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HOUSEHOLD SALT (NACL) FOR OPTICALLY STIMULATED LUMINESCENCE DOSIMETRY: AN OVERVIEW

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***Abstract*:** This brief overview of the use of household salt (NaCl) in optically stimulated luminescence (OSL) dosimetry is focusing on the use of NaCl pellets. It is suggested that the most optimal use of household NaCl, in general prospective dosimetry, is to compress the salt grains to pellets and read the radiation induced signal using OSL rather than TL. A summary of the main OSL dosimetric properties is provided for two Swedish household salts, and compared to the OSL properties of 100 different salts from all over the world.

Keywords: OSL, NaCl, salt pellet, dosimetry

1. Introduction

Optically stimulated luminescence (OSL) is an increasingly used technique for determining radiation absorbed doses in *e.g.* occupational, environmental, emergency/accident dosimetry and in applications for luminescence dating in geology and archeology. In OSL, luminescence is stimulated from the target sample by a light source. The registered OSL signal is a measure of the absorbed dose from previous radiation exposure of the sample material. In thermoluminescence (TL), or thermally stimulated luminescence, heat is used to stimulate the target sample and the resulting TL signal is a measure of the radiation absorbed dose of the material. Although TL has traditionally been standard for broad range of dosimetry applications, the use of OSL in research and for personal dosimetry has strongly increased during the recent two decades. There are benefits and disadvantages of the TL vs OSL methods. This have been discussed over the years, for example in 2003 [1], where the two debater's main arguments condensed to the principle of the stimulation mode *i.e.* there are advantages and disadvantage with OSL as well as TL, vs the other. Since then there has been a fast development in terms of OSL readers and materials, and the use of the technique is further increasing in various dosimetry applications as well as in luminescence dating. For personal dosimetry, both OSL and TL will be used for many years to come. However, it has been shown that there are advantages of using OSL as compared to TL when using certain household materials for retrospective dosimetry (*i.e.* luminescence dating and accident dosimetry). This brief overview will focus on one such household material, in particular salt (NaCl) for OSL dosimetry, specifically for prospective dosimetry (pre-manufactured dosemeters) using NaCl pellets.

2. Luminescence dosimetry with NaCl

Research on TL and OSL has a long history. In fact, the TL phenomenon was first observed as early as 1663, although it was not until the 1950s that the research found practical applications [2]. About a decade later it was shown that illumination of radiation exposed salt reduces the intensity of the TL peaks [3], and shortly after that the phenomenon OSL was first mentioned in the literature [4], see *e.g.* Yukihara & McKeever [5] and references therein for a brief history on TL and OSL. With the advent of compact and optimized OSL/TL readers, analytical grade salt was studied as a dosemeter for applications in luminescence dating [6, 7]. The main results observed were that the OSL response in NaCl, after irradiation, can be measurable and reproduced, and there is no significant short term fading of the OSL signal. Furthermore, and obviously, it was shown that the signal may easily be bleached when the salt is exposed to daylight. At about the same time, household and workplace chemicals (including household salt) were investigated as a dosemeter for retrospective dosimetry *i.e.* accident dosimetry [8]. The results in the latter survey of household and workplace chemicals showed a significantly high OSL signal yield per unit absorbed dose and sample weight for household salt (>99% NaCl), as compared to the other materials investigated, and a fading of only 5% after 2 weeks. Despite these encouraging findings for the use of NaCl in dosimetry, it would take one more decade before several different groups started to evaluate and use NaCl in various applications for OSL and TL dosimetry.

The first salt application within OSL dosimetry was for retrospective dosimetry (luminescence dating and accident dosimetry) *e.g.* [6-8], using relatively high radiation doses (several Gy) for benchmarking the salts investigated. Later it was shown that household NaCl has a linear dose response also for doses below one gray, with detection limits of about 1 mGy [9-10]. With promising dosimetric properties also in the dose range for occupational radiation protection, research began to evaluate the use of household NaCl for prospective dosimetry *i.e.* pre-prepared dosemeters with salt. One of the first field tests of household NaCl, packed in temporal but dedicated dosemeter holders consisting of NaCl and LiF chips, was carried out in a Chernobyl contaminated village in Belarus [12]. The results showed a good comparison to TLDs of LiF and very good agreement with a handheld NaI(Tl) radiation detector that was used at the same measurement positions as the combined NaCl and LiF dosemeter kits. The same study was repeated during three years with the same results [13]. Approximately at the same time, in-house made NaCl and LiF dosemeters were carried by people living in Chernobyl contaminated villages in Russia [14] and on phantoms in the laboratory [15]. The results from these studies showed a surprisingly good agreement between conventional dosemeters of LiF to OSL materials (NaCl) used in retrospective dosimetry in terms of absorbed dose assessments. This was encouraging for further investigations of NaCl as a dosemeter beyond retrospective purposes.

Therefore, a refined dosemeter dedicated for salt grains was suggested for measurements of personal dose equivalent, $H_p(10)$ [16]. This dosemeter was tested in the laboratory at different photon energies and incident angels of the radiation field. It was shown that the dosemeter need proper filtration for accurate $H_p(10)$ dose determinations in order to adjust for the over response at low photon energies (<200 keV) compared with tissue. This was also shown in a parallel study using a different type of a combined NaCl and LiF dosemeter [17]. Furthermore, efforts have also been made to experimentally determine conversion coefficients for NaCl in dosemeter holders, in salt packages, and on physical phantom in different exposure situations [18]. While these studies are supportive for the use of NaCl in OSL dosimetry, it is encouraged to further support these findings with mathematical calculations and simulations.

Although many articles on OSL (and TL) in NaCl refer to its use in retrospective dosimetry applications, the results also apply to OSL dosimetry in general and may be useful for modeling and optimisation of the OSL in NaCl after exposure to ionizing radiation *e.g.* [19-23]. Although more research is needed for understanding the physics of the OSL in various types of NaCl, the well-established advantageous OSL properties of NaCl have encouraged to evaluate the use of the salt from salted snacks and nuts for accident dosimetry [24, 25]. There are also suggestions of using NaCl for mixed neutron-photon fields by using a dedicated dosemeter with a neutron converter (gadolinium) [26] and by using a specially made NaCl detector and analyzing ^{24}Na from neutron activation of NaCl [27].

3. OSL dosimetry with NaCl pellets

OSL and TL has been investigated for solid dosemeters made from natural calcium fluoride and NaCl powders pressed together (CaF_2:NaCl) *e.g.* [28]. In that study NaCl pellets were also studied. Although not observed in other studies of NaCl pellets the results from [28] showed that the radiation induced OSL and TL signals were rapidly removed from the pure NaCl pellets by either a pre-heat or a 1 h waiting time. With the intention of using pure household NaCl for prospective dosimetry, a method for producing physically stable NaCl pellets was developed and the OSL dosimetric properties of these pellets were studied using an optimized read-out sequence [29, 30]. These initial studies showed a linear dose response for low doses (from about 5 mGy), low detection limit (<10 μGy), and high signal yield per unit absorbed dose and weight. At about the same time, household NaCl pellets were investigated for retrospective TL dosimetry [31]. It was shown that the TL signal was linear over the dose range 0.25 Gy to 20 Gy, and that the fading after 2 weeks was 40%. Recently, the TL properties of NaCl pellets of different thickness (0.1 and 0.3 cm) have been studied for doses from 2 to 10 Gy [32] and NaCl pellets with a thickness of 1 mm in the absorbed dose range of 5 mGy to 5 Gy [33]. Although the studies [32,33] are not directly comparable the conclusion from the first one is that the thinner pellets (0.1 cm) has better TL characteristics than the thicker ones, with 3 times higher TL intensity but with higher fading after 7 days as compared to the 0.3 cm pellets. The study in [33], with even thinner pellets than 0.1 cm, indicates a fading of 20% after 2 weeks and a linear TL signal to dose response in the dose range 5-100 mGy. Although TL dosimetry with NaCl pellets is interesting and may be useful in some situations, the dosimetric properties of household NaCl is greatly improved by using an optimized OSL read protocol with individual single-dose calibration of each pellet. A summary of the comprehensive work made on OSL in NaCl pellets is given in the section below. References therein may be used to fully apply or test the suggested NaCl pellets in various practices.

3.1. Justification for household NaCl pellets in prospective dosimetry

Several researchers have studied NaCl for the use in OSL and TL dosimetry applications. Although there are some difficult issues to overcome in retrospective dosimetry for luminescence dating and accident dosimetry, research in these areas have opened for studies of using NaCl for occupational and environmental dosimetry applications. After it was shown that household NaCl could be used to measure low-doses (<100 mGy), relevant for personal dosimetry [9], efforts have been made to further evaluate the usefulness of household NaCl for prospective OSL dosimetry applications by compressing the salt to pellets.

Although the main area of use of the suggested dosemeters might be within environmental and accident dosimetry, one promising approach is to apply OSL dosimetry with NaCl pellets within the medical use of ionizing radiation.

According to international guiding documents by *e.g.* IAEA, ICRP and ICRU there are three broad fields for the application of OSL dosimetry. The first is the use of point detectors together with dedicated physical phantoms (CIRS ATOM, Rando, etc.) that allow estimation of organ absorbed doses in different radiosensitive organs/tissues from diagnostics or therapies with ionizing radiation. Estimates or measurements of such radiation absorbed doses are used as a basis for the development and validation of dedicated computational software for patient dose estimation as well as for the optimization of imaging protocols in medical facilities.

The second is the use of point detectors for direct estimation of the entrance surface doses of patients for different diagnostic imaging modalities. IAEA recommends using the entrance surface dose (incident air kerma on the patient body) as one of the main dosimetric quantities for the process of optimization, mainly for the estimation of typical patient doses and for establishing diagnostic reference levels.

The third is the use of point detectors for individual dosimetry of workers, especially those working in highly non-uniform radiation fields (*e.g.* X-ray guided surgery, interventional examinations, nuclear medicine applications).

In many countries, the use of LiF based point detectors is associated with various complications, such as significant costs for the detectors and equipment for annealing and calibration, resource demanding methods for calibration, and significant costs for the lost/damaged detectors. With the one-time use of the in-house made NaCl detectors for OSL, many of these shortcomings can be overcome, with comparable dosimetric properties.

It has been clearly identified that these advantages are important, especially in developing countries that recently or currently started to develop their radiation protection and quality control programs; or, on the contrary, for large countries with significantly varying access and prioritisation to dosimetry services and equipment between different regions (*e.g.* the Russian Federation). As a complement to commercial luminescent dosemeters, or to encourage RP professionals, the NaCl pellets provide an easily accessible tool for accurate dose determinations.

3.2. Dosimetric properties of household NaCl pellets

The research group medical radiation physics, Malmö, Lund University, has studied the OSL properties of household NaCl for applications in dosimetry [34, 35] and lately, for optimal use and dosimetry, as pellets [36]. Provided below is a summary of the main dosimetric properties of the suggested household salt pellets for OSL dosimetry.

Common Swedish household salt was investigated for making physically stable NaCl pellets [37]. Using a press tool made in-house, it was suggested to sieve the salt to grains in the size range 100-400 µm and use a compression force of 3.0±0.5 tons applied over the surface of the press tool (distributed over a column of five pellets) for achieving physically stable and rigid pellets. Later it has been suggested to use a commercially available standard desktop table press tool (TDP 0 Desktop Tablet Press, LFA Machines Oxford Ltd) for more convenient production of NaCl pellets with a circular shape of 4 mm in diameter and 0.8±0.2 mm thick (similar size as many LiF chips) [36]: Fig. 1 and 2.

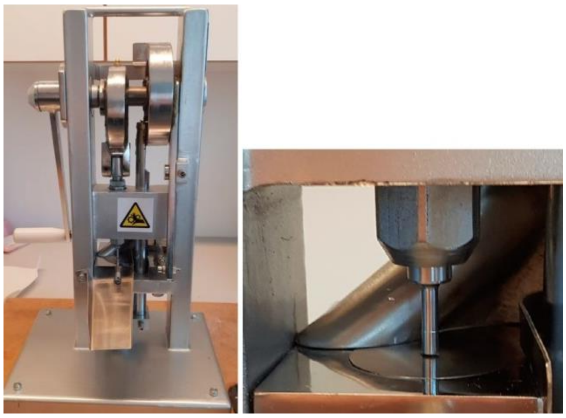

Fig. 1. Photograph of the semi-automatic desktop table press for compresing the salt grains to NaCl pellets.

The pellets are intended for one-time use, using a single individual calibration dose (rather than the common SAR protocol that require repeated heating and irradiation of the sample). An optimized readout protocol, using a Risø TL/OSL-DA reader (DTU Physics, Denmark), is provided in [36]. The most relevant dosimetric properties (see below) were studied for two Swedish household salt (Falksalt finkornigt hushållsalt and Falksalt finkornigt medelhavssalt, Salinity AB, Sweden) and one analytical grade salt (Sodium chloride, reagent grade, Scharlau, Scharlab, Spain) [37]. OSL dosimetric properties were also evaluated for 102 household salt from all over the world (including the Swedish salts) to evaluate the global usability of NaCl pellets for OSL dosimetry [36].

A summary of the dosimetric properties, using the suggested NaCl pellets (Fig. 2) are provided below.

OSL signal to dose response: the OSL signal is linearly increasing with the absorbed dose, from 0 to 300 mGy [37]. The linearity continues at even higher dose (>1 Gy) and is valid also for the estimated absorbed dose [36]. A pre-established calibration curve for a specific salt may be used, albeit with some precaution, to achieve a fast estimate of the absorbed dose.

Minimum detectable dose (MDD): considering the one time use of the NaCl pellets and that they are pre-bleached (emptied of any residual OSL signal in ambient light) the theoretical detection limit, in terms of MDD is low, 5-20 µGy for the Swedish salts investigated [37]. Studies of the 102 salts from all over the world show MDD in the range from 2 to 1036 µGy, with a median MDD of 19 µGy.

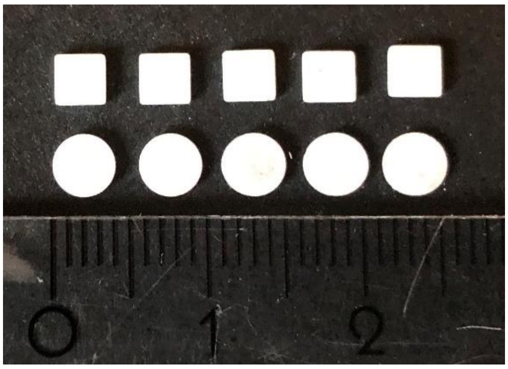

Fig. 2. Photo of the NaCl pellets (round in shape) as compared to standrad LiF chips (squared in shape).

Signal stability over time (fading): The OSL signal is stable over at least one month after exposure. However, and similar to *e.g.* [22], the estimated dose appears to increase over time. For NaCl pellets, this is an effect of the decrease in signal yield over time when using a single calibration dose [38]. To avoid this problem, the pellets may be stored for a couple of weeks before they are used, for the pellets to age. This is however only a problem when the exposure and readout are separated in time. For extended or chronic exposures the effect of decreasing signal yield from the pellets cannot be seen and no special precautions need to be taken before use.

Specific luminescence: The OSL signal normalized to the weight of the pellets and the absorbed dose, ranged from 259 to 576 counts mg^{-1} mGy^{-1} for the two Swedish household salts and one analytical grade salt. This can be compared to the results of the 102 salts investigated, with specific luminescence ranging from 115 to 1950 counts mg^{-1} mGy^{-1}, with a median of 496 counts mg^{-1} mGy^{-1}.

Reproducibility: The OSL signal reproducibility is <4%, in terms of coefficient of variation for 10 equally treated NaCl pellets, when using a single calibration dose. When only comparing the OSL signals, without any normalization, the reproducibility is around 15%.

Energy dependence: The absorbed dose to NaCl pellets has a significant energy dependence at low photon energies, up to a factor of 18 as compared to K_{air} and $H_p(10)$. Experimentally determined and Monte Carlo calculated energy dependence of NaCl pellets in the energy range 30 keV to 1.25 MeV has been established [39]. The results show that the energy dependence must be accurately compensated for *e.g.* by dosemeter filters or mathematically corrected for in order to achieve accurate dose estimates for dosimetry applications with low photon energies especially.

The suggested NaCl pellets have been thoroughly studied in the laboratory. Several tests have also been carried out in different hospital clinics for occupational and ambient exposure studies [40, 41].

To fully utilize the potential of the NaCl pellets, a dedicated badge with filters correcting for *e.g.* the energy dependence are needed. Depending on the application, the dosimeter may be calibrated to measure either $H_p(10)$ or $H^*(10)$. For some applications where energies >200 keV dominate, a simple badge without filtering may be sufficient. Filters for energy discrimination or electron detection may also be implemented in a badge. As for readout of the NaCl pellets, a simple dedicated reader would help make the method become more accessible as the number of OSL readers is still limited.

4. Conclusions

The intention with this overview is two-folded: first it is to provide a short introduction to the use of NaCl in OSL dosimetry, secondly it is to show the potential of using NaCl in various dosimetry applications. If using NaCl pellets in OSL dosimetry, as a complement or as a main tool for dosimetry, depending on the situation or application, many issues can be overcome.

In many countries NaCl pellet based dosemeters may serve as a complement to clinical or personal dosimetry, but in case of an accidental radiation exposure event, NaCl pellets may provide additional information for affected individual doses as well as decision making authorities.

In summary, ordinary salt has superior OSL dosimetric properties as compared to many other fortuitous materials close to man. The dosimetric properties are fairly the same for different types of household salt all over the world, although differences may be observed in the OSL decay curves (not yet evaluated). When compressing the salt grains to NaCl pellets the overall handling and dosimetric properties are improved, as compared to using grains of salt. If the NaCl pellets are constructed with the same dimensions as LiF chips they may be directly used in standard dosimetry phantoms etc. A key issue with the suggested NaCl pellets is the same as for commercial alternatives for OSL dosimetry, the pellets must be kept shielded from light exposure. Provided there is an OSL reader available, it is possible to follow the steps in the papers referred to in this overview to achieve NaCl pellet OSL dosimetric properties that are comparable with commercial alternatives but only at a fraction of the cost as compared to commercial luminescent detectors.

5. References

1. McKeever S.W.S. and Moscovitch M. Topics under debate: on the advantages and disadvantages of optically stimulated luminescence dosimetry and thermoluminescence dosimetry. Radiation Protection Dosimetry, 104(3):263-270, 2003.
2. Daniels F., Boyd C.A. and Saunders D.F. Thermoluminescence as a research tool. Science, 117(3040):343-349, 1953.
3. Stoddard A.E. Effects of illumination upon sodium chloride thermoluminescence. Physical Review, 120(1):114-117, 1960.
4. Fowler J.F. Solid state dosimetry. Physics in Medicine and Biology, 8(1):1-32, 1963.
5. Yukihara E.G. and McKeever S.W.S. Optically stimulated luminescence – fundamentals and applications. A John Wiley and Sons Ltd, UK. ISBN: 978-0470-69725-2, 362 pp.
6. Bailey R.M., Adamiec G. and Rhodes E.J. OSL properties of NaCl relative to dating and dosimetry. Radiation Measurements, 32:717-723, 2000.
7. Zhang J.F., Yan C. and Zhou L.P. Feasibility of optical dating using halite. Journal of Luminescence, 114:234-240, 2005.

8. Thomsen K.J., Bøtter-Jensen L. and Murray A.S. Household and workplace chemicals as retrospective luminescence dosemeters. Radiation Protection Dosimetry, 101(1-4):515-518, 2002.
9. Bernhardsson C., Christiansson M., Mattsson S. and Rääf C.L. Household salt as a retrospective dosemeter using optically stimulated luminescence. Radiation and Environmental Biophysics, 48:21-28, 2009.
10. Ekendahl D. and Judas L. NaCl as a retrospective and accident dosemeter. Radiation Protection Dosimetry, 145(1):36-44, 2011.
11. Timar-Gabor A. and Trandafir O. On optically stimulated luminescence properties of household salt as a retrospective dosemeter. Radiation Protection Dosimetry, 155(4):404-409, 2013.
12. Bernhardsson C., Christiansson M., Rääf C. and Mattsson S. OSL in household salt (NaCl) for environmental, occupational and medical dosimetry. Proceedings of the 7th International Conference "Medical Physics in the Baltic States", Kaunas, 2009, p. 65-68.
13. Bernhardsson C., Matskevich S., Mattsson S. and Rääf C. Comparative measurements of the external radiation exposure in a ^{137}Cs contaminated village in Belarus based on optically stimulated luminescence in NaCl and thermoluminescence in LiF. Health Physics, 103(6):740-748, 2012.
14. Bernhardsson C., Zvonova I., Rääf C. and Mattsson S. Measurements of long-term external and internal radiation exposure of inhabitants of some villages of the Bryansk region of Russia after the Chernobyl accident. Science of the Total Environment, 409:4811-4817, 2011.
15. Ekendahl D., Bulánek B. and Judas L. Comparative measurements of external radiation exposure using mobile phones, dental ceramic, household salt and conventional personal dosemeters. Radiation Measurements, 72:60-65, 2015.
16. Ekendahl D., Bulánek B. and Judas L. A low-cost personal dosemeter based on optically stimulated luminescence (OSL) of common household salt (NaCl). Radiation Measurements, 85:93-98, 2016.
17. Christiansson M., Bernhardsson C., Geber-Bergstrand T., Mattsson S. and Rääf C. OSL in NaCl vs. TL in LiF for absorbed dose measurements and radiation quality assessment in the photon energy range 20 keV to 1.3 MeV. Radiation Measurements, 112:11-15, 2018.
18. Bernhardsson C. Experimental determination of dose conversion coefficients for external radiation exposure with gamma emitting radionuclides. Radiatsionnaya Hygiene (Radiat. Hyg.), 7(4):125-133, 2014.
19. Polymeris G.S., Kitis G., Kiyak N.G. et al. Dissolution and subsequent re-crystallization as zeroing mechanism, thermal properties and component resolved dose response of salt (NaCl) for retrospective dosimetry. Applied Radiation and Isotopes, 69:1255-1262, 2011.
20. Spooner N.A., Smith B.W., Creighton D.F., Questiaux D. and Hunter P.G. Luminescence from NaCl for application to retrospective dosimetry. Radiation Measurements, 47:883-889, 2012.
21. Christiansson M., Mattsson S., Bernhardsson C. and Rääf C.L. Optimizing a readout protocol for low dose retrospective OSL-dosimetry using household salt. Health Physics, 102(6):631-636, 2012.
22. Biernacka M., Majgier R., Maternicki K., Liang M. and Mandowski A. Peculiarities of optically stimulated luminescence in halite. Radiation Measurements, 90:247-251, 2016.
23. Majgier R., Rääf C.L., Mandowski A. and Bernhardsson C. OSL properties in various forms of KCl and NaCl samples after exposure to ionizing radiation. Radiation Protection Dosimetry, 184(1):90-97, 2019.
24. Christiansson M., Geber-Bergstrand T., Bernhardsson C., Mattsson S. and Rääf C.L. Retrospective dosimetry using salted snacks and nuts: a feasibility study. Radiation Protection Dosimetry, 174(1):1-5, 2017.
25. Maltar-Strmecki N., Vidotto M., Della M.S. et al. Salty crackers as fortuitous dosimeters: a novel PSL method for rapid radiation triage. Frontiers in Public Health 9:661376, 2021. doi: 10.3389/fpubh.2021.661376.
26. Mattsson S., Christiansson M. and Bernhardsson C. A passive neutron dosemeter for measurements in mixed neutron-photon radiation fields. Proceedings of the 12th International Conference "Medical Physics in the Baltic States", Kaunas, 2015. p. 38-42.
27. Ekendahl D., Rubovic P., Zlebcik P., Huml O. and Mala H. Dosimetry with salt in mixed radiation fields of photons and neutrons. Radiation Protection Dosimetry, 178(3):329-332, 2018.
28. Ferreira F.A., Yoshimura E.M., Umisedo N.K. and Nascimento R.P. Correlation of optically and thermally stimulated luminescence of natural fluorite pellets. Radiation Measurements, 71:254-257, 2014.
29. Bernhardsson C., Waldner L. and Vodovatov A. Advancements in prospective dosimetry with NaCl read-out by optically stimulated luminescence. Proceedings of the 13th International Conference "Medical Physics in the Baltic States", Kaunas, 2017. p. 26-29.
30. Waldner L. NaCl pellets for improved dosimetry. [MSc thesis], Malmö: Lund University, 2017.
31. Elashmawy M. Study of constraints in using household NaCl salt for retrospective dosimetry. Nuclear Instruments and Methods in Physics Research B, 423:49-61, 2018.
32. Muhammad Azim M.K., Abdul Sani S.F., Daar E. et al. Luminescence properties of natural dead sea salt pellet dosimetry upon thermal stimulation. Radiation Physics and Chemistry, 176:108964, 2020.
33. Ahmad K., Kakahel M.B., Hayat S. et al. Thermoluminescence study of pellets prepared using NaCl from Khewra salt mines in Pakistan. Radiation and Environmental Biophysics, 60(2):365-375, 2021.
34. Bernhardsson C. Radiation exposure of human populations in villages in Russia and Belarus by fallout from the Chernobyl reactor. [PhD thesis], Malmö: Lund University, 2011.
35. Christiansson M. Household salt as an emergency radiation dosemeter for retrospective dose assessments using optically stimulated luminescence. [PhD thesis], Malmö: Lund University, 2014.
36. Waldner L. Optically stimulated luminescence dosimetry with NaCl pellets. [PhD thesis], Malmö: Lund University, 2021.
37. Waldner L. and Bernhardsson C. Physical and dosimetric properties of NaCl pellets made in-house for the use in prospective optically stimulated luminescence dosimetry applications. Radiation Measurements, 119:52-57, 2018.
38. Waldner L., Rääf C. and Bernhardsson C. NaCl pellets for prospective dosimetry using optically stimulated luminescence: signal integrity and long-term versus short-term exposure. Radiation and Environmental Biophysics, 59(4):693-702, 2020.
39. Waldner L., Hinrichsen Y., Herrnsdorf L. and Bernhardsson C. Experimentally determined and Monte Carlo-simulated energy dependence of NaCl pellets read by optically stimulated luminescence for photon beams in the energy range 30 keV to 1.25 MeV. Radiological Protection, 40:1321, 2020.
40. Wilke P. Radiation protection measurements in clinical practice – dosimetry with NaCl pellets. [MSc thesis], Malmö: Lund University, 2019.
41. Solak E. A comparison between LiF, Al_2O_3 and NaCl pellets for luminescence dosimetry based on clinical and laboratory measurements. [MSc thesis], Malmö: Lund University, 2020.