Master of Science Thesis
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Radiation protection measurements in clinical practice - Dosimetry with NaCl pellets

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Strålskyddsbestämningar i kliniska verksamheter - dosimetri med NaCl chips

Persondosimetri för vårdpersonal, som i sitt yrke exponeras för joniserande strålning, är ständigt ett hett ämne och under konstant utveckling. Stråldosen mäts och registreras för att uppfylla riktlinjer och lagar, som syftar till att hålla personal säkra vid arbete med joniserande strålning. Det finns en rad olika sätt att mäta stråldoser till en människa. För att effektivt uppskatta och mäta strålningsexponering är arbetstagare inom vården utrustade med så kallade dosimetrar, vilka kan placeras på olika delar av kroppen. En ny och lovande sådan dosimeter är baserad på vanligt hushållssalt (NaCl). Denna dosimeter kan komma att bli ett effektivt, lätthanterligt och billigt alternativ till de kommersiella dosimetrar som används på sjukhusen idag.

I detta MSc arbete har dessa saltbaserade dosimetrar undersökts för dosimetri inom olika kliniska applikationer, och i de fall där det varit möjligt har resultaten jämförts med en etablerad metod för dosimetri som används inom sjukvården idag. Bl.a. har dosimetrarna utvärderats för användning på händer hos personal inom brachyterapi och radiofarmakaproduktion samt för bakgrundsmätningar i vissa utvalda lokaler. Vanligt hushållssalt i lös form har pressats samman till pellets, och en dedicerad förpackningsmetod för dessa har tagits fram. De inpackade pelletsen placerades i sin tur på strategiska positioner på operationshandskar. Dessa handskar har sedan använts i klinisk verksamhet av personal vid hantering av radioaktiva preparat vid Skåne Universitetssjukhus. Saltpellets placerades även på strategiska platser i och nära lokaler där radioaktiva läkemedel produceras, administreras till patienter eller handskas på annat vis.

Resultaten i detta MSc arbete visar att vanligt hushållssalt har bra egenskaper för att uppskatta stråldoser, både till personal och i arbetsmiljö, samt möjliggör dosuppskattningar i många mätpunkter samtidigt utan någon extra kostnad mer än i tid. Dosuppskattningar till många punkter på händerna ger goda indikationer på hur personalen arbetar och rör sina händer i strålfälten, vilket kan fungera som ett bra verktyg för att optimera det dagliga arbetet för att minska doserna samt ett mer rättvist mätvärde än exempelvis mätvärdet från en persondosimeter fäst på bröstet. Även långtidsmätningar i lokaler ger en bra fingervisning om hur och var personalen kan röra sig i lokalerna för att minska doserna ytterligare. Därmed visar detta på potentiella möjligheter för saltpellets att användas som dosimeter i kliniska tillämpningar.

Abstract

Within the field of medical radiation protection, radiation safety and personal dosimetry, there is a constant pursuit for improving existing methods and evaluating new approaches for measuring and quantifying the radiation doses that hospital staff may be exposed to in their clinical work. There are numerous ways of determining what doses the staff are being exposed to and the most commonly used is based on thermoluminescent dosemeters (TLD) with *e.g.* chips of lithium fluoride. However, these traditional TLDs tend to be expensive which limit the possibilities of having many simultaneous measuring points on the same occasions in clinical practice. Furthermore, the TLDs based on lithium fluoride are toxic and have a limited lifetime, both physically and in terms of calibration.

Ordinary sodium chloride (NaCl) has, in many studies, been found to possess good properties for quantifying exposure to ionizing radiation, making it a good candidate as a potential dosemeter in clinical applications. NaCl is cheap, non-toxic and the use of NaCl for dosimetry is based on one-time usage of the dosemeters with an individual calibration directly after reading the signal. These factors in combination with the read out of the signal is based on optical stimulation rather than thermal, provides for potentially high accuracy in the dose determinations as well as lower detection limits.

The aims of this study have been to investigate the potential of ordinary household salt, in the form of NaCl pellets, for radiation dose assessments in a variety of clinical applications: to determine “hand doses”, “body doses” and to perform dose mapping of laboratory premises. In the study it was also evaluated what advantages and disadvantages salt pellets has as a potential dosemeter within these clinical applications as well as investigating which what type of packaging technique that are beneficial in order to keep the NaCl pellets protected and easy to handle, and what possible improvements that might be needed.

The project has shown that a good packaging technique, sufficient to keep the NaCl pellets protected from both light exposure and mechanical stress during use in clinical work, is necessary. An initial layer of ordinary household plastic followed by 4 layers of aluminum foil was determined to be optimal. The study further showed that the equivalent dose to the treating physicians hand surface, during low-dose-rate (LDR) brachytherapy, was between 0-0.33 mSv using 96 measuring points evenly distributed over the hands. It also showed that the nurse, during the same treatment and with the same amount of measuring points, received between 0-0.27 mSv over the hand surface. Furthermore, using the NaCl pellets it was shown that the equivalent dose to the hand surface, of the staff working with ^{18}F-FDG synthetization, was between 1.04-15.10 mSv for a 30-minutes session. The staff working with Ammonia synthetization received a dose to the hand surface between 0.9-5.2 mGy per preparation. All measurements of hand surface doses thus showed a large diversity in terms of dose magnitude and how the dose is distributed over the hands. Also, the premises where ^{18}F-FDG and Ammonia synthetization takes place, were measured for 7 days and showed large variation in the room depending on where the “sources” were placed and handled during the measurement period. In addition, prolonged measurements were performed during 6 weeks at office premises

close to patient administration rooms (^{18}F-FDG), which showed a mean dose rate of 0.032 uSv/h i.e. well under the normal background level of 0.16 uSv/h. All together, these results show potential for optimization of the various clinical practices and may be used when educating the personal for planning and conducting their work. The NaCl pellet results also opens for more elaborate assessments in other routine and complex clinical irradiation geometries. ‘

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1. Introduction

Personal dosimetry is under constant development to keep track of doses in order to fulfill the guidelines and laws established to keep workers safe when exposed to ionizing radiation. The radiation exposure of workers within clinical practices with ionizing radiation is constantly monitored by dosimeters placed on various parts of the body. Since many commercially available dosimeters, such as thermoluminescent dosemeters (TLD) with *e.g.* lithium fluoride, are expensive, it would be desirable with an alternative dosimeter that is readily accessible, non-expensive, easy to evaluate and with similar or better dosimetric properties as TLDs. If, in clinical practices (and nuclear industry) the commercially available personal dosimeters could be supplemented with a cost-effective alternative, the number of measuring points could be significantly increased. Many measuring points could yield a better spatial resolution of the dose distribution, which in turn can lead to more precise dosimetry as compared to a limited number of TLDs.

It is well known that NaCl possess suitable properties for measuring and quantifying the amount of ionizing radiation it has been exposed to (Bailey *et al.*, 2000; Thomsen *et al.*, 2002; Bøtter-Jensen *et al.*, 2003), when read by optically stimulated luminescence (OSL). More recently, NaCl has been suggested for prospective personal dosimetry (Bernhardsson, 2011) and as an environmental dosimeter (Bernhardsson, 2012). It has previously been shown that the dose response for salt in grain form is linear (Bernhardsson *et al.*, 2009). However, salt compressed to pellet form is easier to handle than salt gains, can thus potentially give more reproducible results and has a strong OSL signal that is easily quantified. The dose response for salt pellets, as used in this thesis, has previously been investigated for 3 different types of salt, which shows to be linear in the range from (at least) 1 mGy up to 300 mGy (Waldner e Bernhardsson, 2018). A linear dose response, in combination with a low fading, low detection limit and high reproducibility (Waldner e Bernhardsson, 2018) indicates that NaCl may have excellent prerequisites for replacing or supplementing existing commercial dosemeters for personal and ambient dosimetry, possibly making dosimetry available to a larger extent since NaCl is very common and cheap to buy.

The specific aims of this thesis are:

1. Which packaging techniques are beneficial for NaCl pellets when used in clinical applications, to keep them well protected while still being easy to handle, and what potential improvements that can be made.
2. Investigate the potential of NaCl in the form of pellets for radiation dose assessments in selected clinical practices and to evaluate what are the benefits and drawbacks as compared to available alternatives, hence, to determine:

    a) The dose distribution over the hand surface of relevant staff within brachytherapy and radiopharmaceutical production.
    b) The dose distribution in the premises of a radiopharmaceutical production unit and at offices close to a room for radiopharmaceutical administration to patients.
    c) Compare, when possible, the results with established dosimetry alternatives.

2. Theory

2.1 The basics of optically stimulated luminescence (OSL)

Optically stimulated luminescence is a process (Figure 1) derived directly from the fundamental physics of crystalline structures in semiconductor and insulator materials and the corresponding energy levels (ground state and excited states) within those. In crystals, which are made of a repeated pattern of ions, the constituent electrons are subjected to an electronic field and thus experience a periodic potential which keep the electron-hole pairs at certain strictly allowed energies. In a perfectly pure crystal, *i.e.* a crystal with no impurities and defects in the crystal lattice, the electrons and holes can only occupy two states; the ground state (the valence band) and the excited state (the conduction band). The energy states in between these two are called the bandgap and is forbidden for the electrons and holes to occupy. However, perfectly pure crystals do not provide the mechanism for keeping electrons and holes in metastable states in such way that the energy later can be released through the OSL process. For this process to occur the crystal need to have impurities or defects within its lattice. These impurities and defects may consist of extraneous atoms, missing atoms, extra atoms and dislocations as well as other defects in the crystal lattice (Yukihara e Mckeever, 2011). The defects and impurities introduce energy levels within the bandgap in which the electrons and holes can be trapped. When the structure is exposed to ionizing radiation with an energy above a certain threshold energy, the electrons are excited to the bandgap where they can be trapped in forbidden states (Joerkov Thomsen, 2004). Stimulating the system with light of certain wavelengths, or heat, luminescence is emitted when electrons recombine with a hole, that may take place in a so called recombination center at a certain energy level, and this is referred to as the TL and OSL signal, respectively (Yukihara e Mckeever, 2011). In this thesis only the OSL technique was used to obtain the radiation induced signal.

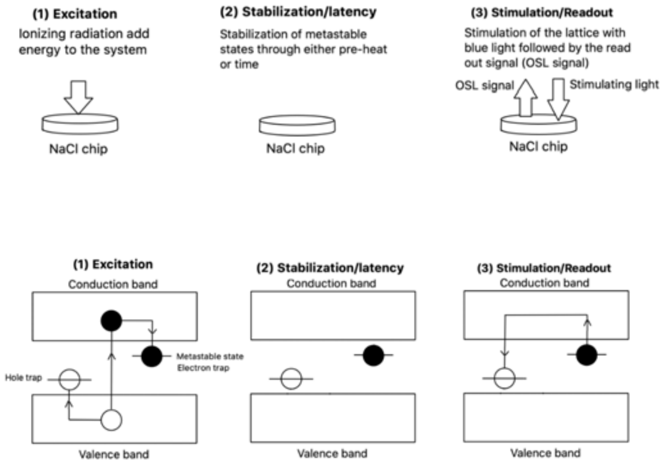

Figure 1. Schematic drawing of the stages in the OSL process with the corresponding energy state diagram: (1) the excitation process in which ionizing radiation excites the system and creates free holes and electrons; (2) a latency or preheat period in which the electrons and holes are stabilized in the metastable states; (3) the stimulation process in which stimulating light makes the electrons and holes recombine, a process followed by the emission of OSL light.

2.2 The Risö TL/OSL reader

The system used to read the OSL signal from the NaCl is the commercially available Risø (DTU Nutech, Denmark) TL/OSL-DA-15 system (Figure 2). This reader is a complete research system for both irradiation of multiple samples and readout through either thermoluminescence or optically stimulated luminescence. The irradiation system can be used to initially irradiate the samples and/or to give a calibration dose when calculating doses to samples. In order to read a TL or OSL signal, the samples can be stimulated to de-excite either by heat from a heating element or by light from light emitting diodes (LEDs). In this thesis, only OSL is used. The calibration process is performed using an internal $^{90}Sr/^{90}Y$ beta source that yields a dose rate of 0.72 mGy/s to NaCl at the sample position in the reader. The OSL signal is detected by a photomultiplier tube (PMT) during the LED stimulation and the whole process is controlled with a software in which different sequences can be assembled. The NaCl pellets are placed in small metal cups on a large rotating carrousel containing 48 cups (Figure 2). When read, each disc is fitted inside the readout chamber containing the PMT, irradiation unit, heat element and the LEDs.

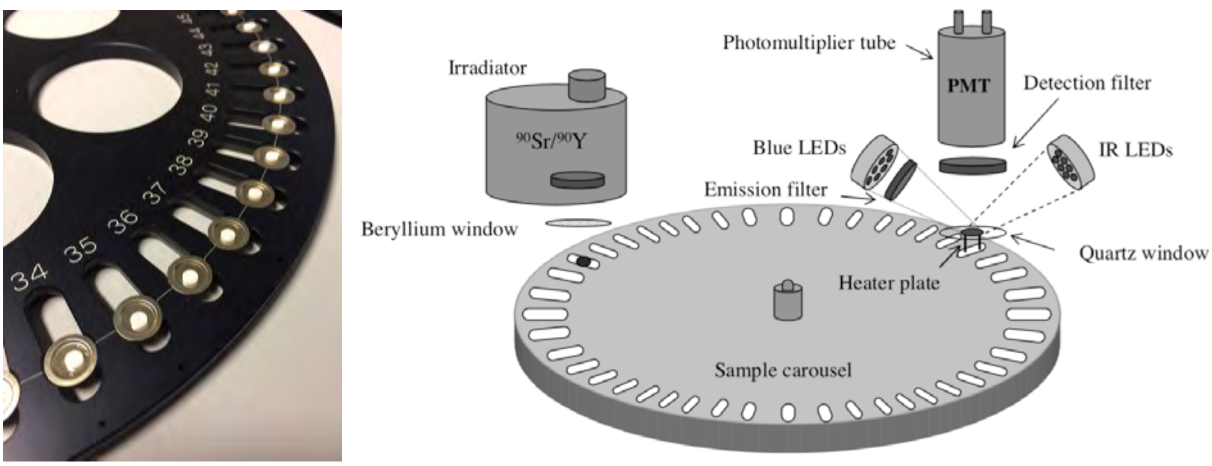

Figure 2. Left: NaCl pellets placed on the cups of the Risö TL/OSL sample carrousel. Right: Schematic overview drawing showing the carousel wheel, LEDs, radiation source and the photomultiplier (Joerkov Thomsen, 2004).

2.3 Read out protocol

In order to read the signal from the samples, different protocols need to be used in the reader software. The protocols may vary depending on the desired process and the material studied. The readout protocol (as suggested by Waldner 2017) used in this thesis to read the OSL signal from the samples of NaCl is presented in Table 1.

Table 1. Readout protocol for NaCl (Waldner 2017).

Step	Settings and process
1	Readout of the OSL signal, 20 sec
2	Administration of the calibration dose, D_c, with the internal $^{90}Sr/^{90}Y$ source
3	Paus, 3600 sec
4	Readout of the OSL signal corresponding to D_c, 20 sec

When administrating an initial calibration dose D_c to the pellets, it has previously been shown that a pause between the administration and read of the signal S_c is needed in order for the signal to stabilize (Waldner e Bernhardsson, 2018)

2.4 OSL properties of NaCl

It has been shown that NaCl possess properties for suitable for dosimetry using either OSL or TL processes (Bailey *et al.*, 2000; Thomsen *et al.*, 2002; Bernhardsson *et al.*, 2009). The thermal stability, sensitization, temperature dependence, dose response, signal stabilization after manufacturing, minimal detectable dose and signal resetting have been studied thoroughly for NaCl grains, showing promising OSL dosimetric properties of NaCl also for low-doses (Thomsen *et al.*, 2002; Bernhardsson *et al.*, 2009; Waldner e Bernhardsson, 2018). The dose response for NaCl compressed to pellets is shown in Figure 3. For the three salts shown in Figure 3, and especially for salt 1 which is the salt used in this study, the absorbed dose in the salt, as a function of the OSL signal, is linear in the range from 1 mGy up to 300 mGy (Waldner e Bernhardsson, 2018).

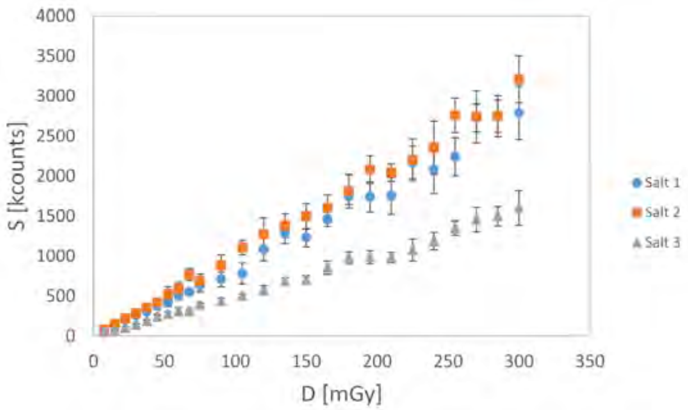

Figure 3. Average OSL signal as a function of the administered dose for three different types of salt for which salt 1 is the salt used in this study. The uncertainty bars correspond to 1 SD of ten NaCl pellets. Picture from (Waldner e Bernhardsson, 2018)

The OSL signal of NaCl is optimally read using light with a wavelength of 420-560 nm (Bailey *et al.*, 2000), corresponding to blue light. Because the OSL signal will reset when the crystal lattice is exposed to light, the NaCl pellets need to be kept in total darkness between irradiation and readout (Hunter *et al.*, 2012; Waldner e Bernhardsson, 2018).

The minimum detectable dose (MDD), the smallest signal that can be separated from the background signal, is defined as three times the standard deviation of the background signal (Currie, 1968; Thomsen *et al.*, 2002; Yukihara e Mckeever, 2011) and has previously been investigated to be as low as 5-21 µGy for the salt used in this study (Waldner and Bernhardsson 2018). Further, the minimum measurable dose (MMD), the smallest dose that can be quantified, have been determined to be in the range of 20-70 µGy (Waldner e Bernhardsson, 2018).

2.5 Dosimetry with NaCl

2.5.1 Personal dosimetry in clinical practice

In all clinical practices where staff may be exposed to ionizing radiation, a well-elaborated radiation protection and safety system must be present in order to minimize the exposure. The personal dosimetry and radiation safety are based on the recommendations and guidelines developed by the International Commission on Radiological Protection (IRCP) and the International Commission on Radiation Units and measurements (ICRU). In radiation protection and safety, a few dosimetric quantities are of fundamental importance. One of the most important quantity and the one mainly used in the work of this thesis is the physical quantity absorbed dose, *D* [Gy], which is defined as the amount of deposited energy [Joule] in unit mass of matter [kg]:

$$D = \frac{energy\ [Joule]}{mass\ unit\ [kg]}\ [\text{Gy}] \qquad [1]$$

The absorbed dose[1] is the fundamental quantity measured in the salt and may be used to correlate the energy deposited in matter to any detriment of ionizing radiation, i.e. the effective dose *D* [mSv]. By using radiation quality weighting factors on the absorbed dose in an organ or tissue and then applying special tissue weighting coefficients for the various tissues and organs, the sum of these weighted organ equivalent doses gives the effective dose (Icrp, 2007).

1. Absorbed dose to salt

2.5.2 Dosimetric properties of NaCl

The signal from the NaCl pellets is determined by integrating the OSL signal over a pre-defined interval. The typical OSL signal in NaCl is almost instantly emitted when exposed to stimulating (LED) light. In Figure 4 this is seen as a sharp peak around 0.5 s (x-axis), after which the signal is fading to a negligible OSL after about 10 seconds. Hence, the integration area of the OSL signal of interest is defined between 0 and 5 seconds of the total read time of 20 seconds. An obtained absorbed dose D_u in a NaCl pellet can be determined by relating the corresponding unknown signal S_u to a known given dose D_c, with a corresponding known signal S_c. When administrating D_c, the best results (dose estimate of D_u) are achieved when $D_c \approx 2 \cdot D_u$ (Waldner e Bernhardsson, 2018).

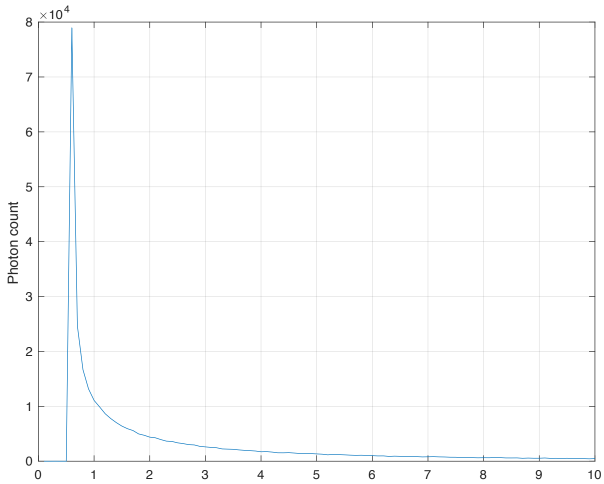

Figure 4. Typical OSL signal from a single NaCl pellet irradiated with 0.72 mGy/s for 40 s. The signal is almost instantly emitted when exposed to the stimulating light, seen as a sharp peak around 0.5 s, then decreasing to a negligible signal after about 10 seconds.

From the relationship:

$$\frac{D_u}{D_c} = \frac{S_u}{S_c} \qquad [2]$$

it is possible to determine the absorbed dose D_u, using the following equation:

$$D_u = \frac{S_u}{S_c} \cdot D_c \quad [3]$$

The dose estimations, $D_{u,}$ compared to the given calibrations dose, D_c, has been shown to be linear for the salt used in this thesis (Figure 5) (Waldne*r e* Bernhardsson, 2018).

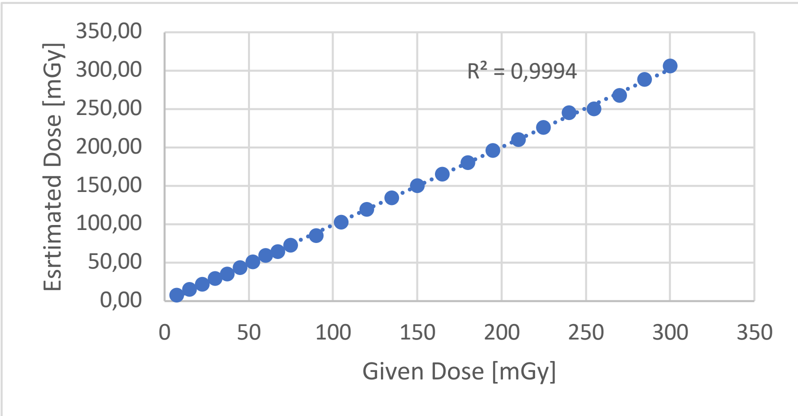

Figure 5. Dose estimations of D_U as a function of administered D_U for the salt used in this study. The uncertainty bars represent 1 SD of 10 NaCl pellets. Picture from (Waldner e Bernhardsson, 2018).

In order to account for any background signal remaining in S_c from the initial signal S_u, the an integration area, defined between 15-20 s of the unknown signal S_u, is subtracted from the integration area between 0-5 s of the known signal S_c (Waldner e Bernhardsson, 2018). The unknown dose D_u is then defined as:

$$D_u = \frac{\int_0^5 S_u}{\int_0^5 S_c - \int_{15}^{20} S_u} \cdot D_c \quad [4]$$

3. Materials and methods

3.1 Manufacturing of NaCl pellets

The NaCl pellets, as seen in Figure 6, consists of ordinary household salt of the brand Falksalt (Hansson & Möhring, Halmstad, Sweden), commercially available from most grocery stores in Sweden. Grains from this salt are compressed into small pellets using a compression tool. The cavities of the compression tool are filled with salt of grain sizes of 100-400 µm, which has been shown to be most suitable (Waldner, 2017), and then put under 3-4 metric tons of pressure which instantly compress the salt into pellets with a diameter of 4 mm and a thickness of around 1 mm. The compression tool produces 5 pellets at each time.

Figure 6. NaCl pellets used in the study, here compared with a standard tweezer.

3.2 Light sensitivity and packaging thickness of NaCl pellets

Since the pellets are sensitive to light, they must be kept in total darkness from the first intended exposure of ionizing radiation until the readout process in the OSL reader. Therefore, the pellet packages needed to be stress tested, *i.e.* in direct daylight. In order for light photons not to reach the pellets and deplete the OSL signal, the packaging material and number of layers of it must be taken into consideration when manufacturing the packages containing the pellets. At the same time, it must be considered not to have too thick layers of protective light shielding for not influencing photons from ionizing radiation.

Figure 7. Packages of aluminum foil containing three NaCl pellets side by side.

A test of the minimum number of layers of aluminum foil needed to keep the OSL signal stable in daylight in combination with being easy to package was performed. This was done by analyzing how the OSL signal from a pre-defined given dose to the NaCl pellets, was affected after the packages was kept in daylight for several days. The pellets were pre-irradiated for 40 seconds with 0.72 mGy/s using the built-in $^{90}Sr/^{90}Y$ beta source and packaged in 1, 3, 5, 7 and 10 layers of aluminum foil along with reference packages wrapped in 13 layers of foil and kept in a light sealed bag. For each thickness layer, 5 packages were prepared and placed on a windowsill. Every 24 hour for 5 days, one of each package was removed and the pellets were unwrapped under darkroom-conditions and the remaining signal was determined. After the exposure, the pellets were unpacked under red light (dark-room conditions) and placed in the Risø reader for readout according to Table 1.

Additionally, to protect the pellets from any moisture, they were packaged in pieces of 3-5 layers of ordinary household plastic film before being wrapped in aluminum foil. The plastic also mechanically protects the pellets and makes it easier to remove the pellets prior to the read-out process.

3.3 Long-term monitoring with NaCl pellets at office premises in connection with rooms for radiopharmaceutical distribution

The offices closest to the radiopharmaceutical distribution rooms, at the nuclear medicine unit at SUS in Malmö, have lead sheets built into the walls for shielding when administering ^{18}F to patients in the form of a radiopharmaceutical called FDG. In order to determine if the staff in these offices receive a dose that can be derived from the administration of these radiopharmaceuticals, the radiation exposure outside the door frames of 7 such offices were monitored for 6 weeks using NaCl pellets positioned at static measurement points (see Figure 8). Six dosemeter packages, with 6 NaCl pellets in each, were positioned on the windows outside each of the offices using light sealed tape to minimize exposure to daylight. Each week for six weeks, one package from each office was removed and the signal from the pellets was read. In order to account for the normal background radiation, two reference packages with NaCl pellets was kept at an office at Medical Radiation Physics in Malmö. These NaCl pellets were readout after 28 days. Based on the reference packages, a mean value of the background signal was calculated and then subtracted from the signals received from the pellets placed at the office premises.

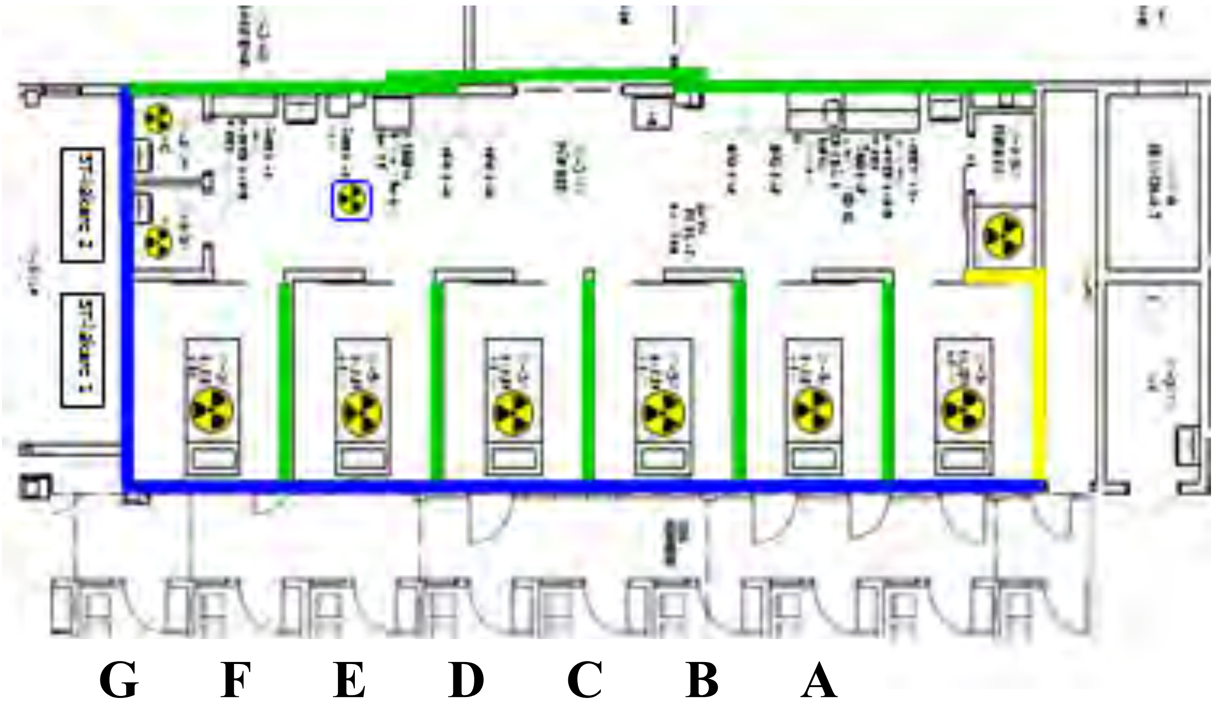

Figure 8. A schematic overview of the administration rooms (marked with a Radiac symbol) and the office premises (A-G) located below the administration rooms, shielded with a 20 mm thick lead sheet (blue line). The green lines correspond to a 4 mm thick lead sheet in the walls between the radiopharmaceutical administration rooms, while the yellow correspond to a 14 mm thick lead sheet towards a corridor for personal and patients (the picture is used with the kind permission of Sigrid Leide Svegborn, SUS, Malmö).

3.4 Dosimetry of hand surfaces using NaCl pellets mounted on gloves during insertion of ^{125}I seeds for brachytherapy

In order to estimate equivalent doses to the surface of the hands of the treating physician and the nurse preparing the needles during one brachytherapy session, as well as to measure the dose distribution over the hands, the physician and nurse used gloves prepared with 48 measuring points per hand. Measurements were carried out during the insertion of needles containing small ^{125}I-seeds. The NaCl packages attached to the gloves were wrapped in ordinary household plastic bags in order to protect the pellets from hand sanitizer, and in addition, 4 outer layers of aluminum foil for light protection. The physician then used the gloves during the whole process of inserting the needles, which lasted for approximately 90 minutes, and for the nurse about 60 minutes during the preparation of the needles.

3.5 Dosimetry of hand surfaces during clinical practice using NaCl pellets

The gloves (Figure 7) were sterilized before they were used in a clinical environment. Packages containing 3 NaCl pellets each were placed on surgical tape and thereafter placed, as dense as possible on the gloves, roughly 15 mm apart in order to maintain the mobility of the fingers in the glove (Figure 8). Each glove was prepared with 49-54 packages (~150 NaCl pellets per hand) evenly distributed on each side of the gloves. The gloves were then sealed and kept in a sterile cloth until they were used in the clinic. An initial test of prepared gloves was performed and are presented in appendix II.

Figure 7. Examination gloves prepared with 3 NaCl pellets in each package. In total 54 measuring points for each glove.

3.6 Monitoring doses in a radiopharmaceutical production lab using NaCl pellets at static measurement positions

3.6.1 Monitoring of a radiopharmaceutical clean room using NaCl pellets at static measurement points

To investigate the radiation environment at various locations inside and around the clean room of the radiopharmaceutical preparation room, close to the cyclotron unit (SUS, Lund), 24 NaCl packages containing 3 pellets each were placed at various positions in the clean room as seen in Figure 8. During these 7 days, the staff in the clean room handled a total activity of 475 GBq of ^{18}F. The packages were removed after 7 days and the signals were read in the Risø TL/OSL reader. In order to account for the normal background radiation, 2 reference packages with NaCl pellets were kept at an office at Medical Radiation Physics in Malmö and the corresponding signals were read after 7 days. Based on these 3 packages, a mean value of the background signal was calculated and then subtracted from the average signals received in the individual NaCl pellet packages positioned in the clean room and the laboratory.

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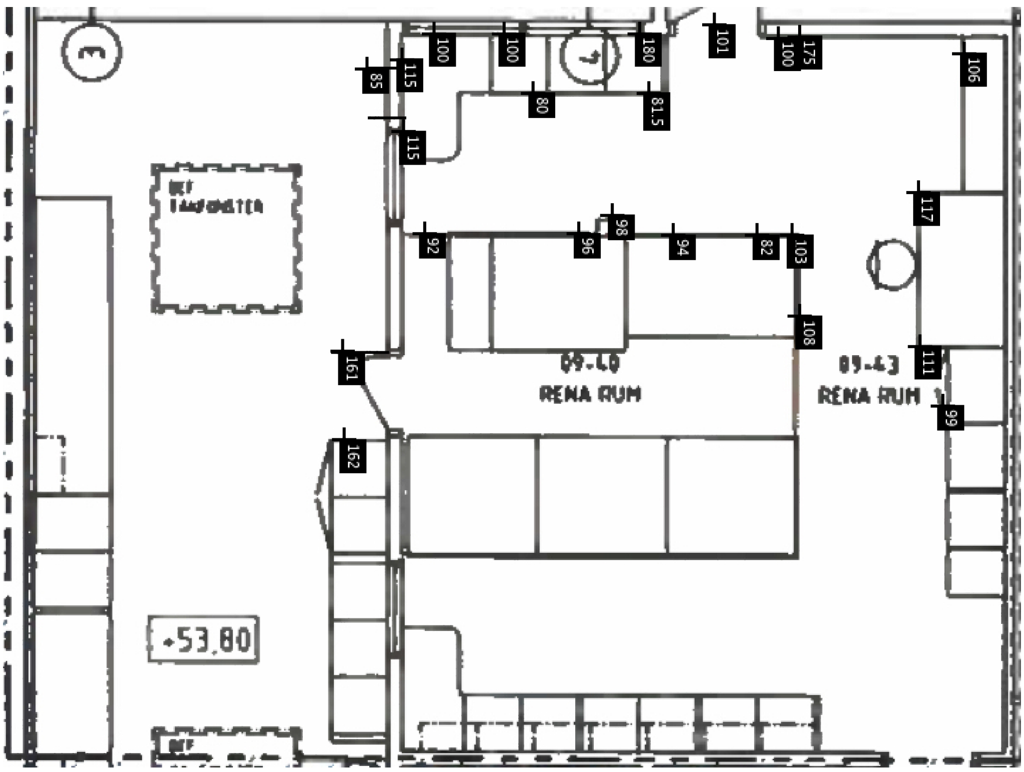


Figure 8. Schematic view of the clean room and laboratory at the radiopharmaceutical preparation unite in Lund. The NaCl packages are marked with the height in centimeters above the floor level (average height 100 cm) (the picture is used with the kind permission of Birgitta Roos, SUS, Lund).

3.6.2 Dosimetry with NaCl pellets mounted on a syringe lead shield

The staff at radiopharmaceutical production units often comes in close contact with high activities when synthesizing *e.g.* ^{18}F-FDG. Hence, finger and hand doses are of special interest in order to keep track of the staff's annual exposure. To determine the potential finger doses of the staff, when holding a shielded syringe during synthetization in the clean room, measurements with NaCl pellets were performed on the surface of a syringe shield made of Wolfram (normally used for FDG preparation at the cyclotron unite). The syringe shielding has a thickness of 0.5 cm and 0.7 cm on the back, with lead glass on the front. Three pellet packages were positioned on the upper, middle and lower part of the front, back and the sides of the syringe shielding as seen in Figure 9. In total, 12 packages were positioned on the syringe shielding. One package was placed on the piston, 10 cm from the volume of the radioactivity, and one NaCl package was positioned on the piston head. The syringe, which contained 0.25 ml FDG at the bottom, corresponding to an activity of about 300 MBq of ^{18}F, was placed in the lead shielding (which in turn was placed in a thick lead jar in order to shield the surroundings) for 30 minutes. In addition, one NaCl package was positioned at the bottom of the lead jar along with a reference TLD

Figure 9. The positions of the measuring points (+) on the syringe wolfram shielding used when handling radiopharmaceuticals in syringes.

3.6.3 Dosimetry to hand surfaces and fingers during $^{18}F^{-}$FDG and Ammonia-synthetization using NaCl pellets

To estimate the equivalent dose to the hand surface and fingers for workers synthetizing $^{18}F^{-}$FDG and Ammonia, gloves prepared with 48 measuring points per hand (as described in section 3.5), were worn under a pair of sterile gloves. The synthetization processes lasted 30 minutes. As reference measurements during the ^{18}F-FDG synthetization, two standard TLD (LiF dosemeters) were positioned at the ring position of the right ring finger and on the middle of the right middle finger.

4. Results and discussion

4.1 Packaging and light sensitivity

The long-term (5 days) measurement with NaCl pellets packed in various thickness of aluminum foil are shown in Figure 11. The relationship between layers and days in direct daylight in relation to the remaining OSL signal is shown for 1, 3, 5, 7 and 10 layers for 1-5 days. As seen in Figure 10, with only one layer of aluminum foil the signal output is significantly influenced by transmitted light. There is a small tendency of a decrease in signal for 3 layers of foil, but with 5 layers of foil (and more) the signal is kept stable and unaffected by the light exposure. Also, with an increasing number of foil layers the stability of the package increase, making the packages easier to handle and thus the pellets less sensitive to impacts and mechanical stress. The photon attenuation in the foil has been calculated as 3% at 30 keV for a 100 µm thick layer using data from National Institute of Standards and Technology (NIST). This can be considered to be negligible and is thus not accounted for in the measurements i.e. photons from ionizing radiation are not attenuated whereas light photons are completely absorbed.

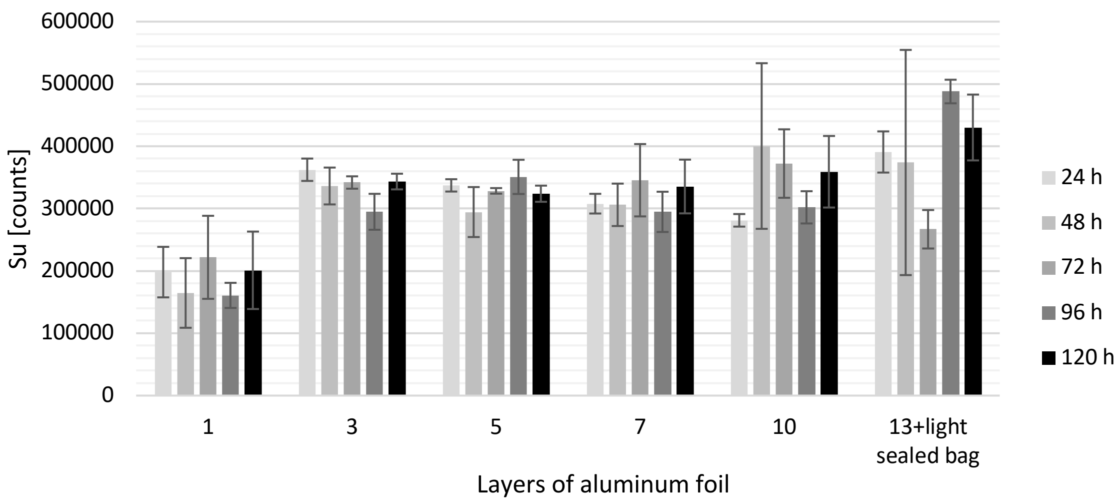


Figure 10. OSL signal output after 1-5 days for pellets, initially irradiated for 40 s at 0.72 mGy/s, placed in direct daylight for different packaging approaches and materials. The error bars correspond to 1 SD of 3 NaCl pellets.

4.2 Long-term dose mapping using NaCl pellets at office premises in connection with radiopharmaceutical distribution rooms

The mean dose rate (µGy/h), derived from the administration of ^{18}F-FDG, at 7 office premises close to the administration rooms at SUS Malmö is shown in Figure 11. The measurements indicate that there are no significant deviations from the background dose rate. The background dose rate at SUS in Malmö was determined to 0.16 µGy/h, so the lead shielding between the administration rooms and the offices are, at the place where the measurements were made, thick enough to attenuate the greater part of the 511 keV photons emitted from ^{18}F. One important thing to note is that during the time of the measurement there was only patients in the administration rooms during daytime from Monday to Friday. The mean dose rate for all weeks are 0.032 µGy/h with a maximum of 0.08 µGy/h for room F during week 6.

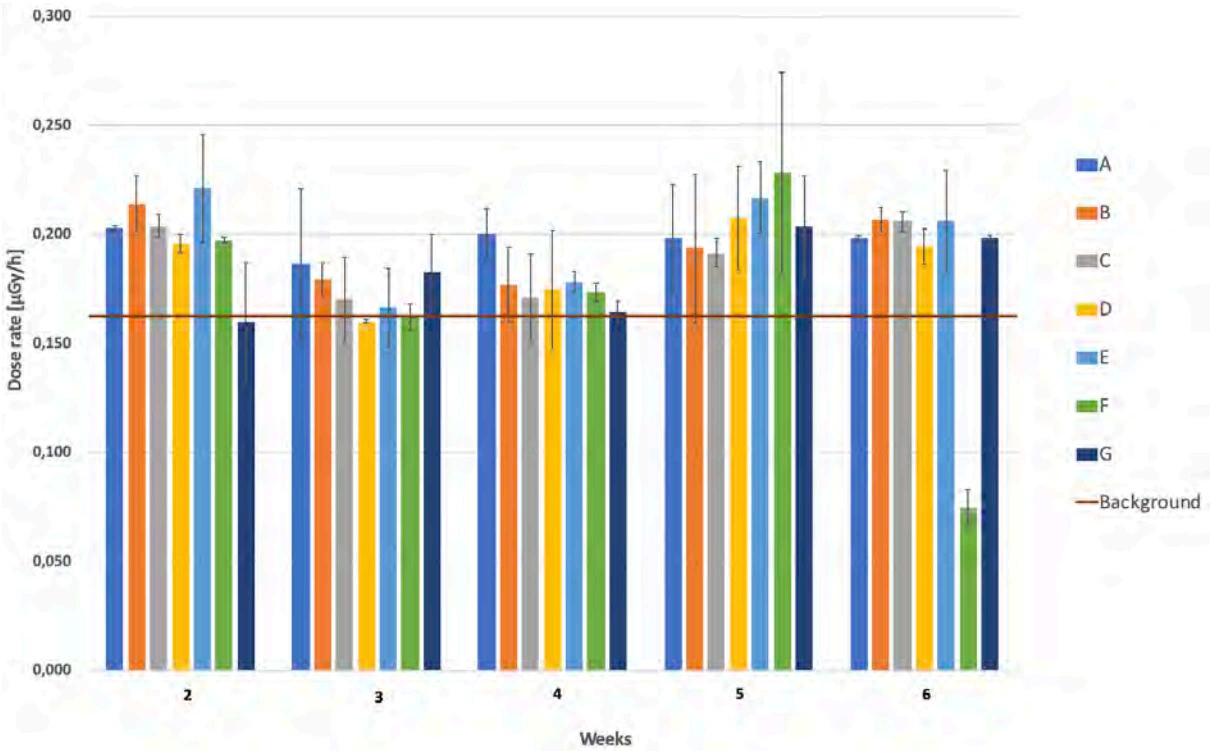
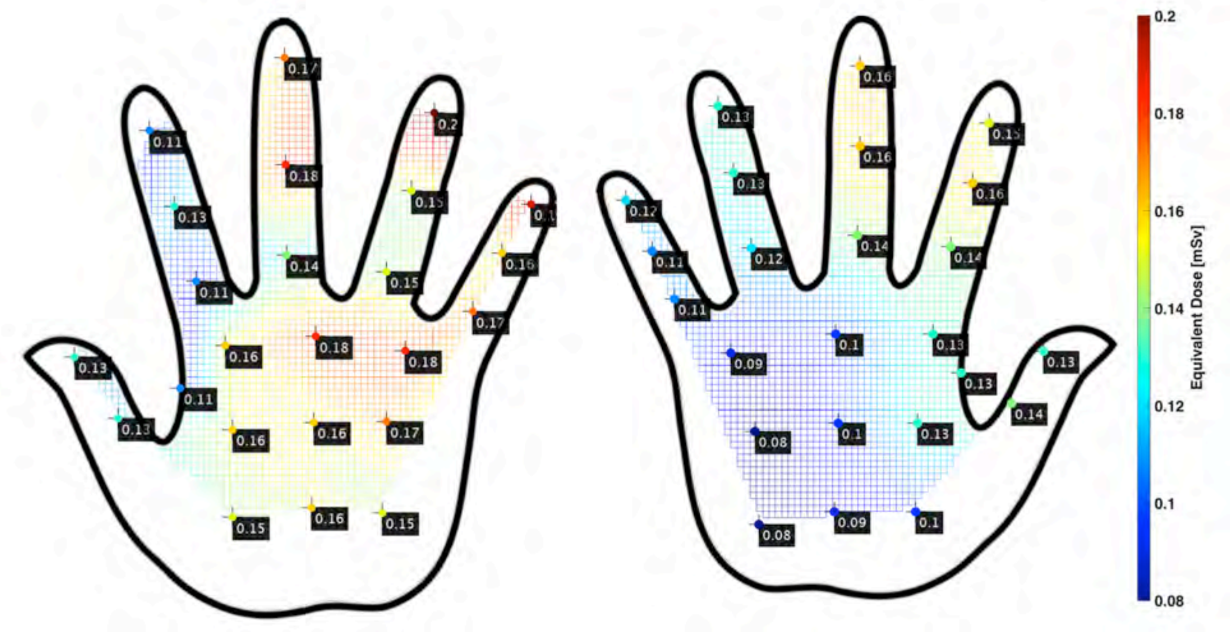


Figure 11. Mean dose rate (Background plus FDG) during two to six weeks for each of the office premises (A-G) along with background reference (brown line).

4.3 Estimation of doses to hand surfaces using NaCl pellets ^{125}I seeds insertion in brachytherapy

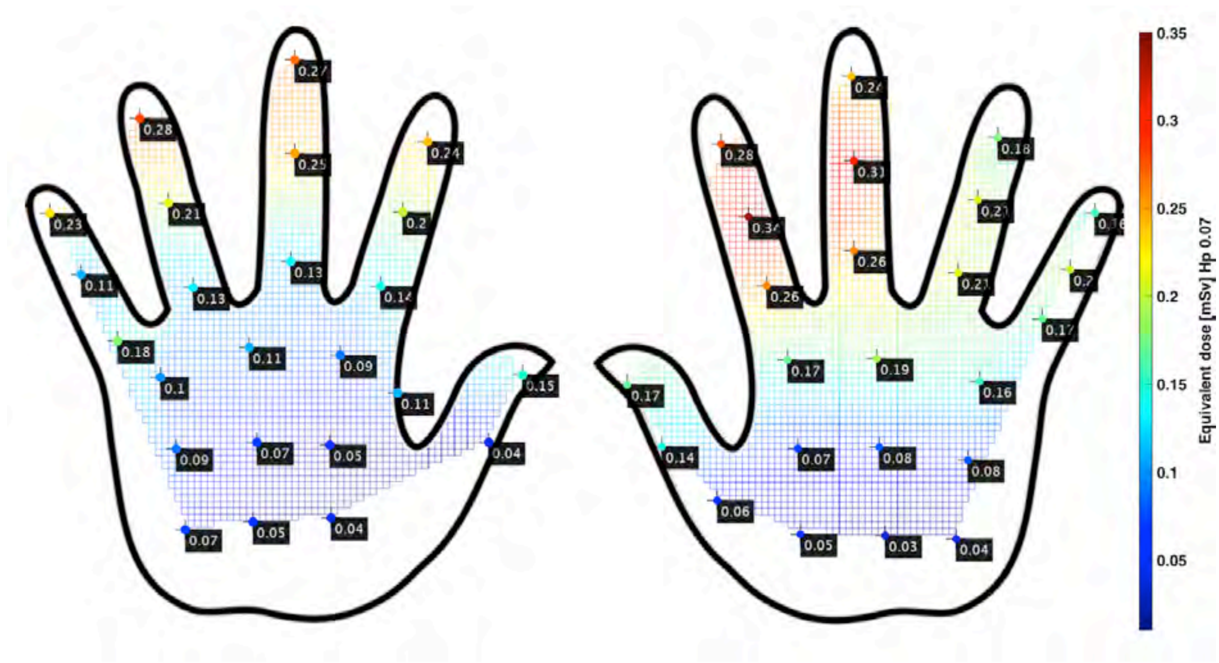
4.3.1 Estimation of doses to hand surfaces of a treating doctor during insertion of radioactive seeds

The estimated equivalent dose distribution to the hands of the physician, received during needle insertion at one occasion, is shown in Figures 12 and 13. The back of the fingers on both hands received a higher equivalent dose as compared to the fingertips of both hands. Overall, the fingers on the left hand received a higher dose as compared to the fingers on the right hand, which probably can be directly derived from how the physician had his hands positioned when the needles were inserted into the patient, rather than the physician being right – or left handed. In Figure 14, it is interesting to observe that the dose increases on the left hand palm, indicated as a red area below the ring finger. This hotspot can probably also be deduced from how the physician placed his hand at the very moment of the seed insertion. However, the radiation exposure originates not only from the seeds but also from the fluoroscopy x-rays used to visualize the prostate and its surroundings. This needs to be taken into consideration but is also more complex to derive from a specific fluoroscopy exposure when moving the hands in a variable X-ray field. The two TLDs positioned on each fingertip showed 0.36 mSv on the right hand and 0.21 mSv on the left hand, respectively. As compared to the doses determined by the NaCl pellets at the same positions, 0.15 mSv and 0.11 mSv respectively, this difference can be explained by the fact that the TLDs and the NaCl pellets were positioned 0.5-1.0 cm apart, with the TLDs closer to the radioactive seeds.



a) b)

Figure 12. Estimated equivalent dose to NaCl pellets (average of 3 pellets at each position) on a) the left hand palm and b) the right hand palm. The mean uncertainties of the equivalent dose for all measuring points are 4%.

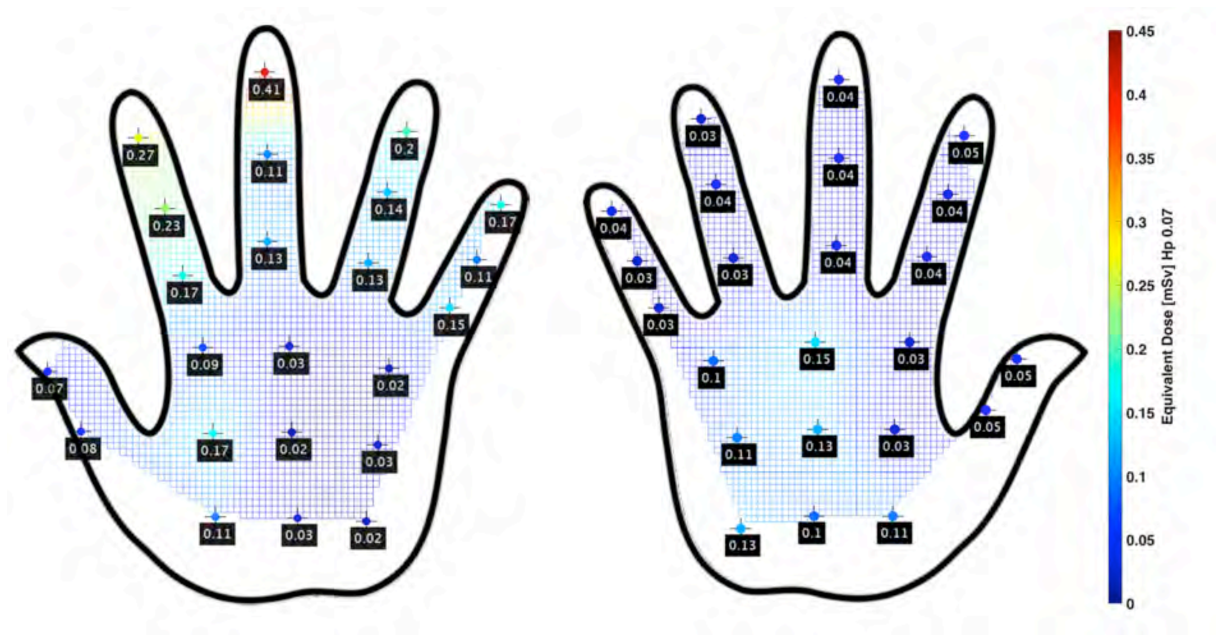


a) b)

Figure 13. Estimated equivalent dose to NaCl (average of 3 pellets at each position) on a) the left back hand and b) the right back hand. The mean uncertainties of the equivalent dose for all measuring points are 4%.

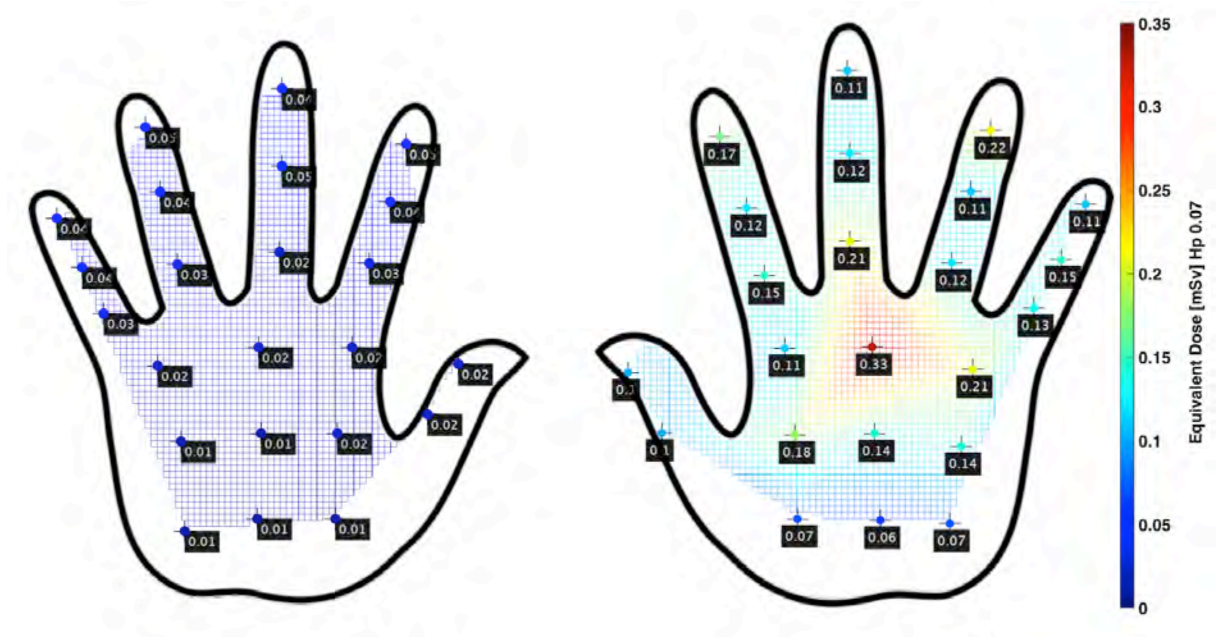
4.3.2 Estimation of doses to hand surfaces of a treating physician during seed insertion, second occasion

The estimated equivalent dose to the surface of the hands of the same physician during needle insertion at occasion two is shown in figure 14 and 15. The dose distribution clearly deviates from the first occasion and shows that there can be large deviations for different sessions for the same physician. This is probably due to the fact that every patient is unique, and therefore the time spent for needle insertion can differ from patient to patient. Also, since the radioactive seeds are placed at different positions within the needles, the dose to the physician can vary between the sessions.



a) b)

Figure 14. Estimated equivalent dose to NaCl pellets (average of 3 pellets at each position) on a) the left hand palm and b) the right hand palm. The mean uncertainties of the equivalent dose for all measuring points are 4%.

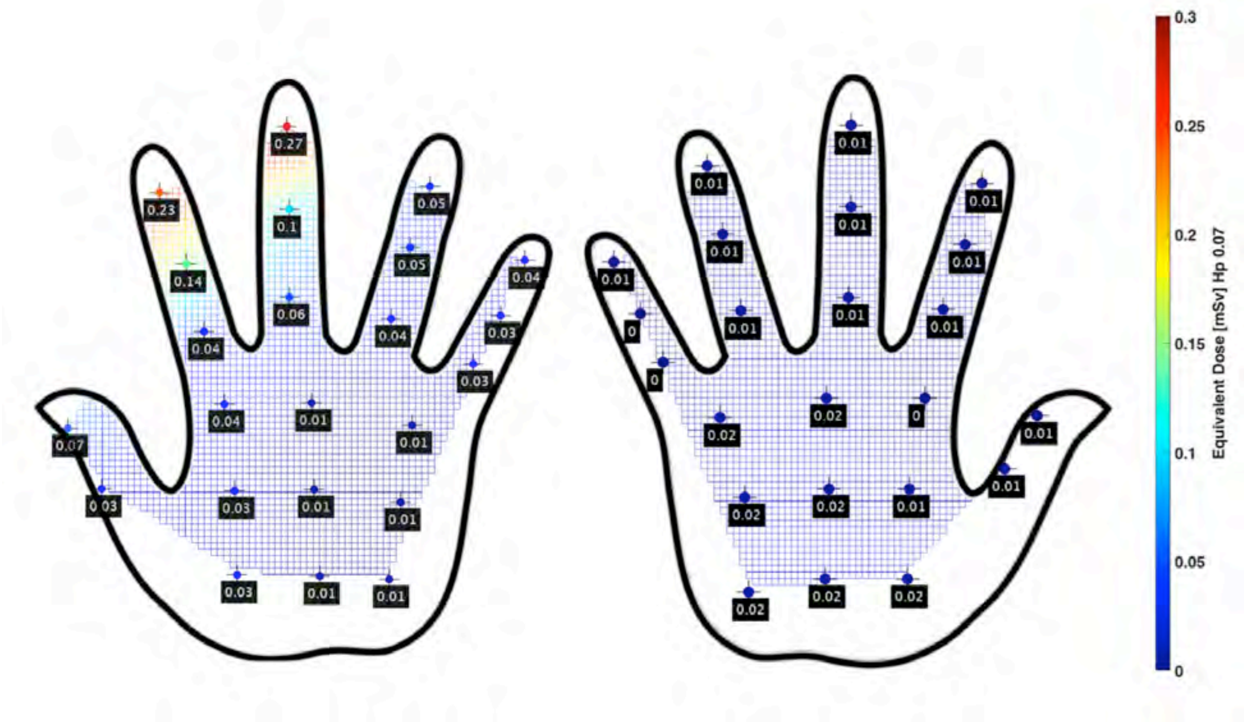


a) b)

Figure 15. Estimated equivalent dose to NaCl (average of 3 pellets at each position) on a) the left back hand and b) the right back hand. The mean uncertainties of the equivalent dose or all measuring points are 4%.

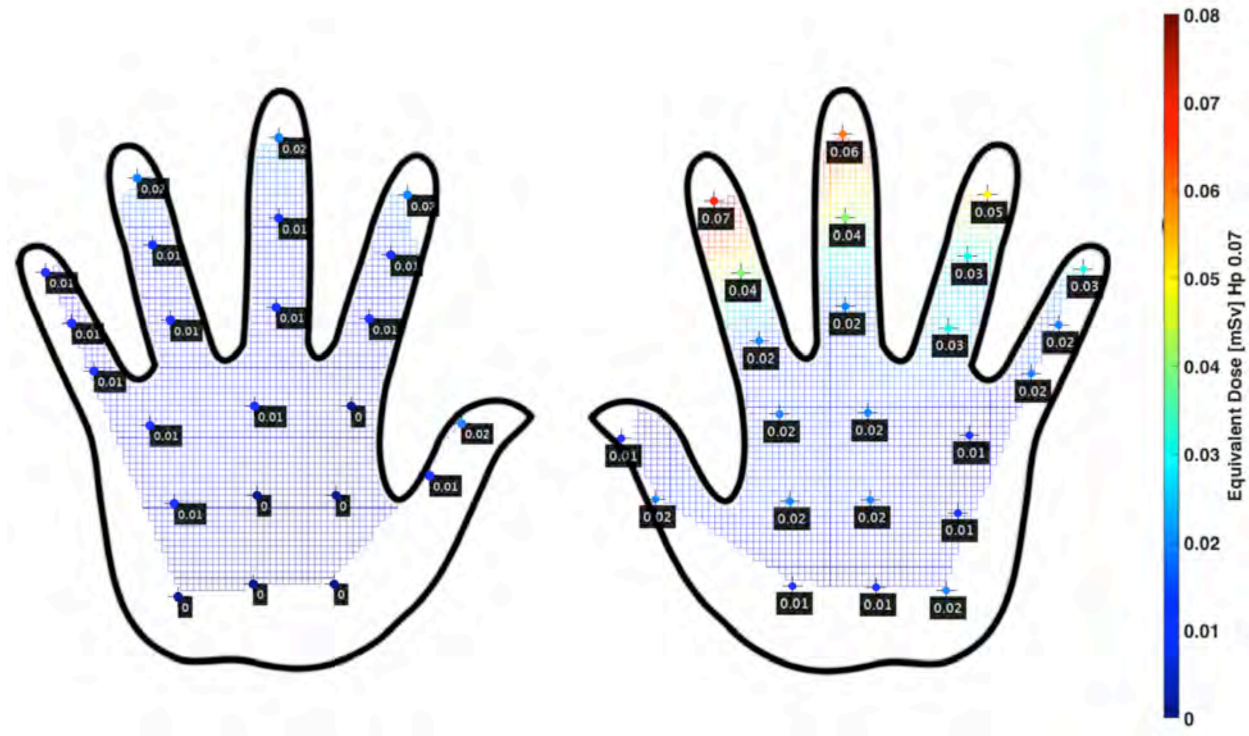
4.3.3 Estimation of doses to the hand surfaces of a nurse during needle preparation

The estimated equivalent dose distribution to the surface of the hands of the nurse during needle preparation with radioactive ^{125}I seeds are shown in Figures 16 and 17. The nurse received the highest dose (0.33 mSv) to the right hand palm, whereas the left hand palm received a much smaller dose (0.01-0.06 mSv). For the back of the hands, the left hand received the highest dose (0.27 mSv) at the tip of the middle finger. This can probably be derived from the method used when loading the needles with radioactive seeds. The needles are prepared in a machine where the nurse expose the right hand palm and the left backhand to the radioactive seeds.



b) b)

Figure 16. Estimated equivalent dose to NaCl pellets (average of 3 pellets at each position) on a) the left hand palm and b) the right hand palm. The mean uncertainties of the equivalent dose for all measuring points are 4%.



a) b)

Figure 17. Estimated equivalent dose to NaCl (average of 3 pellets at each position) on a) the left back hand and b) the right back hand. The mean uncertainties of the equivalent dose for all measuring points are 4%.

4.4 Dose mapping of hands of staff and premises using NaCl pellets at the radiopharmaceutical production unit at SUS, Lund

4.4.1 Long-term dose monitoring around radiopharmaceutical production premises

The results from the 7 days measurement inside the clean room and some of its surroundings are shown in Figure 18. The highest absorbed dose of the 24 measurement points was observed close to the middle of the working area (0.24<D_{max}<0.30 mGy), and at one of the sides of the hatch, used to hand vials to the outside of the clean room, which showed 0.33 mGy. The high dose at the hatch, as compared to the other measurement points at the premises, can be explained by the staff temporarily putting lead jars containing radiopharmaceuticals to the right in the hatch close to the NaCl package. The higher doses, 0.22-0.28 mGy, in the middle of the room can be explained by the fact that a robot system stores high activities inside a radiation-protected area of the room, which at the same time can leak radiation to the surroundings through small joints. At the upper part of the room, the radiation levels are also elevated, seen as a small hotspot where the dose varies between 0.21-0.25 mGy. These hotspots may be derived to the activity being placed to the right on the bench during the processes when activity is handled, but it cannot be ruled out that the hotspots result from spilled activity.

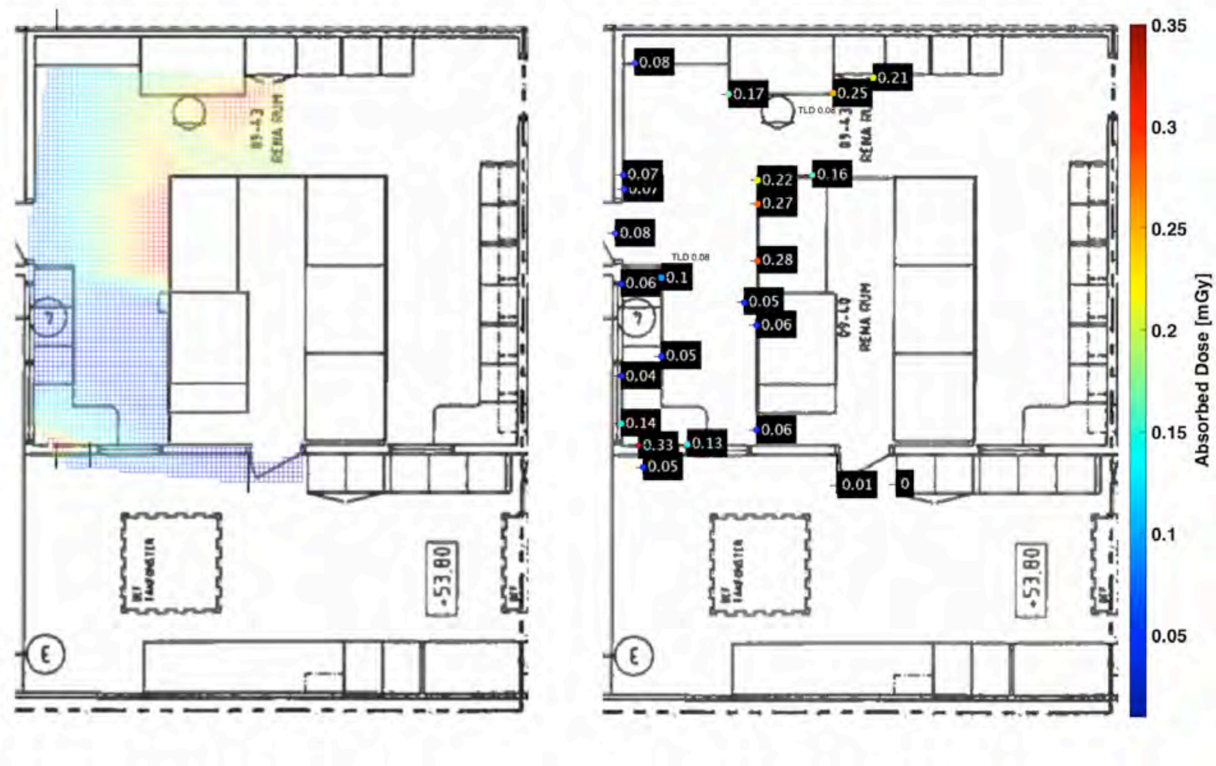
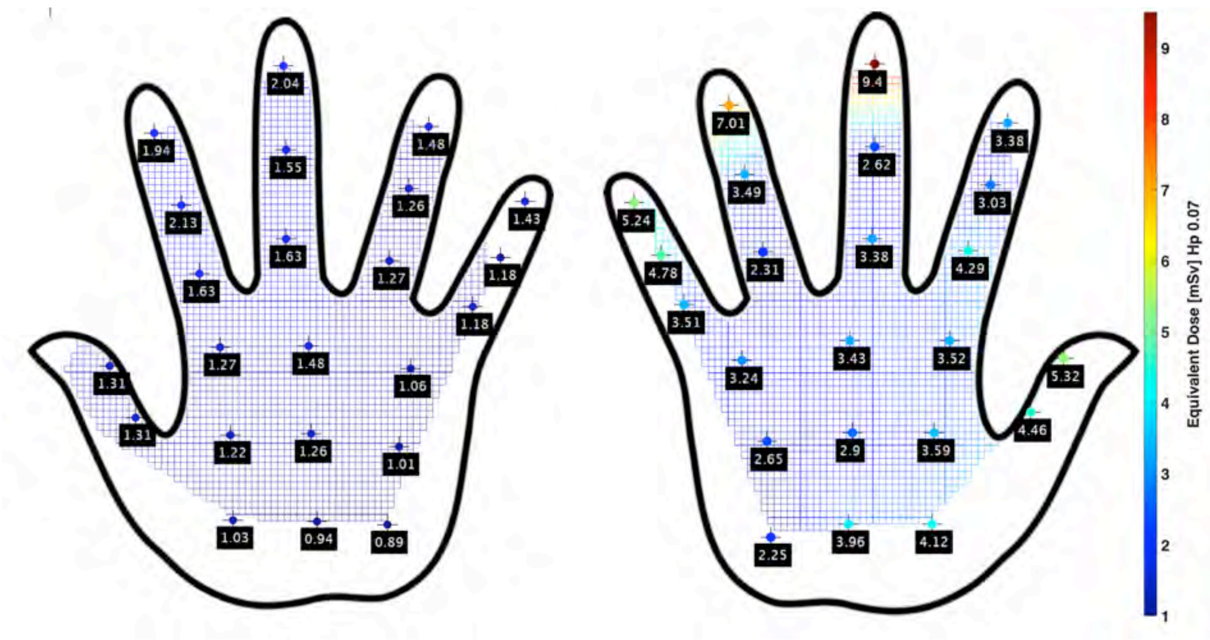


Figure 18. Left: Dose mapping, with interpolated values between measuring points, fused with the schematic drawing of the room. The errors of the absorbed dose for all measuring points are 7%. Right: Schematic view over the clean room and laboratory at the radiopharmaceutical preparation unit in Lund with the accumulated absorbed doses (7 days) marked at the position of the NaCl dosimeters. The reference TLDs both showed 0.08 mGy (from the picture is used with the kind permission of Birgitta Roos, SUS, Lund).

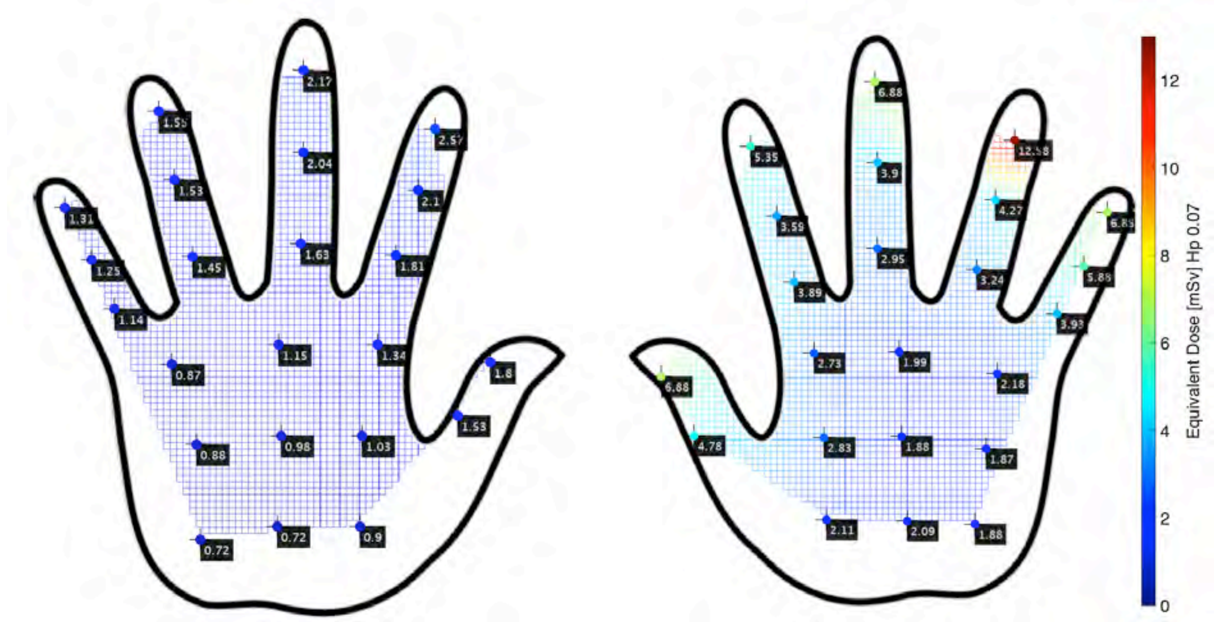
4.4.2 Estimation of doses to hand surfaces using NaCl pellets on gloves during ^{18}F-FDG synthetization

The estimated equivalent dose distribution over the hands of a worker, during one occasion of ^{18}F-FDG synthetization is shown in Figures 19 and 20. The higher doses, up to 9.4 mSv for the middle finger tip of the right hand and up to 12.6 mSv to the top of the same finger, clearly shows that the worker receive the larger part of the hand dose to the finger tips. The uneven distribution further shows that the worker is most likely to be right-handed and thus exposes the fingers on the right hand to a greater extent as compared to the fingers on the left hand. The TLD positioned in the center of the right middle finger received 3.9 mSv, the same as the absorbed dose to the NaCl pellets. Further, the TLD positioned on the ring position of the right hand showed 2.7 mSv as compared to the NaCl pellets close to the same location which received 3.2 mSv. The fact that the TLDs received a dose deviating from the dose to NaCl can probably be explained by the fact that the TLD and NaCl package were not placed on the exact same location, instead they were about 0.5 – 2 cm apart.



a) b)

Figure 19. Estimated equivalent dose to NaCl on a) left hand palm and b) right hand palm. The mean uncertainties of the equivalent dose for all measuring points are 6%.

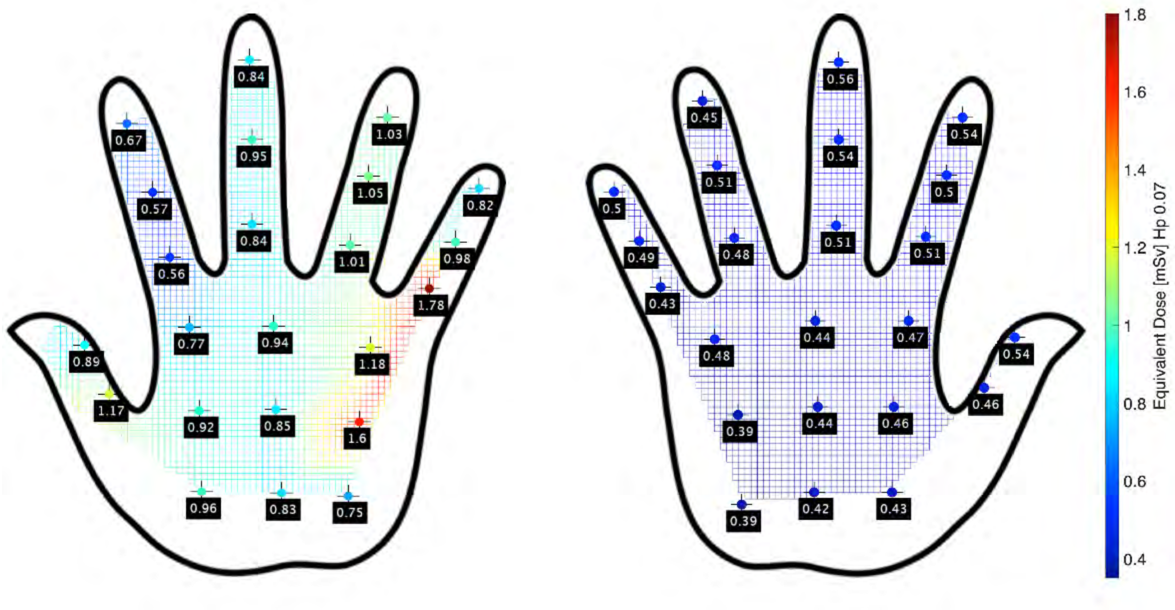


a) b)

Figure 20. Estimated equivalent dose to NaCl on a) left back hand and b) right back hand. The mean uncertainties of the equivalent dose for all measuring points are 6%.

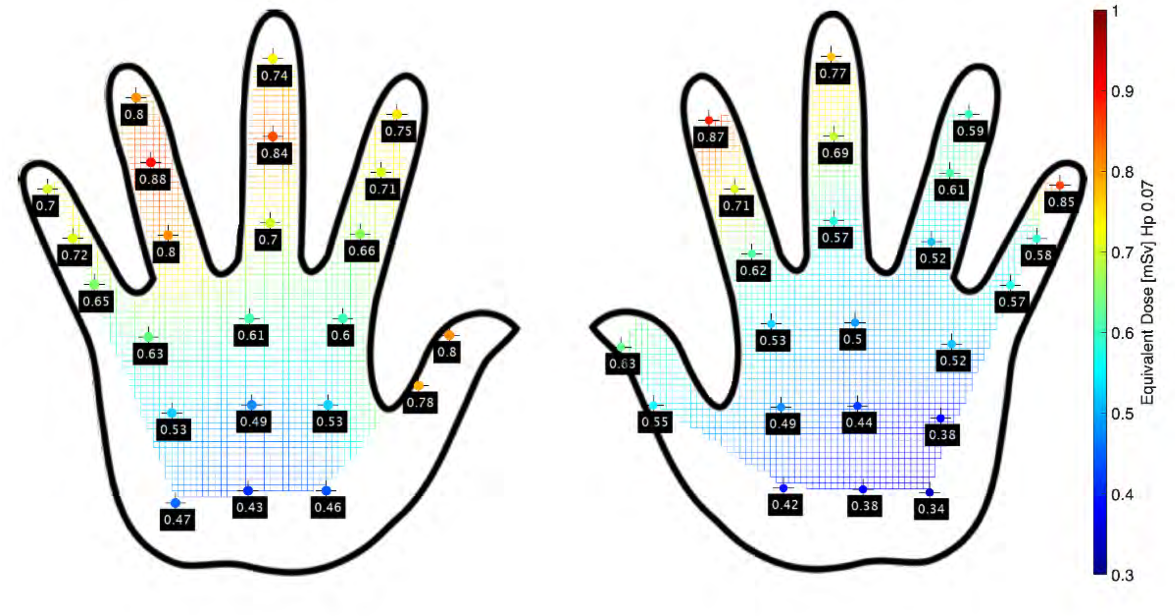
4.4.3 Estimation of doses to hand surfaces using NaCl pellets on gloves during Ammonia synthetization

The estimated equivalent dose distribution over the hands of a worker, during one occasion of Ammonia synthetization, can be seen in Figures 21 and 22. The finger doses (on the backhand sides), with a maximum of 0.9 mSv to the middle of the left ring finger. This is slightly lower as compared to the doses received to the left hand palms which received a maximum finger dose of 1 mSv to the top of the ring finger. One explanation to this is the working method of the staff, the method used involves handling a small plastic hose containing radiopharmaceutical. However, there is a hotspot on the palm of the left hand, with one measured point that received 1.8 mSv which cannot be seen on the back side of the hand. This hotspot may occur due to the staff being left handed or dropping of activity on the hand, alternatively, that the method used during the dispensing of activity resulted in an increased dose to certain parts of the palm. The doses to the right hand palm and back of the hand are slightly lower as compared to the left hand, which can be directly derived from the fact that the person is left handed. During this session no TLDs were available for comparison.



a) b)

Figure 21. Estimated equivalent dose to NaCl on a) left hand palm and b) right hand palm. The mean uncertainties of the equivalent dose for all measuring points are 6%.

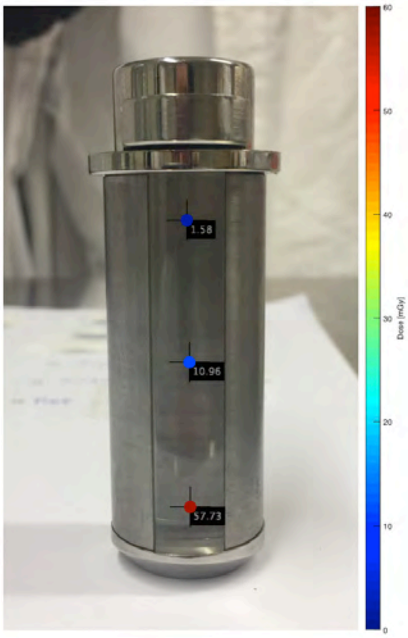


a) b)

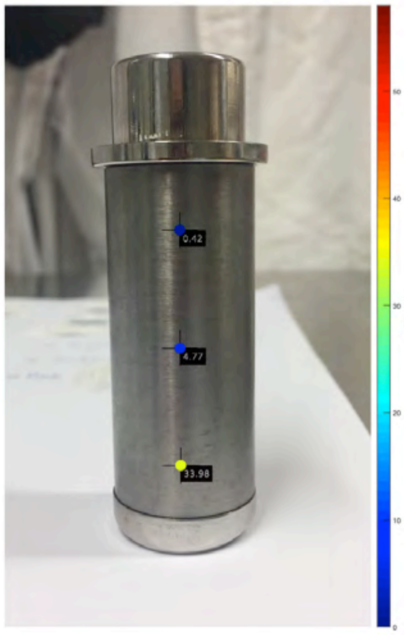
Figure 22. Estimated equivalent dose to NaCl on a) left back hand and b) right back hand. The mean uncertainties of the equivalent dose for all measuring points are 6%.

4.4.4 Dose mapping of a syringe with wolfram shielding

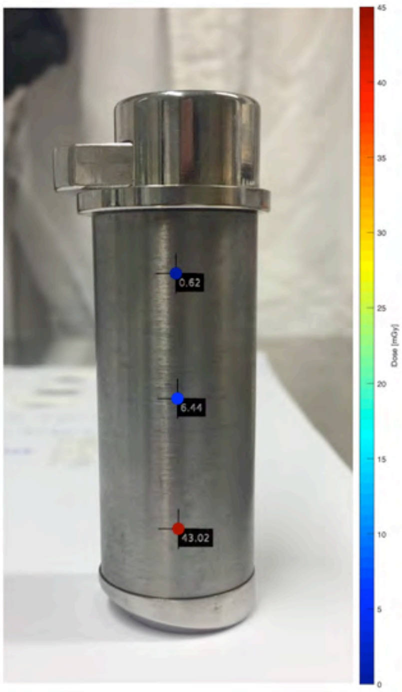
The estimated absorbed doses to the salt placed on the syringe shield as seen in Figure 23, clearly shows how the dose decrease with distance from the activity at the bottom of the syringe. Also, the dose increases to the pellets placed on the lead glass at the front of the syringe shield, whereas the doses to the left and right sides are lower. This can be explained by the fact that the glass attenuates less radiation as comparted to the solid wolfram. These measurements provides a good indication on how the staff should handle the shielding when using them.



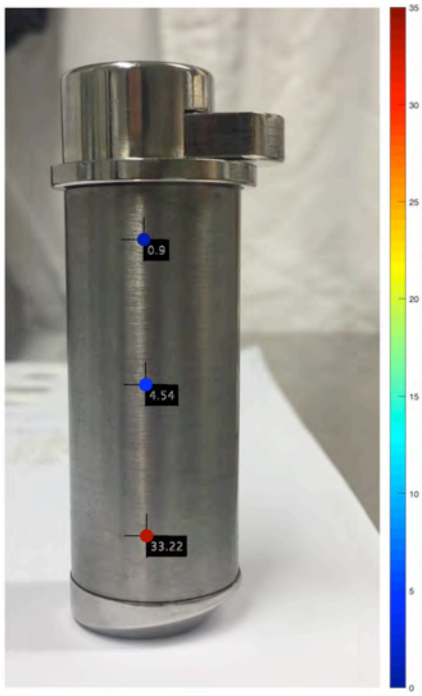
a)



b)



b)



d)

Figure 23. Absorbed dose to the **a)** front (glass) of the syringe shield **b)** back (wolfram) **c)** left side (wolfram) **d)** right side (wolfram).

5. Conclusions

This study clearly shows that NaCl, when compressed as pellets, can be used for dosimetric applications in hospital environments. Even though the entire design of the project were strongly dependent on getting access to relevant and meaningful assessments and that this limited the possibility to use TLDs in all applications, the results are surely comparable to TLD measurements. As in the case with TLD, NaCl pellets can be used for both short-term measurements such as during the synthetization processes and brachytherapy sessions, and for long-term measurements in various premises where radiopharmaceuticals are being handled even at low absorbed doses. NaCl clearly benefits from being easily accessible, non-toxic and cheap, hence, many pellets can be used during the same time of measurement and by using OSL the background signal is always zero. Consequently, many measuring points at the same time allows for establishing dose distributions over large or small regions of interest and gives a good picture of how staff can optimize the daily work to lower the doses, and a more fair dose value than, for example, the dose value from a personal dosimeter attached to the chest. Also, long-term measurements in the premises give a good indication of how and where the staff can move in the premises to further reduce the doses. Thus, this indicates potential opportunities for salt pellets to be used as dosimeters in various clinical applications. It can also pave the way for how and where further measurements should be carried out. Overall, this provides a new tool for monitoring, educating and optimizing various fields in clinical practices even though the number of accessible readout units are (so far) limited.

Although the method still is at a research stage, it can easily be implemented for clinical practitioners using the manufacturing and packaging technique suggested in this study. However, the manufacturing and packaging technique should be further investigated to achieve a standardized, replicable, fast and easy method that can be certified and implemented in all clinical applications where radiation dose assessments are desirable. Such techniques can include automated pellet production and package material in light sealing tape or small plastic cases printed on a 3D-printer, allowing for the pellets to be kept in a light sealed environment and easily worn by the staff.

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Appendix I

Effects of marking the NaCl pellets

To investigate how marking of the pellets might influence the results, pellets were initially marked in different ways with a lead pencil and a marking pen, followed by irradiation for 40 seconds with 0.72 mGy/s using the built-in ^{90}Sr/^{90}Y beta source the OSL signal was read along with 5 unmarked reference pellets. For all marked pellets, the marked side faced the photomultiplier tube in order for the luminescence to be filtered through the marking. Five pellets were marked on one side with a coverage of 100%, 50% and 25%, for each marking type, and 5 pellets were also numbered on one side.

The effects on assessing the OSL signal when marked with a pen and a pencil directly on the pellet is shown in Figure 24. The pellets fully marked (to 100%) with a black marker clearly shows a loss in OSL signal due to the marking ink attenuating the luminescence photons. The signal is (almost linearly) increased as the marked area decrease (to 25%), allowing a larger fraction of the photons to reach the photomultiplier tube (PMT). The signal in the pellets marked with the lead pencil increase with the decrease of the marked area, although not as significant as for the black marker. However, the total retrievable signal, for each degree of marked area, is proportionally much higher for pellets marked with the lead pencil as compared to marking with a black marker. The pellets marked with numbers (using a led pencil) exhibit the same signal output as pellets marked to 25% and 50% with a lead pencil. In comparison to the non-marked reference pellets, all marked pellets show that the signal is affected by the marking.

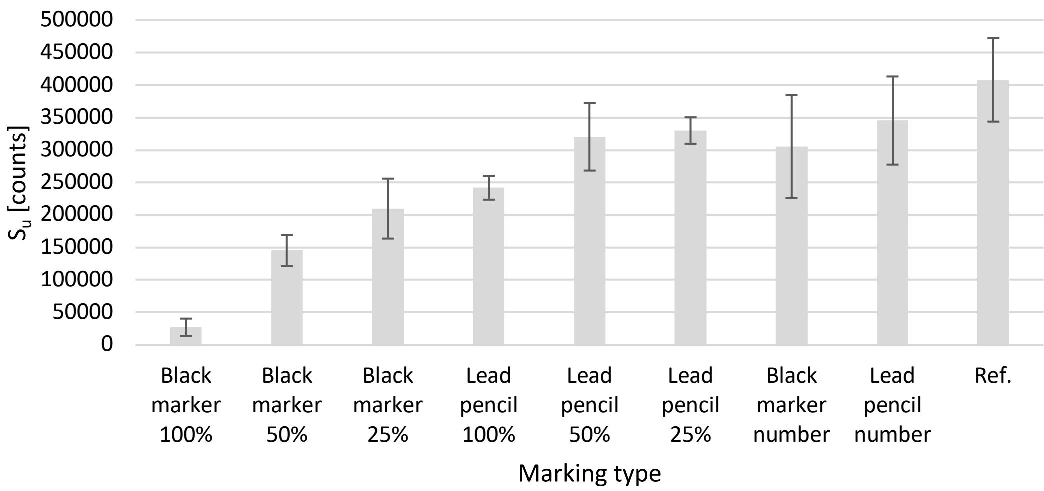


Figure 24. OSL signal output for different marking techniques of one side of the NaCl pellets (towards the PMT) together with non-marked reference pellets. The error bars correspond to 1 SD of 3 NaCl pellets.

Appendix II

Initial test of NaCl pellets on gloves placed in a high dose rate radiation field

In order to determine how well NaCl perform on gloves in terms of measuring absorbed dose, and how the packages can be best placed over the gloves, an initial test was performed using 12.14 GBq ^{18}F with a measured dose rate of 4.60 mSv/h at a distance of 60 cm. The gloves were filled with water (Figure 25A) to imitate the tissue in the hand and placed in an upright position in a radiation shielded workbench, 20-30 cm from the source to simulate a real-life situation where the workers use tweezers to keep distance to the source (Figure 25B). As a reference, 2 TLD (LiF dosemeters) were placed on the gloves, one on each index fingertip close to the salt packages. The gloves were kept in the radiation field for exactly 120 minutes after which the ^{18}F source was removed. The gloves were emptied of water and the NaCl packages were thoroughly dismantled, after which the pellets were readout with the Risø TL/OSL reader using the readout protocol in section 2.3.

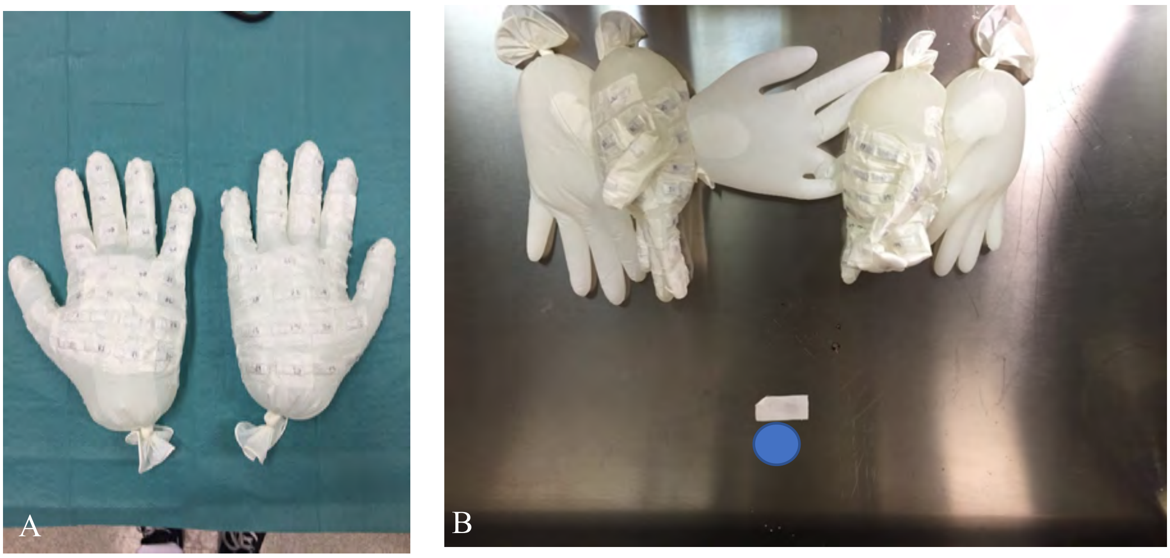
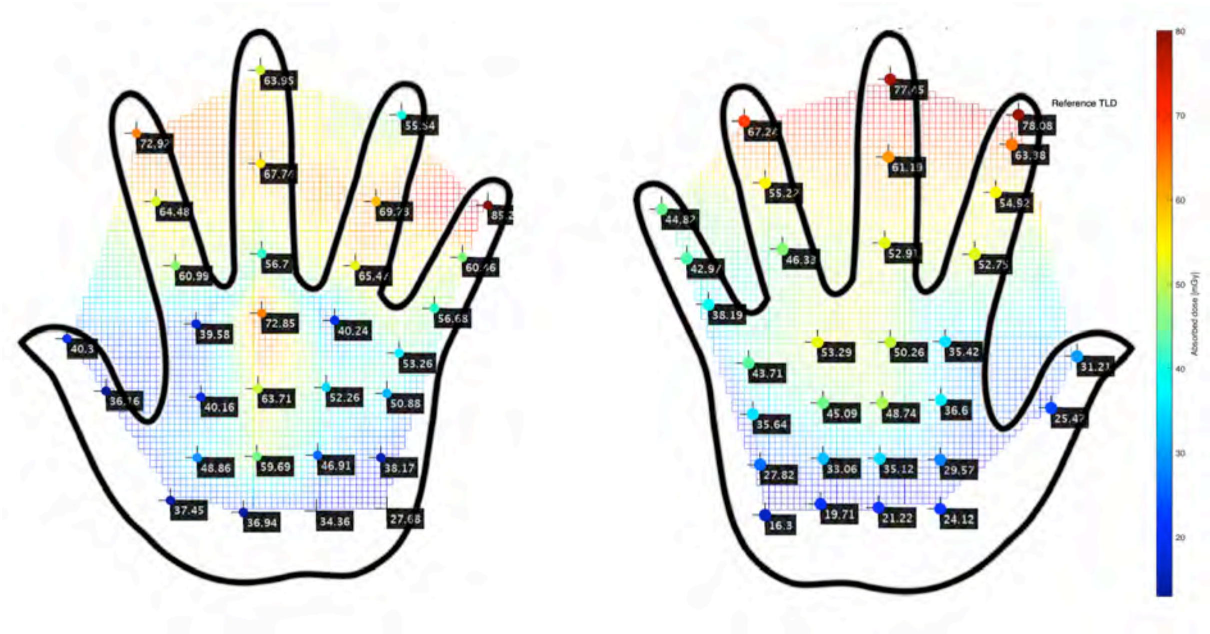


Figure 25. A) The test gloves prepared with NaCl packages and filled with water; B) The test gloves placed in an upright position to simulate real working conditions, the index and middle finger of the left glove have been placed in a position simulating the position as when holding a tweezer. The blue ring mark the position of the vials containing 12.14 Gbq of ^{18}F.

The hand palm of the gloves are shown in Figure 27. The fingers, which were closest to the source, clearly received higher doses compared to the palm of the hands. The TLD placed close to the NaCl pellets on the tip of the right index finger received a higher dose (78 mGy) as compared to the NaCl pellets that received a slightly lower dose (63 mGy). This is probably because of the TLD being placed in front of the NaCl package, hence yielding a higher absorbed dose. The test shows that the NaCl in pellet form performs well also in high dose rate radiation fields and that the results are in comparison with the results from the TLD.



b)

Figure 27. Estimated absorbed dose to NaCl (average of 3 pellets at each position) on a) the left hand palm and b) the right hand palm. The reference TLD was positioned in front of the NaCl pellets on the right index finger. The mean uncertainties of the equivalent dose for all measuring points are 6%.