity) have challenged the conventional view. Addressing these concerns with high-quality research is important, and assessment of the possible risks of MRI has high priority in our future research (if funding is available on this topic).

4.5.1.5 Recent publications

Herrala M, Mustafa E, Naarala J, Juutilainen J. Assessment of genotoxicity and genomic instability in rat primary astrocytes exposed to 872 MHz radiofrequency radiation and chemicals. International Journal of Radiation Biology 2018; doi: 10.1080/09553002.2018.1450534

Juutilainen J, Herrala M, Luukkonen J, Naarala J, Hore PJ. Magnetocarcinogenesis: Is there a mechanism for carcinogenic effects of weak magnetic fields? Proceedings of the Royal Society B 2018; 30:1879.

Khan MW, Roivainen P, Herrala M, Tiikkaja M, Sallmen M, Hietanen M, Juutilainen J. A pilot study on the reproductive risks of maternal exposure to magnetic fields from electronic article surveillance systems. International Journal of Radiation Biology 2018; doi: 10.1080/09553002.2018.1439197

Kumari K, Koivisto H, Capstick M, Naarala J, Viluksela M, Tanila H, Juutilainen J. Behavioural phenotypes in mice after prenatal and early postnatal exposure to intermediate frequency magnetic fields. Environmental Research 2018; 162:27-34.

Höytö A, Herrala M, Luukkonen J, Juutilainen J, Naarala J. Cellular detection of 50 Hz magnetic fields and weak blue light: effects on superoxide levels and genotoxicity. International Journal of Radiation Biology 2017; 93:646-652.

Kumari K, Capstick M, Cassara AM, Herrala M, Koivisto H, Naarala J, Tanila H, Viluksela M, Juutilainen J. Effects of intermediate frequency magnetic fields on male fertility indicators in mice. Environmental Research 2017; 157:64-70.

Kumari K, Koivisto H, Viluksela M, Paldanius KMA, Marttinen M, Hiltunen M, Naarala J, Tanila H, Juutilainen J. Behavioral testing of mice exposed to intermediate frequency magnetic fields indicates mild memory impairment. PLOS ONE 2017; 12:e0188880.

Naarala J, Kesari KK, McClure I, Chavarriaga C, Juutilainen J, Martino CF. Direction-dependent effects of combined static and ELF magnetic fields on cell proliferation and superoxide radical production. BioMed Research International 2017; doi: 10.1155/2017/5675086.

4.5.2 Ionising radiation

4.5.2.1 Biological and health effects of ionising radiation

Research on radiation biology, biomarkers and biological dosimetry is related to two main areas: risks from low doses of ionising radiation that are relevant for radiation protection (mechanisms of cancer and non-cancer diseases); and the use of ionising radiation in medicine (exposure of normal tissues in radiotherapy and diagnostics). The risks of high doses of radiation are fairly well known but there are uncertainties on the effects of low doses (less than 100 mGy) and the validity of the extrapolation of health effects from high to low doses (the LNT hypothesis) is in question. In addition to cancer, ionising radiation has been shown to induce other tissue reactions, such as vascular diseases and lens opacities at much lower doses than previously assumed. Another scientific question is individual sensitivity. To obtain better understanding of the risks of low dose radiation, knowledge of mechanisms of radiation action at low doses and low dose rates is needed. In the long term, the objective is to combine mechanistic information and epidemiology into molecular epidemiology. Another approach is development of biology-based risk models. A prerequisite for such approaches is the development of reliable biomarkers (of exposure, dose, disease, susceptibility) and the validation of such biomarkers in populations exposed to ionising radiation. Subjects exposed to medical radiation during diagnostics and radiotherapy are an ideal group for biomarker studies. UEF's objective is to enhance research on radiation biology and biomarkers. To facilitate this aim, UEF has brought together a multidisciplinary network that include scientists from the Department of Environmental and Biological sciences, the Clinical Medicine Unit, University Hospital (Cancer Centre, Vascular Surgery Unit), the Biobank of Eastern Finland and ISLAB clinical laboratory, as well as biomarker researchers from several EU countries. Good practice and guidance for radiation biomarker studies were developed as part of the biobanking activities of the Euratom-funded OPERRA project (Open project for European radiation research area).

A particular focus in radiation biology is radiation-induced genomic instability. We aim at understanding the mechanisms and health relevance of induced genomic instability. The approach is mainly in vitro studies, and a systems biological approach is also being developed.

4.5.2.2 Recent publications

Averbeck D, Salomaa S, Bouffler S, Ottolenghi A, Smyth V, Sabatier L. Progress in low dose health risk research: Novel effects and new concepts in low dose radiobiology. Mutation Research. Reviews in Mutation Research 2018; 776:46-69.

Hamada N, Salomaa S, Dörr W. Towards tailoring radiation protection strategies at an individual level. International Journal of Radiation Biology (Sept 2018)

Salomaa S, Niwa O, Brooks AL. Summary of the Bill Morgan Memorial Symposium Part 2: low dose epidemiology. International Journal of Radiation Biology 2017; 93:1118-1120.

Salomaa S, Jourdain JR, Kreuzer M, Jung T, Repussard J. Multidisciplinary European low dose initiative: an update of the MELODI program. International Journal of Radiation Biology 2017; 93:1035-1039.

Huumonen K. Studies on Genomic Instability Induced by Radiation and Chemicals. 2016; PhD Thesis. University of Eastern Finland.

4.5.3 Radioecology

Radioecological research aims at understanding transfer of radionuclides in ecosystems, as well as assessment of radiation effects on wildlife/ecosystems.

Our research focuses on developing improved radioecological modelling based on adequate theoretical and empirical understanding of the uptake of elements into organisms. Applicability to Finnish forest and water ecosystems is central in this research, with particular focus on the assessment of the risks of the final disposal of spent nuclear fuel.

Another focus area is the assessment of radiation effects on non-human biota. The radiation sensitivity of species varies a lot, but the biological basis of this variability is still largely unknown. Therefore, we aim at conducting experimental and field studies on inter- and intra-species radiation sensitivity and the underlying molecular mechanisms, and developing sensitive methods to detect effects on wildlife species exposed to low levels of radiation. Apart from studies on individual species, an important goal is to understand radiation effects on ecosystems; this will be addressed using cosm (microcosm, mesocosm) experiments.

4.5.3.1 Recent publications

Tuovinen TS, Kolehmainen M, Roivainen P, Kumlin T, Makkonen S, Holopainen T, Juutilainen J. Nonlinear transfer of elements from soil to plants: impact on radioecological modeling. Radiation and Environmental Biophysics 2016; 55:393-400.

Tuovinen TS, Kasurinen A, Häikiö E, Tervahauta A, Makkonen S, Holopainen T, Juutilainen J. Transfer of elements relevant to nuclear fuel cycle from soil to boreal plants and animals in experimental meso- and microcosms. Science of the Total Environment 2015; 539: 252-261.

4.5.4 Kuopio University Hospital

CHIEF PHYCICIST JAN SEPPÄLÄ, KUH CANCER CENTRE

Kuopio University Hospital (KUH) is closely involved in radiation research, mainly focusing on optimising treatment delivery techniques and minimising normal tissue irradiation in radiotherapy, developing new imaging methods and protocols in radiology, and evolving and enhancing new imaging modalities in nuclear medicine. The more detailed research projects related to medical use of radiation are described below.

4.5.4.1 Radiotherapy

The clinical use of modern radiotherapy (RT) techniques, such as volumetric-modulated arc therapy (VMAT) and stereotactic body radiotherapy (SBRT) has increased tremendously in recent years. The new techniques have allowed the use of high radiation doses given in fewer fractions, known as hypofractionation. The long-term effects of the new treatment modalities have been investigated and reported by our radiotherapy centre. In addition, the Centre of Oncology has developed new methods for RT for breast cancer radiation therapy. The developed techniques enable reducing the doses of normal tissues, especially the heart and lungs. In addition, the importance and management of the risks associated with the new techniques has been investigated with systematic dosimetric measurements. The new RT treatment modalities are unfortunately also associated with increased volumes of low doses, and the dose calculation accuracies and possible harmful effects of these low doses have been under investigation in our research group.

Currently, neither the individual variation in radiation sensitivity, the functional variations within the patient anatomy nor the radiobiological aspects of treatment prolongation are accounted for in the RT treatment planning and decision-making of the dose prescription of a patient. In our research projects the radiobiological and biological aspects will be incorporated into the radiotherapy treatment planning systems. This will enhance and individualise the RT dose prescriptions and the well-functioning areas can be avoided and protected from radiation injury. This will hypothetically increase tumour control and thus increase the cancer patient's chances of survival and decrease the normal tissue toxicities resulting from RT treatments.

4.5.4.1.1 Recent publications

Koivumäki T, Fogliata A, Zeverino M, Boman E, Sierpowska J, Moeckli R, Vallet V, Cozzi L, Heikkilä J, Väänänen A, Vuolukka K, Sillanmäki S, Seppälä J. Dosimetric evaluation of modern radiation therapy techniques for left breast in deep-inspiration breath-hold. Phys Med. 2018 Jan; 45:82-87.

Fogliata A, De Rose F, Franceschini D, Stravato A, Seppälä J, Scorsetti M, Cozzi L. Critical Appraisal of the Risk of Secondary Cancer Induction From Breast Radiation Therapy With Volumetric Modulated Arc Therapy Relative to 3D Conformal Therapy. Int J Radiat Oncol Biol Phys. 2018 Mar 1;100(3):785-793.

Koskela K, Palmgren JE, Heikkilä J, Virsunen H, Sailas L, Auvinen P, Seppälä J, Kataja V. Hypofractionated stereotactic body radiotherapy for localized prostate cancer - first Nordic clinical experience. Acta Oncol. 2017 Jul;56(7):978-983.

Koivumäki T, Tujunen J, Virén T, Heikkilä J, Seppälä J. Geometrical uncertainty of heart position in deep-inspiration breath-hold radiotherapy of left-sided breast cancer patients. Acta Oncol. 2017 Jun;56(6):879-883.

Seppälä J, Suilamo S, Tenhunen M, Sailas L, Virsunen H, Kaleva E, Keyriläinen J. Dosimetric Comparison and Evaluation of 4 Stereotactic Body Radiotherapy Techniques for the Treatment of Prostate Cancer. Technol Cancer Res Treat. 2017 Apr;16(2):238-245.

Fogliata A, Seppälä J, Reggiori G, Lobefalo F, Palumbo V, De Rose F, Franceschini D, Scorsetti M, Cozzi L. Dosimetric trade-offs in breast treatment with VMAT technique. Br J Radiol. 2017 Feb;90(1070):20160701

Seppälä J, Voutilainen H, Heikkilä J, Vauhkonen M. Surface doses of FFF and VMAT dose delivery for breast cancer. Physics & Imaging in Radiation Oncology. 2:17-22, 2017.

Heikkilä J, Seppälä J, Nuutinen J, Vanne A, Lahtinen T. A photographic technique for quick assessment of mechanical isocenter of a linear accelerator. Technical Innovations and Patient Support in Radiation Oncology. June 2017; 2: 1-4.

Koivumäki T, Heikkilä J, Väänänen A, Koskela K, Sillanmäki S, Seppälä J. Flattening filter free technique in breath-hold treatments of left-sided breast cancer: The effect on beam-on time and dose distributions. Radiother Oncol. 2016 Jan;118(1):194-8.

4.5.4.2 Radiology

The additional diagnostic benefits of various radiology imaging methods have been investigated by several research projects in the Department of Radiology. Since 2006, imaging studies of all breast cancer patients have been screened and an additional benefit of diagnostic imaging has been assessed. The aim is to find out whether breast cancer has been observed or not. Another aim is to develop breast cancer screening overall. The project is ongoing and is currently in the data collection phase. This project involves one postdoc researcher and one PhD student.

A stroke research project has investigated the predictive value of various CT perfusion parameter maps of the brain (with different thresholds) for thrombectomy patients. Maps are automatically generated by using an artificial intelligence algorithm. This part is in the reporting stage. The second part of the thesis examines the utility of interventional radiological thrombectomy in elderly patients over the age of 80. This project involves one PhD student.

Research projects on the possible replacement of CT imaging by new magnetic resonance (MR) imaging techniques have also been widely investigated by our research groups. For example, a routine monitoring of aorta dilation is currently performed with CT imaging. One research project is focused on replacing the CT and using 4D-flow measurement with MR imaging to find predicting factors for defining patient follow-up frequency. The research work is in the recruitment phase and one PhD student is working on the project.

One research topic is focused to determine radiologists' eye doses in various CT and X-ray procedures. The aim is to find out how well a person-metering device can estimate the eye dose and whether there is a connection between a radiologist's eye dose and the patient's radiation dose. This work is in the reporting phase. The dosimetry project also includes calibrating MOSFET semiconductor detectors and the determination of patient dosage in CT and X-ray examinations.

Research projects are also underway to enhance the image quality of CT imaging devices. They include comparing the image quality of various iterative reconstruction methods of the head CT, investigating image quality by various imaging parameters using dual energy CT and contrast agents for pulmonary embolisation, and comparing the image quality produced by different CBCT devices for sinus imaging.

4.5.4.2.1 Recent publications

Sipari S, Iso-Mustajärvi M, Matikka H, Tervaniemi J, Koistinen A, Aarnisalo A, Sinkkonen ST, Löppönen H, Dietz A. Cochlear Implantation With a Novel Long Straight Electrode: the Insertion Results Evaluated by Imaging and Histology in Human Temporal Bones. Otol Neurotol. 2018 Oct;39(9):e784-e793.

Iso-Mustajärvi M, Matikka H, Risi F, Sipari S, Koski T, Willberg T, Lehtimäki A, Tervaniemi J, Löppönen H, Dietz A. A New Slim Modiolar Electrode Array for Cochlear Implantation: A Radiological and Histological Study. Otol Neurotol. 2017 Oct;38(9):e327-e334.

4.5.4.3 Nuclear medicine

The research projects at the Department of Nuclear Medicine have recently been related to radiation respiratory gating and myocardiac perfusion imaging with SPECT and PET imaging devices. The myocardial studies have included new 3D printed thorax phantoms for use in nuclear medicine imaging in collaboration with Savonia University of Applied Sciences. The respiratory gating studies on PET imaging includes research collaboration with Siemens Healthcare. New reconstruction methods used in PET and SPECT imaging are being developed in collaboration with the University of Eastern Finland's Department of Applied Physics. In addition, brain metabolic changes in sleep apnoea – amyloid PET – imaging with 11C-PiB has been studied in detail.

4.5.4.3.1 Recent publications

Kortelainen MJ, Koivumäki TM, Vauhkonen MJ, Hedman M, Kärkkäinen S, Quintero JN, Hakulinen MA. Respiratory Motion Reduction with a Dual Gating Approach in Myocardial Perfusion SPECT: Effect on Left Ventricular Functional Parameters. Journal of Nuclear Cardiology, [Epub ahead of print], 2017

Koivumäki T, Nekolla S, Fürst S, Loher S, Vauhkonen M, Schwaiger M, Hakulinen M. Integrated bioimpedance – ECG gating technique for respiratory and cardiac motion compensation in cardiac PET. Physics in Medicine and Biology 2014; 59, 6373-6385.

Sillanmäki S, Koivumäki T, Laitinen TM, Hakulinen M, Hedman M, Laitinen T. BMI influence on the reproducibility of phase analysis in comparison with novel echocardiographic dyssynchrony estimation methods. Nuclear Medicine Communications 2016; 37(7):767-74.

Kortelainen MJ, Koivumäki TM, Vauhkonen MJ, Hakulinen MA. Dependence of left ventricular functional parameters on image acquisition time in cardiac-gated myocardial perfusion SPECT. Journal of Nuclear Cardiology 2015; 22(4):643-51.

4.5.5 Institute of Dentistry – radiation-induced changes in oral mucosa, jaw bone and saliva

PROFESSOR ARJA KULLAA, ORAL MEDICINE INSTITUTE OF DENTISTRY

The aim of our research project is to investigate in vivo the process of irradiation-induced changes in both jaw bone and oral mucosa. Moreover, salivary biomarkers are explored. In order to avoid or decrease irradiation-induced complications, it is of vital importance to get more insight into the histological and molecular background of the effects of irradiation on oral soft and hard tissues. Furthermore, the aim is to find salivary biomarkers of cancer patients for diagnostics and disease monitoring after radiotherapy.

4.5.5.1 Publications

Asikainen P, Mikkonen JJW, Kullaa AM. Surface Morphology of Superficial Cells in Irradiated Oral Mucosa: An Experimental Study in Beagle Dog. Ultrastructural Pathology. 2014; 38: 268-72.

Singh SP, Parviainen I, Dekker H, Schulten EAJM, ten Bruggenkate CM, Bravenboer N, Mikkonen JJ, Turunen M, Koistinen AP, Kullaa AM. Raman microspectroscopy demonstrates alterations in human mandible bone after radiotherapy. J Anal Bioanal Tech 2015; 6, 276-79.

Asikainen P, Dekker H, Sirviö E, Mikkonen JJ, Schulten EAJM, Bloemena E, Koistinen A, ten Bruggenkate CM, Kullaa A. Radiation-induced changes in the microstructure of epithelial cells of the oral mucosa a comparative light and electron microscopic study. J Oral Path Med 2017; 46, 1004-1010.

Lampi T, Dekker H, ten Bruggenkate CM, Schulten EAJM, Mikkonen JJW, Koistinen A, Kullaa AM. Acid-etching technique of non-decalcified bone samples for visualizing osteocyte-lacuno-canalicular network using scanning electron microscope. Ultrastruct Pathol 2018; 42, 74-79.

Asikainen PJ, Kullaa AM, Koistinen A, Schulten EAJM, Ten Bruggenkate CM. A phd completed. The effect of radiotherapy on oral mucosa cell morphology. Ned Tijdschr Tandheelkd. 2018; 125, 169-171.

Heinonen V, Ruotsalainen TJ, Paavola L, Mikkonen JJW, Asikainen P, Koistinen AP, Kullaa AM. Alveolar bone remodeling after tooth extraction in irradiated mandible: An experimental study with canine model. Ultrastruct Pathol 2018; 42, 124-132.

Mikkonen JJW, Singh SP, Akhi R, Salo T, Lappalainen R, Gonzalez-Arriagada WA, Ajudarte Lopes M, Kullaa A, Myllymaa S. Potential role of nuclear magnetic resonance spectroscopy to identify salivary metabolite alterations in patients with head and neck cancer. Oncol Letter 2018 (in press)

Ukkonen H, Vuokila S, Dekker H, Mikkonen JJW, Asikainen P, Bruggenkate C, Schulten EAJM, Koistinen A, Bloemena E, Arja M. Kullaa, Singh SP. Molecular structural changes of irradiated oral epithelium studied by FTIR spectroscopy. 2018 (manuscript)

4.6 University of Jyväskylä

PROFESSOR PAUL GREENLEES, DEPARTMENT OF PHYSICS

4.6.1 Application of state-of-the-art nuclear spectroscopic techniques to problems in safety, security, safeguards and surveillance

4.6.1.1 Introduction

Progress in basic nuclear physics research is closely intertwined with advances in detection of ionising radiation, and in associated analysis techniques. In nuclear structure research, where the basic goal is to obtain a better understanding of the interaction of nucleons in the nucleus, the information concerning the properties of the nucleus is mainly obtained through alpha, beta, gamma, electron and neutron spectroscopy (or indeed a combination of several of these).

In order to study nuclei at the extremes of the nuclear chart, where new and interesting phenomena are likely to be found, it is usually necessary to detect an extremely weak signal in an overwhelming background of radiation from other processes or nuclei which are not of interest. Selection of the events of interest requires state-of-the-art instrumentation for radiation detection and advanced analysis techniques and algorithms. Exploitation of multi-parameter data acquisition systems with high data rates and simultaneous detection of several radiation types is commonplace.

FIGURE 6. A large volume 36-fold segmented germanium detector mounted above a phantom used to investigate the methods to improve background suppression in full-body counting experiments.

Many of the detection systems currently used in the fields of radiation safety, security, safeguards (3S) and surveillance rely on measurements of a single parameter at a time, and can involve long measurement periods and/or significant background from unwanted radiation. Often this means that the minimum detectable activity (MDA) is relatively high, or that the reliability of radioisotope identification is compromised due to the presence of background.

It is often possible to reduce the MDA or measurement times and increase the reliability of identification through application of the advanced techniques developed in fundamental nuclear physics research.

4.6.1.2 Aims and methods

The Nuclear Spectroscopy group at JYFL has significant experience and expertise in the use and development of modern radiation detection and data acquisition techniques, along with simulation of detector characteristics and analysis techniques. It is envisaged that this expertise will be exploited to develop improved instrumentation for applications in the fields of 3S and in health and environmental surveillance. JYFL has already collaborated with STUK in a number of projects of this type, for example in the use of gamma-gamma coincidence techniques to better identify activities found in aerosol particulate filters and to reduce the MDA in such measurements (Konki et al.). An additional example was an investigation of the use of segmented germanium detectors and pulse-shape analysis of digitised waveforms in order to improve suppression of background in full-body counting experiments (see figure below). This work resulted in the production of a research training report and an MSc thesis at JYFL (P. Hallikainen, MSc JYFL 2016).

Under an extension to the agreement of the University of Jyväskylä to join the Finnish Consortium for Radiation Safety Research, equipment including the PANDA (PArticles and Non-Destructive Analysis) device was transferred to JYFL. PANDA can be used to make position-sensitive measurements of aerosol particulate filters and is sensitive to alpha and gamma radiation. Future projects include improvement of the PANDA system to enable sensitivity to beta activities and conversion electrons, use of coincidence techniques and standardised list mode data to improve measurements in STUK's VAM laboratory, and investigation of the possibilities to produce mobile and versatile detection systems for use in-field.

4.6.1.3 Funding

To date, most funding for these projects has come from the budgets of JYFL and STUK. In future, project and programme grants from the Academy of Finland will be applied for. In addition, STUK-related research is now mentioned as a new opening in the planning documents of the Faculty of Science and Mathematics.

4.6.1.4 Publications

Konki J, Greenlees PT, Jakobsson U, Jones P, Julin R, Juutinen S, Ketelhut S, Hauschild K, Kontro R, Leppänen A-P, Lopez-Martens A, Mattila A, Nieminen P, Nyman M, Peräjärvi K, Peura P, Rahkila P, Ruotsalainen P, Sarén J, Scholey C, Sorri J, Toivonen H, Turunen J, Uusitalo J, Comparison of gamma-ray coincidence and low-background gamma-ray singles spectrometry. Applied Radiation and Isotopes 2012; 70; 392-396. https://doi.org/10.1016/j.apradiso.2011.10.004

4.6.2 Total gamma-ray absorption measurements for reactor decay heat simulations

4.6.2.1 Introduction

The products from the fission process in an operational nuclear reactor are neutron-rich, beta radioactive nuclei whose decay continues even after the fission process is stopped. Approximately 8 per cent of the thermal energy released from a reactor is generated by the decay of fission products. Simulation of the decay heat is possible on the basis of independent fission yield measurements and data concerning the decay properties of individual radionuclides.

The accuracy of the simulations is limited by the simple fact that the detailed decay properties of individual nuclides are not sufficiently well known. Integral measurements carried out at reactors are not in complete agreement with the simulated results. The nuclear decay energy is shared between the emitted beta particles, the antineutrino and the gamma rays emitted following the population of excited nuclear states in the beta decay process. The absorption processes for beta particles and gamma rays in the reactor are different, and the energy taken by the antineutrinos does not remain in the reactor. Due to these facts, the measurement of atomic masses can only give an upper limit for the decay heat generated.

In 2007, the Nuclear Energy Agency of the OECD published a report in which an analysis was made of the most important nuclides relevant for decay heat and in which a prioritised list of nuclides whose decay properties should be measured was presented [NEA No. 6284 (https://www.oecd-nea.org/science/wpec/volume25/volume25.pdf)].

4.6.2.2 Aims and methods

The total energy released in the beta decay of fission products and also the ratio of beta/gamma-ray contributions to decay heat can be determined using the technique of Total Gamma Absorption Spectrometry (TAGS). In such measurements, the goal is not to measure individual gamma rays, but rather the total energy emitted by gamma rays in the cascade following the population of excited states by beta decay.

JYFL has participated as part of an international collaboration to develop instrumentation for TAGS measurements of the beta decay properties of critical fission products in the NEA/WPEC-25 priority list. Institutes involved in the TAGS project:

- Instituto de Fisica Corpuscular (CSIC-Universitat de Valencia), Apartado de Correos 22085, E-46071 Valencia, Spain
- Centro de Investigaciones Energéticas Medioambientales y Tecnólogicas, E-28040 Madrid, Spain
- University of Surrey, Department of Physics, Guildford GU2 7XH, United Kingdom
- University of Jyväskylä, Department of Physics, P.O. Box 35, FI-40014 University of Jyväskylä, Finland
- Universitat Politecnica de Catalunya, E-08028 Barcelona, Spain
- Nuclear Engineering Division, Argonne National Laboratory, Argonne, Illinois 60439, USA
- NNDC, Brookhaven National Laboratory, Upton, New York 11973, USA
- Institute of Nuclear Research of the Hungarian Academy of Sciences, H-4001, Debrecen, Hungary
- National Physical Laboratory, Teddington, TW11 0LW, United Kingdom
- SUBATECH, CNRS/IN2P3, Université de Nantes, Ecole des Mines, F-44307 Nantes, France
- Petersburg Nuclear Physics Institute, RU-188300 Gatchina, Russia
- Instituto Estructura de la Materia, IEM-CSIC, Serrano 123, E-28006 Madrid, Spain

In a typical TAGS measurement, the nuclide of interest is implanted inside a gamma-ray detector which effectively has 100 per cent efficiency for detection of gamma rays, in front of a detector for beta particles that is also placed inside the gamma-ray detector. In order to “trigger” the measurement of gamma rays, a coincidence with the detection of beta particles is required. In this way, it is possible to measure the total energy emitted in a single beta decay event. Performing the measurement in this manner also ensures that the energy of the emitted beta particle does not contribute to the total gamma-ray energy detected. In JYFL, the detector used for TAGS measurements is based on scintillator technology, which allows a highly efficient detector to be built at reasonable cost.

An additional but important part of the measurements is to separate the individual fission products such that only a single isotope is brought to the implantation point inside the detector. In order to separate individual isotopes, a mass resolving power of M/dM = 50000 or greater is required, which far exceeds that achievable with ordinary magnetic fields (e.g. a simple dipole magnet). The most important contribution of the IGISOL group at JYFL is to realise this part of the measurements. The IGISOL group has expertise in the use of so-called “Penning Traps”, of which JYFLTRAP is an example. The mass resolving power of such traps is such that they can be used for high-precision mass measurements or to purify a beam of ions down to a single isotopic species. In the future, sufficient resolving power for purification purposes will be achievable with MR-ToF (Multi-Reflection Time-of-Flight) devices, which are simpler to operate. Such a device is currently under construction at JYFL.

The measurements have shown that simulations based on reliable nuclear data give better agreement with the integral measurements from reactors [Algora et al., PRL 105, 202501, https://doi.org/10.1103/PhysRevLett.105.202501]. As can be seen from the published manuscripts, the measurements are not only restricted to those nuclides on the NEA priority list.

4.6.2.3 Funding

For the main part, the developments at JYFL have been funded through the department budget. In order to carry out the measurements at JYFL, the participants have also received support from EU projects (ENSAR, ERINDA, CHANDA).

4.6.2.4 Recent publications

Rice S, et al., Total absorption spectroscopy study of the -decay of 86Br and 91Rb. Phys. Rev. C 2017; 96, 014320; https://doi.org/10.1103/PhysRevC.96.014320

Guadilla V, et al., Experimental study of 100Tc -decay with total absorption -ray spectroscopy. Phys. Rev. C 2017; 96, 014319. https://doi.org/10.1103/PhysRevC.96.014319

Tain JL, et al., Enhanced -Ray Emission from Neutron Unbound States Populated in -Decay, Physical Review Letters 2015; 115 062502; https://dx.doi.org/10.1103/PhysRevLett.115.062502

Zakari-Issoufou A-A, et al.: Total Absorption Spectroscopy Study of 92Rb Decay: A Major Contributor to Reactor Antineutrino Spectrum Shape, Physical Review Letters 2015; 115 102503; https://dx.doi.org/10.1103/PhysRevLett.115.102503

Algora A, et al., Total Absorption Study of Beta Decays Relevant for Nuclear Applications and Nuclear Structure. Nuclear Data Sheets (2014); 120, 12 – 15 https://dx.doi.org/10.1016/j.nds.2014.06.129

Algora A, et al., Decay heat studies for nuclear energy. Hyperfine Interact 2014; 223: 245; https://doi.org/10.1007/s10751-012-0623-6

Jordan MD, et al., Total absorption study of the -decay of 102,104,105Tc. Phys. Rev. C 2013; 87, 044318

Algora A et al., Reactor Decay Heat in 239Pu: Solving the -Discrepancy in the 4–3000-s Cooling Period, Phys. Rev. Lett. 105, 202501; https://doi.org/10.1103/PhysRevLett.105.202501

Algora A, et al., Improvements on decay heat summation calculations by means of total absorption gamma-ray spectroscopy measurements. J. Korean Phys. Soc. 2011; 59 1479 - 1482.

Tain JL, et al., Beta decay studies of neutron rich nuclei using total absorption gamma-ray spectroscopy and delayed neutron measurements. J. Korean Phys. Soc. 2011; 59 1499 - 1502.

4.6.3 Investigation of applicability of MR-ToF based isotope separation for production of calibration sources

4.6.4.1 Introduction

In order to verify adherence to the Comprehensive Nuclear Test Ban Treaty, the Comprehensive Nuclear Test Ban Treaty Organisation (CTBTO) runs an International Monitoring System to detect possible clandestine nuclear tests or releases. In a nuclear test, gases such as xenon can escape to the atmosphere and be transported over large distances. By collecting air samples, and searching for the decay signatures of isotopes such as 131mXe, 133mXe, 133Xe and 135Xe, it is possible to detect and locate nuclear tests. Calibration of the monitoring network requires samples of the isotopes listed above to be transported to the measurement stations. In a previous collaboration between JYFL and STUK, a system to produce, isolate and contain pure samples of 131mXe and 135Xe was developed.

4.6.4.2 Aims and methods

In the previous work, the of Xe isotopes were produced by proton-induced fission of a natural uranium target at the IGISOL facility. The isotopes of interest were then separated using the Penning Trap, in a similar manner as described above for the TAGS measurements. The separated ions were then implanted into a foil, and subsequently converted back into a gas and bottled in a so-called "foil-to-gas converter". The bottled samples could then in principle be transported around the world to be used in calibration of the measurement network.

In the near future, the MR-ToF mass spectrometer will be developed at JYFL. As described above, the MR-ToF device will be simpler and faster to operate than the Penning Trap. It is envisaged that an investigation will be made of the suitability of the MR-ToF device to separate the isotopes and isomers of interest, along with other isotopes of potential interest for CTBTO and other organisations.

4.6.4.3 Funding

Once again, these development projects were mainly funded through the budgets of JYFL and STUK, but in the case of Xe samples future production could be funded via an official contract with the CTBTO.

4.6.4.4 Recent publications

Peräjärvi K, et al., Production of pure samples of 131mXe and 135Xe. Applied Radiation and Isotopes 2013; 71, 34-36; https://doi.org/10.1016/j.apradiso.2012.09.007

4.7 University of Oulu

PROFESSOR JUHA RÖNING, COMPUTER SCIENCE AND ENGINEERING

At the University of Oulu there are some quite diverse activities in the radiological area, stemming from autonomous robotics research and their possibilities to monitor and survey contaminated environments to adjust the effectiveness of radiological examinations and their justifications. There is also interest in following the effects of environmental and low dose radiation on molecular biology of cells and viruses.

4.7.1 UAS and RN within Nordic R&D: Nordic unmanned aerial monitoring platforms

PROFESSOR JUHA RÖNING, BIOMIMETICS AND INTELLIGENT SYSTEMS GROUP

4.7.1.1 Introduction

With the developments taking place in aerial imaging and advancements in battery technologies, UAVs have become cheaper and much more viable in performing large-scale radiological data collection missions. Also, the weight of sensitive radiation detection sensors and other onboard hardware has reduced significantly.

Recent multicopters can fly in very challenging environments with high positional accuracy. Localisation of radiation sources can be performed accurately and safely, at least in outdoor environments. Cheaper and more advanced UAVs also mean less expenses for surveying contaminated environments. However, lightweight yet sensitive radiation sensors are still expensive and need to be protected against crash landings.

A collaboration forum has been created for the Nordic countries as an extension of the NORDUM seminar. This forum can be used to improve cooperation, standardisation and a common strategy.

This research project is part of a large international research effort to identify the capabilities of unmanned vehicle utilisation in radiation incidents and maintenance works. This is related to the wider application scope of collaborative mobile robots (http://www.eurathlon.eu/ and https://eu-robotics.net/robotics_league/erl-emergency/about/index.html).

4.7.1.2 Objectives

With the coming of UAVs, new possibilities for radiological surveys have arisen. UAVs can be used as a supplement to existing measurement capabilities. UAVs makes it possible to make fast measurements in potentially hazardous areas without causing danger to humans. The project makes a first approach to cover and compare different systems and approaches for the use of UAVs in the Nordic countries. The project shows that all Nordic countries have UAVs projects but different approaches, each with different benefits.

4.7.1.3 Materials and methods

The exercises are multiple scenarios with one or several different radiation sources to be located and measured. During the first trials in Norway (2016), the exercise consisted of three different scenarios with different radiation sources and obstructions. The radiation sources used were Cs-137, U-238, Am-241, Eu-152, Co-60, Pu-238 and Sr-90. The sources were hidden in the environment and had different activities in different scenarios. The 2017 exercise took place in Björka from 31 October. The 2018 exercise is planned as a collaborative effort between the Nordic countries and Russia.

4.7.1.4 Financial support

This research project is financed by NKS along with grants for the period of 2016-2017.

4.7.1.5 Publications

Gårdestig M, Tazmini K, Robøle D, Drefvelin J, Röning J, Kauppinen M, Östlund K. Nordic Exercise for Unmanned Systems. Final Report from the NKS-B NEXUS activity. NKS-407, April 2018. ISBN 978-87-7893-496-3.

4.7.2 Justification and effectiveness of radiological examinations

HELJÄ OIKARINEN, MD, PHD AND OSMO TERVONEN, PROFESSOR
DEPARTMENT OF DIAGNOSTIC RADIOLOGY, OULU UNIVERSITY HOSPITAL

4.7.2.1 Introduction

The appropriate use of different radiological examinations is important both medically and economically. In particular, justification must always be considered with examinations using ionising radiation due to the possibility of radiation-promoted carcinogenesis. Due to longer life expectancy, the risk is higher in patients aged approximately 35 or younger.

Developing organs are also sensitive to radiation. Justification includes consideration of all alternative procedures requiring no exposure to radiation, i.e. it is important to utilise ultrasonography (US) or magnetic resonance imaging (MRI) whenever possible. Referrers and practitioners as well as patients are involved in the justification process. According to international recommendations and legislation, patients should be provided with sufficient information to allow them to make an informed decision.

The global radiation burden has been increasing. Although the risk to a single individual is small, concern is related to long-term public health problems. Radiography examinations are by far the most common examinations exposing people to radiation. However, computed tomography (CT) induced dose accounts for approximately 60 per cent of the collective effective dose in Europe.

Every imaging examination should have an effect on the diagnosis or treatment of the patient. However, there has been a suspicion that up to 30–50 per cent of examinations might be inappropriate. There may be unjustified or unnecessary imaging, or the examinations selected may not be optimal. We have previously found that at Oulu University Hospital, about 30 per cent of the CT examinations performed on young patients – and about 70 per cent of lumbar spine CTs – have been unjustified. Studies related to appropriateness are sparse or they focus on specific diseases. Publications of efforts to improve appropriateness are also rare. Furthermore, it is suspected that patients do not receive proper information in connection with examinations exposing them to radiation. Nevertheless, there is a lack of comprehensive studies regarding the information provided or expectations.

4.7.2.2 Purpose

The purpose of our studies is to enhance the appropriateness of imaging for the benefit of patients. This may also decrease exposure to radiation and have economic relevance. As far as radiation is concerned, it is essential to focus on children and young adults and on examinations that are common and that expose patients to higher doses or where radiation is directed to areas of radiosensitive organs.

Regarding the studies of justification, the purpose is to find out whether interventions could improve justification. According to our previous study, guidelines, education and increased MRI capacity were able to improve the level of justification of CTs from 70 to 90 per cent in young patients. With guidelines and education, the number of spine radiographies in primary care was also decreased by 50 per cent. Next, we will assess the effect of these interventions on lumbar spine radiographies and CTs in young patients.

Concerning the efficiency studies, the purpose is to find out if there is overuse of imaging and a need for specific guidelines. The effectiveness of repeated CT in the follow-up of subdural haematoma, of CT or MRI in the first epileptic seizure, and of CT angiography and MR angiography in transient ischaemic attack (TIA) patients will be assessed. Furthermore, MRI will be compared with CT in patients with suspected acute appendicitis. MRI defecography and fluoroscopic defecography will also be compared. In these studies, the aim is to find out if one or the other examination is optimal for diagnostic purposes.

Concerning patient information, the purpose is to chart the present situation and wishes for the content and source of information. The aim is to provide content and guidelines for information and to set up systematic information. Improved information may, for its part, also help to enhance justification. So far, our studies have revealed that patients obtain inadequate information and they expect to receive diverse information – including on the dose and risks of radiation.

4.7.2.3 Methods

In the follow-up study of justification, the effect of previous interventions – guidelines and education – on the number and justification of lumbar spine radiographies and CTs in young patients will be assessed. The results will be followed up for three years in order to see if there is any change. Samples from different radiology departments of Oulu University Hospital are collated. Paediatric patients will be analysed separately, and guidelines in use are used as a reference. The share of positive findings in justified and unjustified examinations is also analysed.

Regarding effectiveness, patients with operated chronic subdural haematoma, first epileptic seizure or TIA who have had a CT and/or MRI will be retrospectively picked up from the electronic patient files of Oulu University Hospital over a 5- to 7-year period. All the relevant examinations and clinical information will be assessed in order to find out different risk factors and various subgroups and to estimate the possibility of different imaging schedules in the future.

Patients with suspected acute appendicitis who will take part in a prospective multicentre study at Oulu University Hospital will have an abdominal CT examination. CT is essential if antibiotic therapy is being considered. Patients who consent will undergo an abdominal MRI as well. The findings of these examinations will be compared with each other and the clinical information. Furthermore, patients who have undergone both fluoroscopic and MRI defecography within a short time period will be retrospectively picked up from the patient files of Oulu University Hospital. The findings of the two examinations will be compared with each other and with the findings of the operation.

Concerning patient information, in addition to interviews with patients (n=147), a questionnaire survey for the staff of radiological departments (n=209), referring doctors (n=60) and parents of paediatric patients have been carried out. Enquiries about current information practices and wishes for future information were made. The results relating to the parents' questionnaire and the wishes of the radiographers and the radiologists will be analysed. Furthermore, the opinions of the staff regarding the current practice will be assessed and compared to the experience of the patients.

Cooperation with the IAEA and WHO has resulted in the review article (Bettmann et al. 2015). It deals with referring guidelines which are essential in order to enhance appropriateness. Furthermore, there is cooperation with the Ludwig Boltzmann Institute for Health Technology Assessment, Vienna. The two papers related to appropriateness of CT and MRI examinations have been submitted (Emprechtinger 2018).

Funding for the studies has come and will come from the research fund of Oulu University Hospital.

4.7.2.4 Recent publications

Oikarinen H, Meriläinen S, Pääkkö E, Karttunen A, Nieminen MT, Tervonen O. Unjustified CT examinations in young patients. Eur Radiol. 2009 May; 19(5):1161-5.

Tahvonen P, Oikarinen H, Pääkkö E, Karttunen A, Blanco Sequeiros R, Tervonen O. Justification of CT examinations in young adults and children can be improved by education, guideline implementation and increased MRI capacity. Br J Radiol. 2013 Sep;86(1029):20130337.

Tahvonen P, Oikarinen H, Niinimäki J, Liukkonen E, Mattila S, Tervonen O. Justification and active guideline implementation for spine radiography referrals in primary care. Acta Radiol. 2017 May; 58(5):586-592.

Ukkola L, Oikarinen H, Henner A, Honkanen H, Haapea M, Tervonen O. Information about radiation dose and risks in connection with radiological examinations: what patients would like to know. Eur Radiol. 2016 Feb;26(2):436-43.

Ukkola L, Oikarinen H, Henner A, Haapea M, Tervonen O. Patient information regarding medical radiation exposure is inadequate: Patients' experience in a university hospital. Radiography 2017, http://dx.doi.org/10.1016/j.radi.2017.04.001

Bettmann MA, Oikarinen H, Rehani M, Holmberg O, del Rosario Perez M, Naidoo A, Do KH, Dreyer K, Ebdon-Jackson S. Clinical imaging guidelines part 4: challenges in identifying, engaging and collaborating with stakeholders. J Am Coll Radiol. 2015 Apr;12(4):370-5.

Emprechtinger R, Fischer S, Holzer LA, Klimek P, Stanak M, Oikarinen H, Wild C. Detecting inappropriate use of CT and MRI in the musculoskeletal system: a systematic review of methods. Submitted (2018).

Emprechtinger R, Holzer LA, Stanak M, Oikarinen H, Fischer S, Klimek P. Relation of MRI use to hip or total knee replacements: signs of inappropriate use related to potentially unnecessary interventions. Submitted (2018).

4.7.3 The effects of environmental and low dose radiation on molecular biology of cells and viruses

DR JAANA JURVANSUU, DEPARTMENT OF BIOLOGY

4.7.3.1 Introduction

The biological effects of low dose radiation (in the range of 10-100 µSv/h) on cells and organisms is still controversial. The conservative view is that since ionising radiation causes DNA damage, its effects are accumulative and thus all radiation is harmful. Another view is that low dose radiation is beneficial, because it stimulates DNA damage and antioxidant-related processes and could thus decrease the incidence of cancers and inflammatory diseases, for example. For the past 30 years the wildlife at the Chernobyl nuclear accident site in Ukraine has been exposed to low dose radiation; a duration which, for example, for bank voles means many exposed generations. Thus, wildlife inhabiting the Chernobyl area provides the best opportunity available to study the effects of chronic low dose radiation on populations, organisms and cells.

If the information on the impact of low dose radiation on cells and organisms is lacking, it is completely absent on viruses. Virus genomes are naturally possible subjects for radiation damage but more relevantly many viruses use host DNA damage response mechanisms for their own reproduction. The sensitivity of viruses to host cell DNA damage helps viruses to avoid host cell death and multiple infections. Furthermore, damaged cellular DNA can serve as a virus integration site into the host genome. Hypothetically, low dose radiation could therefore increase virus amounts, virus evolution rates, and their impact on host genome function.

This research project is part of a large international research effort to study the evolutionary, developmental and ecological consequences of anthropogenic environmental ionising radiation on wildlife and involves research groups from the universities of Oulu, Jyväskylä, Liverpool (UK), South Carolina (USA), Taras Shevchenko National (Ukraine) and South Paris (France).

4.7.3.2 Objectives

During this project we have already discovered that cells from bank voles inhabiting the Chernobyl nuclear accident site have adaptive genetic changes against radiation, that is, higher antioxidant levels and insensitivity to DNA damage-induced programmed cell death. We are further interested to study whether Chernobyl bank vole cells differ from control cell lines in DNA damage repair accuracy – as suggested by our bank vole whole genome analysis – and proneness to cellular ageing (senescence). Faster onset of senescence has been shown to be a cellular response to chronic low dose radiation in laboratory conditions.

The effects of chronic low dose radiation on the amounts, variability and activation of endogenous viruses will be studied both from Chernobyl bank vole blood and DNA samples, and with bank vole and human cell lines in laboratory conditions.

4.7.3.3 Materials and methods

The research materials are cell lines, blood and DNA from bank voles from the Chernobyl area (radiation levels >10 μSv/h) and voles from the Kiev control area (radiation levels <0.2 μSv/h). Additionally, commercial human cell lines are used for virus activation experiments. Laboratory experiments using a high-rate cell irradiator are performed at Nordlab (Oulu University Hospital) and low dose cell irradiation experiments will be done at facilities hosted in Oxford, UK, in collaboration.

4.7.3.4 Financial support

This research project is financed by the Kone Foundation for the period 2016–2019.

4.7.3.5 Recent publications

Mustonen V, Kesäniemi J, Lavrinienko A, Tukalenko E, Mappes T, Watts PC, Jurvansuu J. Fibroblasts from bank voles inhabiting Chernobyl have increased resistance against oxidative and DNA stresses. BMC Cell Biology 2018 Aug 29;19(1):17. doi: 10.1186/s12860-018-0169-9.

4.8 University of Tampere

PROFESSOR ANSSI AUVINEN, DEPARTMENT OF EPIDEMIOLOGY

Research related to radiation protection conducted at the University of Tampere focuses on radiation dose assessment and health risks from radiation. Dosimetry research has focused on doses to off-target tissue in radiotherapy and has involved close collaboration between the Faculty of Medicine and Biosciences and Tampere University Hospital (oncology and medical physics). The long-term health effects of radioiodine therapy have been a focus area, with several studies evaluating risks of subsequent neoplasms, other diseases and mortality in patients treated with radiotherapy versus surgery for thyroid cancer (Saara Metso, Essi Ryödi). In addition, cardiac effects of radiotherapy for left-sided breast cancer have been evaluated (Suvi Tuohinen, Tanja Skyttä). In medical physics, dosimetry from radiotherapy for breast cancer has been a central theme (Maija Rossi, Eeva Boman).

At the Faculty of Social Sciences (health sciences) extensive research has been carried out in radiation epidemiology led by Prof. Anssi Auvinen. The risk of cancer as well as non-cancer diseases has been evaluated among subjects exposed occupationally, from environmental sources or through medical uses of radiation. Radiation exposures of particular importance in Finland include indoor radon, but also to some extent Chernobyl fallout and fallout from atmospheric atomic bomb testing. Health outcomes have included childhood cancers, as well as lens opacities and pregnancy outcomes. Late sequelae of radiotherapy are a current focus, as well as cancer risk from computerised tomography in children (Atte Nikkilä and Olli Lohi). The comprehensive Finnish population and health care registers have been utilised for conducting large-scale studies. Wide international networks of collaboration have also been established and several studies conducted as European projects with funding through the Euratom programme. We collaborate actively with the World Health Organization (WHO), the International Agency for Research on Cancer (IARC) and other organisations. We are also a member of the Childhood Leukemia International Consortium (CLIC).

In the field of non-ionising radiation, a central theme is the effects of ultraviolet radiation on skin and indirect effects on the physiology, particularly the effects of narrow-band UVB at the Medical Faculty/dermatology (Erna Snellman). In Health Sciences, health effects of radiofrequency electromagnetic fields (RF-EMF) from mobile phones are being evaluated in a large international cohort study (COSMOS), with outcomes ranging from symptoms to cancer and neurodegenerative diseases.

4.8.1 Recent publications

Nikkilä A, Raitanen J, Lohi O, Auvinen A. Radiation exposure from computerised tomography and risk of childhood leukemia. Haematologica 2018 (E-publ)

Rossi M, Boman E, Kapanen M. Contralateral tissue sparing in lymph node positive breast cancer radiotherapy with VMAT technique. Med Dosim 2018 (E-publ)

Tuohinen SS, Keski-Pukkila K, Skyttä T et al. Radiotherapy-induced early ECG changes and their comparison with echocardiography in patients with early-stage breast cancer. Anticancer Res 2018;38:2207-15

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Nikkilä A, Erme S, Arvela H, et al. Background radiation and childhood leukemia. Int J Cancer 2016;139:1975-1982

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Jussila A, Huotari-Orava R, Ylianttila L et al. Narrow-band ulytraviolet B induces the expressaion of beta endorphin in human skin in vivo. J Photochem Photobiol B 2016;155:104-108

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Skyttä T, Tuohinen S, Boman E et al. Troponin-T release associates with cardiac radiation doses during adjuvant left-sided breast cancer radiotherapy. Radiat Oncol 2015;10:141

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4.9 University of Turku

4.9.1 Geology

ASSISTANT PROFESSOR PIETARI SKYTTÄ, DEPARTMENT OF GEOSCIENCES AND GEOGRAPHY

4.9.1.1 Introduction

The Geology Section at the University of Turku has strong international level expertise in understanding and investigating the evolution of the Precambrian bedrock (e.g. Väisänen & Skyttä, 2007; Skyttä and Mänttäri, 2008). Recent ongoing research has focused on studying the brittle bedrock structures (Lindqvist et al., 2017), particularly with respect to the older bedrock structures and the heterogeneous (palaeo)stress field of the crust. The investigations have significant application potential generally within ore geology, bedrock engineering, ground water maintenance (Skyttä et al., 2015) and nuclear waste disposal projects. The investigations are typically based on field work, analogic and numerical analysis, and they range from mineral grain to mountain chain scales. The geology units at the University of Turku and Åbo Akademi University are collaborating closely, promoted by the shared facilities of "Geohouse" from 2016 onwards. Important financial support has been directed towards Geohouse in 2016–2017 (–2018), which is consequently becoming an attractive research environment. The University of Turku, under a four-year contract (2014–2018), has given specialist support and statements to the Radiation and Nuclear Safety Authority (STUK) concerning the geological disposal of spent nuclear fuel, with a specific focus on issues related to structural geology and 3D modelling.

4.9.1.2 Aims

The work aims to support STUK in decision-making related to the geological disposal of spent nuclear fuel. In the work, the scientific expertise within bedrock geology is applied to a societally important subject. From the University of Turku's perspective, the work also aims to further develop the skills and expertise within applied bedrock geology by training staff and promising students.

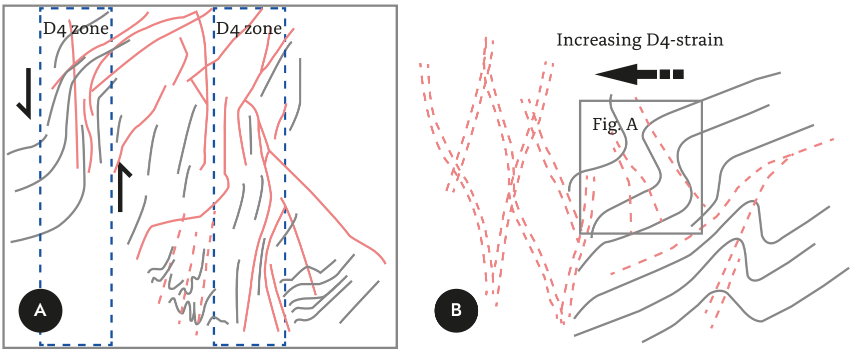

FIGURE 7. A sketch illustrating the relationships of foliations (black lines), deformation zones (dash-lined boxes) and fractures (magenta) in a natural outcrop in Olkiluoto, Finland. B: A conceptual model explaining the structural inheritance (ductile fabric; grey) in the development of the brittle deformation zones (magenta).

4.9.1.3 Methods

Methods include reading and commenting on selected reports, the evaluation of POSIVA's 3D-models, and the generation of alternative 3D models based on the data available through Posiva. The work is reported to STUK and it includes site visits and discussion meetings with Posiva. The results of the work are generally not public, but some of the work will be published in scientific journals in the future.

4.9.1.4 Funding

The work is carried out according to a consultancy agreement (2015-2018) whereby STUK orders specific consultancy from the University of Turku. Prof. Pietari Skyttä and Jussi Kinnunen MSc have acted as consultants

4.9.1.5 Publications

Väisänen M, Skyttä P. Late Svecofennian shear zones in southwestern Finland. GFF 2007; 129, 55–64.

Skyttä P, Mänttäri I. Structural setting of late Svecofennian granites and pegmatites in Uusimaa Belt, SW Finland: Age constraints and implications for crustal evolution. Precambrian Research 2008; 164, 86–109.

Skyttä P, Kinnunen J, Palmu J-P, Korkka-Niemi K. Bedrock structures controlling the spatial occurrence and geometry of more than 1.8 Ga younger glacifluvial deposits – example from First Salpausselkä, Southern Finland. Global and Planetary Change 2015; 135, 66–82.

Lindqvist T, Skyttä P, Koivisto E, Häkkinen T, Somervuori P. Delineating the network of brittle structures with geotechnical, structural and reflection seismic data, Kevitsa open pit, northern Finland. GeoResJ 2017; 13, 159–174.

4.9.2 Space research

PROFESSOR RAMI VAINIO, DEPARTMENT OF PHYSICS AND ASTRONOMY

4.9.2.1 Introduction

The Space Research Laboratory (SRL) at the Department of Physics and Astronomy at the University of Turku performs research on the radiation environment of near-Earth space. Space radiation has three main components: cosmic radiation, solar energetic particles, and radiation belts consisting of charged particles trapped in the Earth's magnetic field. Space radiation causes single event effects (bit upsets, latch-ups) and the degradation of electronics components in space systems and at aircraft altitudes. In addition, it adds to the radiation dose of flying personnel, which can be very high for astronauts. As society is ever more dependent on space applications (satellite communication and global positioning systems) the indirect effects of space radiation affect an increasingly large number of people.

4.9.2.2 Objectives

The objectives of SRL include the development of instruments for measuring the flux and spectral properties of space radiation (e.g. Torsti et al. 1996, Valtonen et al. 2007, Huovelin et al. 2010) and probabilistic models for predicting the peak flux and fluence of particle radiation (http://swe.ssa.esa.int/web/guest/utu-srl-federated), and to understand the particle acceleration mechanisms during solar eruptions (e.g. Vainio & Laitinen 2007, Afanasiev et al. 2014, 2015).

4.9.2.3 Methods

Methods used include the design and manufacturing of energetic particle spectrometers and radiation monitors for satellites and spacecraft; analysis of space radiation observations and statistical modelling of radiation fluence and peak flux; numerical solar energetic particle acceleration and transport modelling.

4.9.2.4 Funding

Traditionally, scientific spacecraft instrumentation in Finland has been funded by Tekes, but the model has become obsolete. The new funding model at the national level has not yet been established, but solutions are actively being sought. The University of Turku is participating, under the lead of SRL, in the Finnish Centre of Excellence (CoE) in Sustainable Space Science and Technology, funded by the Academy of Finland. The CoE is coordinated by the University of Helsinki, and the participants are the University of Turku, Aalto University and the Finnish Meteorological Institute. The statistical modelling of space radiation fluence and flux is funded at SRL by the European Space Agency through its Space Situational Awareness programme. The basic research on the physics of generation and transport of space radiation at SRL has been funded by the Academy of Finland and the EU.

4.9.2.5 Publications

Afanasiev A, Vainio R, Kocharov L. The Effect of Stochastic Re-acceleration on the Energy Spectrum of Shock-accelerated Protons. The Astrophysical Journal 2014; 790, id. 36.

Afanasiev A, Battarbee M, Vainio R Self-consistent Monte Carlo simulations of proton acceleration in coronal shocks: Effect of anisotropic pitch-angle scattering of particles. Astronomy & Astrophysics 2015; 584, id. A81

Huovelin J, Vainio R, Andersson H, et al. Solar Intensity X-ray and particle Spectrometer (SIXS). Planetary and Space Science 2010; 58, 96–107.

Torsti J, Valtonen E, Lumme M, et al. Energetic Particle Experiment ERNE. Solar Physics 1995; 162, 505–531.

Vainio R, Laitinen T. Monte Carlo Simulations of Coronal Diffusive Shock Acceleration in Self-generated Turbulence. The Astrophysical Journal 2007; 658, 622–630.

Vainio R, Desorgher L, Heynderickx D, et al. Dynamics of the Earth's Particle Radiation Environment. Space Science Reviews 2009; 147, 187–231.

Valtonen E, Vainio R, Rodriguez-Pacheco J, Kocharov L, Laitinen T, EPD/LET Team, 2007. A Low Energy Telescope For Solar Orbiter. ESA-SP 641, id. 86.

4.9.3 Turku University Hospital and Turku PET Centre

Radiation safety research at the Hospital District of Southwestern Finland (VSSHP) is performed mainly at Turku University Hospital (Tyks) and is focused on patient safety, dosimetry of patients and personnel, and the development of new methods and instrumentation.

VSSHP works together with the University of Turku (UTU) and Åbo Akademi (ÅA), where the biggest joint venture is the National PET Centre (or Turku PET Centre, TPC).

4.9.3.1 Imaging

PROFESSOR MIKA TERÄS, CELL BIOLOGY AND ANATOMY, INSTITUTE OF BIOMEDICINE & CHIEF PHYSICIST, DEPARTMENT OF MEDICAL PHYSICS, TURKU UNIVERSITY HOSPITAL

4.9.3.1.1 Introduction

The number of medical imaging studies is rapidly increasing, and more complex imaging methods are widely available. Imaging has also become routine during surgery in operating rooms. Dose optimisation is a continuous process led by medical physics experts as new equipment, protocols and methods are taken into use.

In nuclear medicine with multimodality devices such as PET/CT and SPET/CT, optimisation is as vital and low dose CT is often preferable. Working with open sources makes it important for safe processes and automation to reduce finger doses to staff.

4.9.3.1.2 Aims

One aim of optimisation is to influence domestic and international Dose Reference Levels (DRL) and harmonise study protocols nationally. Research activity at VSSHP is continuous but the aim is to finish at least three PhDs within the next 3–5 years.

4.9.3.1.3 Methods

Today all patient doses are stored in PACS, so it is possible to get metadata for the analysis for harmonisation of protocols.

In addition to other hospitals, the research is performed together with national authorities (STUK), R&D departments of major vendors, and smaller companies.

Radiology:

A PhD on radiology was completed in October 2017 by Hannele Niiniviita (see list of publications)

Cardiology:

An ongoing study is evaluating both patient and staff doses during different cardiac interventions in eight Finnish hospitals with the aim of standardising and harmonising protocols and processes (KARPO project). The study is related to an ongoing PhD study (Jukka Järvinen).

Nuclear medicine and Multimodality imaging (PET/CT, PET/MR and SPET/CT):

The development and research of new radiotracers as well as cell and animal models is performed at the TPC at the University of Turku, but when the clinical phase is reached, TPC/VSSHP will become more involved. A dynamic whole body distribution of new tracers is needed for the calculation of human dose estimates of new radiotracers.

When a new imaging device generation is launched, VSSHP is at the forefront of testing its physical performance and clinical usability. This has led to recommendations for international guidelines where dose optimisation plays a major role (see Kajander et al.).

A special challenge in cardiac PET/CT is the dual phase movement (cardiac and respiratory) of the heart. TPC has studied this on a large scale and has presented some recent innovations to measure and correct for movement, and to evaluate metrics of error sources in cardiac perfusion.

In 2017 two scanners with the latest digital techniques have been taken in use and performance measurements are starting again with the aim of reducing patient dose with more accurate quantitative images and speeding up the study to make it more comfortable for the patient.

4.9.3.1.4 Funding

VSSHP participates in funding with five positions for medical physics training. This is the basis from where medical physicists and trainees can search for additional grants from foundations and make RTD contracts with manufacturers.

4.9.3.1.5 Selected publications

Radiology and cardiology

Niiniviita H, Kiljunen T, Kulmala J, Comparison of effective dose and image quality for newborn imaging on seven commonly used CT, Rad Prot Dosim 2016; DOI:10.1093/rpd/ncw229

Niiniviita H, Pölönen T, Kulmala J, Määttänen H, Järvinen H, Salminen E Excess of radiation burden for young testicular cancer patients using automatic exposure control and contrast agent on whole-body CT-imaging, Radiology and Oncology 2017;51(2): 235-240.

Niiniviita H, Virtanen J, Kiljunen T, Hurme S, Kulmala J, Rinta-Kiikko I, Salminen P, Low dose CT protocol optimisation in suspected acute appendicitis: the OPTICAP phantom study, Radiation Protection Dosimetry, 2017, doi:10.1093/rpd/ncx070

Knuuti J, Jarvinen J. Radiation exposure and the risk of cancer for interventional cardiologists and electrophysiologists. Eur Heart J 2014; 35 (10): 599-604

Järvinen J, Teräs M, Parviainen T, Järvinen H, Hallinen E, Pirinen M, Siiskonen T, Larjava HRS, Mäkelä TJ, Matikka H, Strengell S, Kiviniemi T, Rissanen TT, Niskanen E, Eskola M, Kivelä A, Sierpowska J, Contemporary radiation doses in interventional cardiology: A nationwide study in Finland. Submitted.

Nuclear Medicine

Tolvanen T, Karlsson A, Kauppila E, Lafay C, Zanca F, Teräs M. First Impressions on a Commercial Patient Dose Management System in Nuclear Medicine, ePoster EP823, EANM Congress, Barcelona, 2016.

Teuho J, Johansson J, Linden J, Espe Hansen A, Holm S, Keller SH, Delso G, Veit-Haibach P, Magota K, Saunavaara V, Tolvanen T, Teräs M and Iida H. Effect of attenuation correction to regional quantification between PET/MR and PET/CT: a multi-centre study using a three-dimensional brain phantom J Nuc Med, published on January 28, 2016 as doi:10.2967/jnumed.115.166165

Jafari Tadi M, Lehtonen, E Hurnanen T, Koskinen J, Eriksson J, Pänkäälä M, Teras M, Koivisto T. A real-time approach for heart rate monitoring using Hilbert transform in seismocardiograms 09/2016:37(11) Physiol Meas

Klén R, Noponen T, Koikkalainen J, Lötjönen J, Thielemans K, Hoppela E, Sipilä H, Teräs M, Knuuti J. Evaluation of motion correction methods for dual gated cardiac PET-CT imaging. Nucl Med Commun. 2016 Sep;37(9):956-68. doi: 10.1097/MNM.0000000000000539.

Autio A, Virtanen H, Tolvanen T, Liljenbäck H, Oikonen V, Saanijoki T, Siitonen R, Käkelä M, Schüssele A, Teräs M, Roivainen A. Absorption, distribution and excretion of intravenously injected 68Ge/68Ga generator eluate in healthy rats, and estimation of human radiation dosimetry. EJNMMI Research 2015; 5:40 DOI 10.1186/s13550-015-0117-z

Kwon M,*Vorobyev V, Kännälä S, Laine M, Rinne JO, Toivonen T, Johansson J, Teräs M, Joutsa J, Tuominen L, Lindholm H, Alanko T, and Hämäläinen H. No Effects of Short-Term GSM Mobile Phone Radiation on Cerebral Blood Flow Measured Using Positron Emission Tomography. Bioelectromagnetics 2012; 33:247-256

Shepherd T, Teräs M, Beichel RR, Boellaard R, Bruynooghe M, Dicken V, Gooding MJ, Julyan PJ, Lee JA, Lefevre S, Mix M, Naranjo V, Wu X, Zaidi H, Zeng Z and Minn H. Comparative Study with New Accuracy Metrics for Target Volume Contouring in PET Image Guided Radiation Therapy. (IEEE Trans Med Imaging. 2012 Jun 4. [Epub ahead of print])

Kajander S, Ukkonen H, Sipilä H, Teräs M, Knuuti J. Low radiation dose imaging of myocardial perfusion and coronary angiography with a hybrid PET/CT scanner. Clin Physiol Funct Imaging 2009; 29:81-88. [1.000]

4.9.3.2 Medical radiation; diagnostics in breast cancer

EEVA SALMINEN, RESEARCH PROFESSOR (STUK), ADJUNCT PROFESSOR (DEPT OF ONCOLOGY, TURKU UNIVERSITY HOSPITAL), IN COLLABORATION WITH THE DEPARTMENT OF SURGERY (R. AALTONEN, MD), PATHOLOGY (P.BOSTRÖM, MD, PHD), AURIA BIOBANK A. KARLSSON (PHD) AND ONCOLOGY (V.MADEKIVI, MD) AT TURKU UNIVERSITY HOSPITAL AND SOUTH-WESTERN FINLAND'S HOSPITAL DISTRICT.

Many imaging methods are applied in cancer diagnostics, sometimes in an overlapping mode.

Breast cancer is the most common cancer among Finnish women, often diagnosed with screening mammograms. However, when planning the operation, the surgeon may need to repeat the imaging or use different diagnostics to clarify the extent of the forthcoming operation. In the operation, nuclear technique is used to illustrate the sentinel lymph nodes, which will be removed to assess the spread of cancer beyond the primary tumour.

Auria Biobank is collecting data, based on the patient's consent, on all breast cancer patients who are operated at Turku University Hospital. Data on 2,000 breast cancer patients is analysed to clarify the use and role of different imaging methods in preoperative assessments. Findings from imaging will be compared with the assessment of surgical samples in the histopathological evaluation. This study is focusing on the spread of the cancer to lymph nodes, and the requirements for the axillary evacuation of lymph nodes. The study looks at the time lag between initial findings and findings from the operation. We wish to clarify whether the imaging outcome is repetitive or whether fundamentally important new information is obtained when the MRI is used in addition to ultrasound imaging. Thus, the role of MRI compared to traditionally used mammogram and ultrasound imaging in preoperative imaging in breast cancer surgery is assessed.

Sentinel lymph node (SLN) biopsy has become the standard procedure to identify metastases in axillary nodes in breast cancer. Even after careful SLN examination, additional micrometastases and isolated tumour cells (ITCs) are sometimes found, resulting in delayed axillary lymph node dissection (ALND). This study will assess prognostic factors identifying additional axillary lymph node metastases and the factors will be compared to imaging and histopathological outcomes. The role of the sentinel node biopsy is compared to other prognostic and predictive factors such as molecular subtype and proliferation index.

The staging of regional lymph nodes is considered an important step in the selection of breast carcinoma therapy. However, many recent studies have recognised the importance of tumour biology and give rise to further thought as to whether selected SLN-positive patients with limited axillary metastases could avoid axillary evacuation and instead be treated with radiotherapy.

One important outcome of this register-based study is to strengthen the quality management of operative breast cancer patients by clarifying the process of preoperative imaging, helping to avoid or omit overlapping steps and decreasing patients' exposure to the adverse effects of imaging and delays in the treatment process. The close collaboration between experts in breast cancer surgery, pathology, imaging and oncology in this project makes it significant. The project data is used in a PhD study.

The research plan has been approved by the ethical committee of the Hospital District of Southwest Finland, and permission was granted to use the materials of the Auria Biobank and Turku University Hospital in 2017.

The project is in accordance with STUK strategy 2018-22/ 6 - 7.

4.9.3.2.1 Publications

Madekivi V, Boström P, Aaltonen R, Vahlberg T, Salminen E. The Sentinel Node with Isolated Breast Tumor Cells or Micrometastases. Benefits and Risks of Axillary Dissection. Anticancer Res. 2017 Jul;37(7):3757-3762.

Tan MP, Ong EM, Amy D, Tot T.Breast J. Integrating anatomy, radiology, pathology, and surgery: An alternative approach in resecting multifocal and multicentric breast carcinoma. 2017 Aug 22. doi: 10.1111/tbj.12891. [Epub ahead of print]

Hessman CJ, Naik AM, Kearney NM, Jensen AJ, Diggs BS, Troxell ML, Vetto JT. Comparative validation of online nomograms for predicting nonsentinel lymph node status in sentinel lymph node-positive breast cancer. Arch Surg. 2011 Sep;146(9):1035-40. doi: 10.1001/archsurg.2011.201.

Boler DE, Uras C, Ince U, Cabioglu N. Breast. Factors predicting the non-sentinel lymph node involvement in breast cancer patients with sentinel lymph node metastases. 2012 Aug;21(4):518-23. doi: 10.1016/j.breast.2012.02.012. Epub 2012 Mar 10.

Tvedskov TF, Meretoja TJ, Jensen MB, Leidenius M, Kroman N. Cross-validation of three predictive tools for non-sentinel node metastases in breast cancer patients with micrometastases or isolated tumor cells in the sentinel node. Eur J Surg Oncol. 2014 Apr;40(4):435-41. doi: 10.1016/j.ejso.2014.01.014. Epub 2014 Feb 1.

Ouldamer L, Arbion F, Balagny A, Fourquet F, Marret H, Body G. Validation of a breast cancer nomogram for predicting nonsentinel node metastases after minimal sentinel node involvement: validation of the Helsinki breast nomogram. Breast. 2013 Oct;22(5):787-92. doi: 10.1016/j.breast.2013.02.004. Epub 2013 Mar 7

Liikanen J, Leidenius M, Joensuu H, Vironen J, Heikkilä P, Meretoja T. Breast cancer prognosis and isolated tumor cell findings in axillary lymph nodes after core needle biopsy and fine needle aspiration cytology: Biopsy method and breast cancer outcome.Eur J Surg Oncol. 2016 Jan;42(1):64-70. doi: 10.1016/j.ejso.2015.08.170. Epub 2015 Sep 25.

4.9.3.3 Radiation therapy

JANI KEYRILÄINEN, ADJUNCT PROFESSOR, DEPARTMENT OF MEDICAL PHYSICS & DEPARTMENT OF ONCOLOGY AND RADIOTHERAPY, TURKU UNIVERSITY HOSPITAL

4.9.3.3.1 Objectives and methods

The projects are based on a five-way collaboration between local collaborators, national hospitals, radiation safety authority, international institutes and manufacturers. One of the main objectives is to produce undergraduate and postgraduate degrees for physics students, in particular those targeting a vocational certified degree in medical physics. Currently, there are five postgraduate students working on the projects prescribed below.

Dosimetry and dose calculation

Cancer is the most common malignant disease among people in the industrialised countries, and in Finland alone about 29,000 new cases are diagnosed each year. The survival rate of cancer patients has improved in recent decades, due primarily to the earlier detection of smaller tumours and by continuously improving treatment methods.

Radiation therapy (RT), chemotherapy and surgery are the most common types of cancer treatment. The capacity of RT is based on the dose response of cells, which describes the response of the biological object to the ionising radiation. The dose response is characteristic for different types of cells, and the difference between the response of tumour cells and the response of normal cells is the basis from which all doses for clinical treatment are chosen. The clinical requirements on dose accuracy are based on evidence from dose response curves for tumour control probability (TCP) and for normal tissue complication probability (NTCP). These typically have sigmoidal shapes, with a threshold dose, relatively steep rises and saturation at high doses. RT optimisation and many advances in technology and techniques are aimed at improving this balance, i.e. maximising tumour control while maintaining tissue complications at an acceptable level. The steepness of the given TCP or NTCP curve versus dose defines the change in response expected for a given change in delivered dose. Thus, uncertainties in delivered dose translate into either reductions in TCP from the optimised expected value, or increases in NTCP from the optimised expected value, both of which degrade the clinical outcome. The accuracy requirements are defined by the most critical (steepest) curves, observed for normal tissues or steeply responding tumours. At the steepest parts of the dose-response curves, and for the steepest curves, 5 per cent changes in dose can produce 10-20 per cent changes in TCP and 20¬–30 per cent changes in NTCP.

There is a range of published estimates on the required and achievable accuracy in the RT dosimetry of external beam megavoltage X-rays. However, since the mid-1990s there have been ongoing and rapid advances in RT techniques, and developments are also expected in the near future. Thus, we are currently confronted with the critical need for accurate, practical dosimetry for commissioning, development, quality assurance (QA) and both pre-treatment and in vivo verification for these technologies for clinical practice and also for research; indeed dosimetry measurements, methods and resource requirements are recognised as a potential limiting step in the widespread clinical application of some technologies. The need has shifted from the simplest 1D and 2D dosimetry to the requirements at all levels from 1D to 4D for intensity-modulated radiotherapy (IMRT), image-guided radiotherapy (IGRT), volumetric-modulated arc therapy (VMAT), adaptive radiotherapy (ART), and 4D motion-managed RT. The objective of all this development is to improve the balance of tumour control versus normal tissue complication incidence for curative treatments. However, these outcomes will not be safely achieved unless there are also matched improvements in the accuracy of treatment delivery systems and appropriate dose measurement and modelling systems to support this.

Treatment with ionising radiation using small photon fields has been an established practice in stereotactic RT for many years. The technological development of standard medical linear accelerators (linacs) has led to better mechanical accuracy, stability and dosimetric control. At the same time, there has been an increasing availability of novel multileaf collimators on standard linacs as well as the introduction of new treatment units specifically designed for stereotaxy or IMRT/VMAT treatments. These technical improvements implicitly encourage the use of small treatment field sizes on equipment originally designed and commissioned for treatments based on traditional, broad photon fields. The experimental determination of small field dosimetric data is challenging, and the use of RT treatment planning systems (TPS) and treatment units not designed or commissioned for small fields can introduce significant errors in the delivery of treatments. Furthermore, assumptions which are valid for larger fields are often not so relevant for smaller fields.

The project is designed to investigate and understand the physics and challenges behind the small photon fields in measurement, calibration and calculation. The most suitable equipment, detector systems and methods for the determination of dosimetric parameters as well as QA aspects relevant to the use of narrow collimated fields are reviewed. The overall objective is to improve the accuracy of RT for cancer patients. The factors that influence the accuracy of measurement and determination of absorbed dose distribution in a tissue equivalent phantom and the calculation accuracy of TPS in the particular case of small and composite fields are studied. Topics are carefully conducted with extensive measurements by several types of radiation detectors and subsequently compared to the most accurate Monte Carlo (MC) simulations. Uncertainties induced by the detector and measurement process itself are analysed.

The research is based on experiments and collaborative work at major Finnish institutes investigating this subject. Most of the research is carried out at the university hospitals in Tampere and Turku. The experimental instrumentation, i.e. state-of-the-art medical linacs, radiation detectors, tissue equivalent phantoms, MC simulation computers and TPS workstations for accurate dosimetry and dose calculation are already available in these institutes. Any new equipment is ordered or jointly developed by the hospital research teams and specialists at the Radiation and Nuclear Safety Authority of Finland (Säteilyturvakeskus, STUK).

Studies are based on close collaboration with scientists working at Tampere and Turku University Hospitals and STUK. The first two peer-reviewed articles of this project were published in June 2017 (Niemelä et al. 2017, Partanen et al. 2017). The scientific results have also been presented at several national and international conferences and meetings.

MRI-only simulation in radiotherapy planning

Modern treatment techniques enable more accurate implementation of RT that increases the probability of tumour control and reduces complications in healthy tissue. In RT, the estimation accuracy of treatment volume and its localisation, as well as the determination of healthy tissue, is pronounced. In order to address these requirements, the utilisation of magnetic resonance imaging (MRI) – using non-ionising radiation – has significantly increased in recent times.

Superior soft-tissue contrast obtainable in MRI compared with other clinical imaging methods enables more accurate definition and delineation of treatment volume and organs at risk (OAR). Additionally, the monitoring of treatment outcomes and the evaluation of treatment responses can be accurate using MR images. If radiotherapy treatment planning (RTP) was possible using only MRI, the patient-specific optimisation of RT could be possible by conducting an additional MRI scan in the middle of the RT course, for example.

Current practice in the use of MR images for RTP is based on the co-registration of computed tomography (CT) and MR images. This enables the utilisation of additional anatomical details provided by MRI, although the dose calculation is based on electron density information available by CT. The use of two different imaging modalities requires additional work and increases costs. Moreover, the error associated with co-registration increases the uncertainty in treatment accuracy. For the aforementioned reasons, it would be ideal to create a practice which is based on a single imaging modality only. At the same time, the potential harm related to the use of ionising radiation in CT can be removed.

The overall objective of the study is to reduce the radiation dose delivered to patients and improve the accuracy of treatment volume and OAR definition. The specific aim is to examine the effect of MRI's geometric distortion to dose calculation accuracy in MRI-only–based RTP. Significant distortions in MRI are possible, particularly when using larger field-of-views. Another goal is to develop applicable phantoms and software that could enable automatic analysis of distortions to be used for patient-specific corrections of distortions. The realisation of these aims could significantly improve the conditions for MRI-only RTP at all treatment sites. A particular branch of examination is the magnitude of geometric distortions produced during diffusion-weighted imaging (DWI). In rapid imaging sequences the gradient magnetic fields required in image encoding produce local eddy currents that cause permanent distortions to both geometry and image intensity. This complicates the definition of treatment volume, thus reducing the usability of DWI-based techniques for MRI-only RTP.

The work studies the possibilities of using the MRI for dose calculation in pelvic and brain regions that could diminish the need for CT. In MR images the tumour and other structures can be differentiated more effectively than in CT images, but they do not contain the electron density information needed for dose calculation. The MRI scanner located in the RT Department at Turku University Hospital is equipped with software that is capable of producing synthetic CT (sCT) images based on MR image information. These images can be utilised directly in a clinical RTP system. All of the results obtainable from this study are applicable to clinical RT.

In addition to reduced radiation exposure for patients, the methods in development reduce the number of hospital visits for patients and the amount of work for staff. This can cause significant savings in time and costs. The clinical advantage for patients is the result of the improved target and OAR definition. In the long term, this may manifest itself as a reduction of complications caused by radiation and increased tumour control probability. Determining this would, however, require a significant amount of clinical material and a long follow-up period, and is not therefore possible to investigate as part of the current project.

The studies of the MRI-only RTP will be conducted at Turku University Hospital on a designated MRI scanner used mainly for RTP (Ingenia MR-RT 1.5 T, Koninklijke Philips N.V., the Netherlands). The study will be conducted in a close cooperation with the manufacturer Philips MR Therapy (Vantaa, Finland), but the project also has foreign partners. Some of the scientists have previously worked on a project that was carried out with Finland's first similar MRI device at Helsinki University Hospital (Helsinki, Finland). There, the research group developed methods for generating sCT images based on MR image information, among other things.

Studies are based on close collaboration with scientists working at Turku University Hospital and Philips MR Therapy. The first peer-reviewed article of this project was published in June 2017 (Kemppainen et al. 2017) and another one was submitted more recently (Ranta et al. 2018). The scientific results have also been presented at several national and international conferences and meetings.

Synchrotron radiation applications for medical imaging and radiotherapy

The use of synchrotron radiation (SR) has made new methods for medical imaging and RT possible. SR is actually very intense X-rays, which are produced in particle accelerators where electrons (or positrons) circulate almost at the speed of light. The radiation is well-collimated, and it has continuous energy spectrum. Narrow energy bands can be separated by crystal monochromators to suit the needs of the experiment. For instance, in medical imaging beam hardening is avoided and optimal contrast is achieved, while radiation dose is reduced.

Most SR applications in medicine are in the form of basic research, because radiation is available only at large facilities. In Europe, medical research is conducted at synchrotron radiation laboratories in France, Germany, the UK and Italy, and worldwide, the most important research centre is the European Synchrotron Radiation Facility (ESRF) in Grenoble, France. Basic research at SR facilities aims at better understanding of diseases and the development of new diagnostic and therapeutic methods that can be transferred to the clinical environment, for example.

The biomedical beamline ID17 of the ESRF is dedicated to biomedical imaging, radiobiology and RT. The experiments can be run in vitro or in vivo in two endstations on the same line. Finland is a member state of the ESRF as part of the Nordsync consortium (formed by Denmark, Finland, Norway and Sweden). Many Finnish students and young scientists have worked on the projects and have participated in experiments. The project team has the expertise and contacts to continue in an important or even leading role when new methods are developed for clinics. Research is based on close collaboration between scientists working at Helsinki and Turku University Hospitals and at the ESRF. The Academy of Finland supported the first phase of the project, when the methods and instrumentation for the Analyzer-based Imaging (ABI), Small-Angle X-ray Scattering (SAXS) and Microbeam Radiation Therapy (MRT) techniques were developed. The scientific results have been published in several international peer-reviewed scientific journals that have high impact. Recently, some of the key scientists in the field were invited to write chapters for the Handbook of X-ray Imaging: Physics and Technology (Suortti et al. 2018).

4.9.3.3.2 Financial assets

The Hospital District of Southwest Finland participates indirectly in this research by offering positions for medical physics trainees. The main source for financial support is applied funding from different sources such as foundations, the Academy of Finland and the European Union. In addition, there has been active collaboration with various manufacturers in the field.

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4.10 Åbo Akademi University

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4.10.1 Neutrons from proton-induced nuclear reaction – a radiation safety problem around medical cyclotrons

Commercial cyclotrons used for the production of short-lived radionuclides for positron emission tomography (PET) are normally located in small concrete vaults at hospitals to minimise the transport route and thereby also the radiation hazard connected to this. The lifespan of these dedicated cyclotrons is usually about 30 years. During the time the cyclotron is in operation, the surrounding structures are activated by neutrons.

The oldest cyclotron at the Turku PET Centre, the MGC-20, has now been in operation for more than 40 years and will soon be decommissioned. Although the maximal beam current is only a tenth of the beam currents of the cyclotrons used for radionuclide production today, it is possible to obtain a lot of information about the problematic activation that one has to face when newer and more efficient cyclotrons located in smaller vaults are decommissioned.

The aim of the research is to monitor neutron fluxes, measured neutron-induced activities in surrounding structures (parts of the buildings, cyclotron magnets, beam line supports, vacuum pumps etc.), and finally to perform a Monte Carlo simulation to get a better understanding of the processes involved.

The neutron fluxes will be monitored indirectly by using a small amount of carefully chosen materials that will be activated by neutrons produced in a nuclear reaction when accelerated protons hit probes, walls inside cyclotrons or beam lines, vacuum foils or targets. The produced radioactivity in the monitor materials will be measured with gamma spectrometry. The choice of monitor materials with respect to the neutron-induced cross section, as well as the half-lives of the produced radionuclides, is important. A suitable half-life is in the range of several tens of minutes up to a day or two, but not much longer. The cross section of the neutron-induced nuclear reaction should also be considered; both monitor materials where reactions favour thermal neutrons as well as reactions favouring fast neutrons are important for the complete understanding of the production of neutron-activated items and the activity distribution within them.

The long-lived radioactivity, produced in the surrounding structures, will be measured at the old cyclotron in the preparation of a decommissioning plan. The relationship between the activity in the neutron monitors and the long-lived activity in the wall materials will be used to predict the activity that will be produced in walls around other cyclotrons or even better to prevent the build-up of activity in the walls. The results are also crucial in the building of neutron shieldings around the unshielded target stations at Turku PET Centre.

To further increase knowledge about the processes involved, Monte Carlo simulations will be performed. The GEANT4 software package developed at CERN will be applied in the simulations. The additional information on the distribution of activity becomes important in objects that are difficult to sample, such as cryo-pumps, target stations and magnets. Assessing the activity of these bulky objects is problematic due to the complicated structure and strong absorption of gamma rays. The determination of radioactivity in cyclotron auxiliaries, such as different vacuum pumps, is crucial when the parts that need maintenance cannot be provided in the laboratory but have to be sent to authorised workshops abroad.

5. Radiation safety research in other research institutes

The Cores consortium was formed as a consortium between STUK and universities, along the lines envisaged in the Finnish Government Resolution on Comprehensive Reform of State Research Institutes and Research Funding in 2013. At the same time, several government research centres also have key roles in various aspects of emergency preparedness and environmental health, both as research collaborators and authorities with responsibilities in emergency preparedness and response, indoor air quality, food safety or occupational health, for example. Practically all government research institutes, via the Tulanet network, provide a forum for general science policy discussions and research cooperation in broad societal research questions. Cores, on the other hand, is focused on radiation safety research and competence. The Cores consortium is open not only to universities but also to any other research organisations that share an interest in radiation safety research. The first research centre to join Cores in 2018 was VTT Technical Research Centre of Finland Ltd.

The research centres operate under various ministries, providing scientific support for the implementation of policies. Therefore, they have a pronounced impact on society. It is important to note that radiation safety is an interplay between several ministries and civil society, as illustrated in Figure 8. As a result, the government research institutes such as the Finnish Institute of Meteorology, Geological Survey of Finland, National Institute of Health and Welfare, Finnish Institute of Occupational Health, Finnish Environmental Institute, Finnish Food Safety Authority and Emergency Services College have competencies and knowledge that are essential for radiation and nuclear safety in Finland. Furthermore, the universities of applied sciences educate professionals for radiation practices such as radiology nurses educated by Metropolia University of Applied Sciences.

FIGURE 8. Impact on society – the roles of ministries and civil society in radiation safety

6. Roadmap for national and international cooperation 2018–2022

Stakeholder feedback and emerging research needs have been analysed by STUK and the Cores Board of Directors. A new strategy and a roadmap for 2018–2022 has been set up and the national programme has been updated accordingly. This involves engaging new partners, universities as well as research institutes, and organising activities fostering the cooperation, such as joint symposia and working groups. The dissemination of Cores' aims and achievements is supported by the Cores newsletters and its website. Fostering education and training and promoting the joint use of infrastructures and databases (open science) are important lines of action. Cores also promotes national and international funding for radiation sciences and links with the European radiation protection research platforms. In the longer term, the objective is to actively participate in international collaboration, in particular the ninth framework programme (Horizon Europe) and European research activities. A long-term funding plan is among the key objectives for the next strategy period. A firm basis for the funding plan is provided by STUK's decision to invest in research activities during the strategy period. The roadmap for 2018–2022 is illustrated in Figure 9.

2018 - 2020	2021 - 2022
Addressing societal needs	**Linking with international community**

2018 - 2020 – Addressing societal needs

- Reflecting stakeholder feedback
- Updating the national pro-gramme and roadmap
- Engaging new partners
- Publishing Cores Newsletter
- Organising joint symposia
- Fostering education and training
- Promoting the joint use of infrastructures and databases (open science)
- Close co-operation in research
- Promoting national and international funding
- Linking with the European radiation protection research platforms

2021 - 2022 – Linking with international community

- Towards Horizon Europe programme
- Participating in EU research activities
- Organising joint international symposia
- Supporting and coordinating education and training
- A long-term funding plan

Tightening the cooperation between STUK and universities in radiation safety research

FIGURE 9. Roadmap for Cores and the national radiation protection research programme.

6.1 Summary of research activities of Cores partners in the national programme

Table 1 summarises the contribution of Cores partners in the main research areas of the national radiation safety research programme (health, medical radiation, environment, preparedness for emergencies, technologies and measurements, and non-ionising radiation).

TABLE 1. Radiation safety research profiles of Cores partners (National radiation safety research programme)

	H	M	E	P	T	N
STUK	x	x	x	x	x	x
University of Eastern Finland	x	x	x		x	x
Aalto University				x	x	x
Lappeenranta University of Technology				x	x	
Tampere University of Technology			x	x	x	
University of Helsinki	x	x	x	x	x	
University of Jyväskylä			x		x	
University of Oulu		x	x		x	
University of Tampere	x	x				x
University of Turku	x	x				
Åbo Akademi		x				

H Health (biological effects, mechanisms of action, health risks)
M Medical radiation (exposure of patients and personnel, optimisation)
E Environment (transfer of radioactive substances, modelling, effects on biota)
P Preparedness for emergencies (models, decision support, countermeasures, remediation)
T Technologies and measurements (metrology, dosimetry, detectors, models)
N Non-ionising radiation (exposure, dosimetry, effects)

6.2 Cores research activities and the Euratom Joint Programme in radiation protection research

The European Joint Programme CONCERT (2015-2020, Euratom) is preparing a joint roadmap based on the strategic research agendas of all European radiation protection research platforms (MELODI, ALLIANCE, NERIS, EURADOS, EURAMED). The first version of the joint roadmap can be found on the CONCERT website.

One of the CONCERT objectives is to more effectively link the European and national programmes in radiation protection research. Almost all EU countries have one or more national Programme Owner and Manager (POM) as beneficiaries in CONCERT. For the further development of the roadmap, POMs have been consulted on their interest in the proposed exposure scenarios and research challenges, possible other challenges or sub-challenges, and they were also asked, if possible, to estimate resources within 5–10 years linked to some research goals.

The joint roadmap is based on seven exposure scenarios and eight research challenges.

Exposure scenarios:

1. Patients' exposure regarding medical applications of X-rays, electron or particle radiation, including the use of radiopharmaceuticals
2. Exposure of the general public and the environment as a consequence of industrial applications of ionising radiation and the use of NORM in normal operation conditions
3. Exposure of workers in normal operation conditions
4. Exposure of the general public and the environment with regard to legacy
5. Exposure of the public and the environment to the natural radiation environment
6. Exposure of the general public, workers and the environment following a major nuclear or radiological accident or incident, including long-term consequences
7. Radiation protection of the public, workers and environment as a consequence of a malevolent nuclear or radiological act, including long-term consequences

Research challenges:

A. Understanding radiation-related human health effects
B. Improving the concept of effective dose and other quantities
C. Studying the biological and ecological effects on biota
D. Optimised radiation protection in medical applications of ionising radiation
E. Improving radiation protection for workers

F. Integration and optimisation of environmental exposure assessment for ionising radiation and other stressors
G. Optimising emergency and recovery preparedness and response
H. Enhanced integration of radiation protection science with society

The exposure scenarios and research challenges were discussed by the board of Cores (Consortium for Radiation Safety Research, Finland). Two Cores members (STUK and the University of Eastern Finland) are POMs (Programme Owners and Managers) in CONCERT, nominated by the Ministry of Social Affairs and Health and Ministry of Education and Culture, respectively. The University of Tampere is an LTP in CONCERT and all are linked at the national level, based on the long-term agreement signed by the parties). Cores also forms a link in the context of the Euratom EJP on Nuclear Waste Management. Overall, the interests and coverage of the challenges are very similar at the national and European level, with the exception that the national programme also covers non-ionising radiation, which is not part of the Euratom programme. As a general comment, Cores notes that the strategic research agendas of the European RP research platforms (EANM et al. 2017, Hinton et al. 2013, Kreuzer et al. 2018, Rühm et al. 2016, NERIS 2017) are based on scientific challenges, whereas the joint roadmap is structured from the point of view of societal impact. Overall, Cores finds the development of European SRAs in the RP field very useful and looks forward to more active participation in the Euratom research. The question of resources is more difficult. At the national level, there is no single or major source for funding the research in radiation safety.

Tables 2 and 3 summarise the research activities of Cores partners in relation to the planned European Joint Programme. Table 2 shows the exposure scenarios addressed by Cores partners and Table 3 shows which research challenges of the European joint roadmap for radiation protection research are addressed by each Cores partner. It shows that the national programme covers all exposure scenarios and research challenges, thus providing an excellent basis for research collaboration at the European level.

TABLE 2. **Exposure scenarios of the European Joint Programme in radiation protection research addressed by Cores partners (CONCERT survey 2018)**

	1	2	3	4	5	6	7
STUK (POM)	x	x	x	x	x	x	x
University of Eastern Finland (POM)	x	x		x	x	x	
Aalto University						x	
Lappeenranta University of Technology					x		
Tampere University of Technology				x	x	x	x
University of Helsinki	x	x		x	x	x	x
University of Jyväskylä	x			x		x	x
University of Oulu	x					x	x
University of Tampere	x			x	x		
University of Turku	x	x					
Åbo Akademi	x	x					

1. Patients' exposure regarding medical applications of X-rays, electron or particle radiation, including the use of radiopharmaceuticals
2. Exposure of the general public and the environment as a consequence of industrial applications of ionising radiation and the use of NORM in normal operation conditions
3. Exposure of workers in normal operation conditions
4. Exposure of the general public and the environment with regard to legacy
5. Exposure of the public and the environment to the natural radiation environment
6. Exposure of the general public, workers and the environment following a major nuclear or radiological accident or incident, including long-term consequences
7. Radiation protection of the public, workers and environment as a consequence of a malevolent nuclear or radiological act, including long-term consequences

TABLE 3. Euratom Joint Research Challenges – research profiles of Finnish POMs and LTPs (CONCERT survey)

	A	B	C	D	E	F	G	H
STUK (POM)	x	x	x	x	x	x	x	x
University of Eastern Finland (POM)	x	x	x	x	x	x		
Aalto University					x		x	
Lappeenranta University of Technology							x	
Tampere University of Technology			x		x		x	
University of Helsinki		x	x	x		x	x	
University of Jyväskylä		x	x				x	
University of Oulu			x	x			x	
University of Tampere	x			x				x
University of Turku				x	x			
Åbo Akademi				x				

A. Understanding radiation-related human health effects
B. Improving the concept of effective dose and other quantities
C. Studying the biological and ecological effects on biota
D. Optimised radiation protection in medical applications of ionising radiation
E. Improving radiation protection for workers
F. Integration and optimisation of environmental exposure assessment for ionising radiation and other stressors
G. Optimising emergency and recovery preparedness and response
H. Enhanced integration of radiation protection science with society

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ISBN 978-952-309-429-1
ISSN 2243-1888 (pdf)

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