Radiation Measurements 112 (2018) 11–15

Contents lists available at ScienceDirect

Radiation Measurements

journal homepage: www.elsevier.com/locate/radmeas

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

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ARTICLE INFO

Keywords:
OSL
NaCl
TLD
LiF

ABSTRACT

The aim of this study was to determine the photon energy dependence of absorbed dose measurements, in a comparison of optically stimulated luminescence (OSL) in NaCl with thermoluminescence (TL) in LiF:Mg,Cu,P. The comparisons were made at exposure to ionizing radiation in the photon energy range 20 keV to 1.3 MeV. Specially designed dosemeter kits containing both NaCl and LiF were used under *i*) laboratory conditions using defined radiation fields, *ii*) laboratory conditions using sealed point sources mimicking unintentional exposures, and *iii*) field conditions in areas in Japan that were affected by the Fukushima Daiichi nuclear disaster in 2011. The dosemeter kits used in Japan showed that absorbed doses as low as 100 μGy can be assessed from the OSL signal in NaCl. The ratio of the dosemeter readings using OSL in NaCl and TL in LiF increases after irradiation at lower photon energies (less than a few hundred keV) as determined under laboratory conditions. Compensating for this energy dependence of the absorbed dose determinations obtained from OSL in NaCl would thus require an energy-dependent conversion factor for photon energies below 600 keV. On the other hand, the difference in the photon energy dependence between NaCl and LiF may be used to assess the mean effective energy of the photon field. The signal ratios between NaCl and LiF after exposure to radiation in the Fukushima Dashii contaminated areas in Japan, 1.67 ± 0.26 (2013) and 1.63 ± 0.32 (2015), indicate that the mean photon energy in this area was 300–400 keV during the years of the survey.

1. Introduction

In retrospective dosimetry for emergency dose assessments, optically stimulated luminescence (OSL) or thermoluminescence (TL) in common crystalline materials accessible in public surroundings have proven to be very useful (e.g., Bøtter-Jensen, 1995; Hütt et al., 1996; Sholom and McKeever, 2014; Mesterhazy et al., 2014). In particular, household salt (consisting predominantly of NaCl) exhibits a significantly higher OSL signal per unit of absorbed dose than many other materials after exposure to high energy beta ($^{90}Sr/^{90}Y$) and gamma (^{60}Co) radiation (e.g., Thomsen et al., 2002; Bernhardsson et al., 2009; Christiansson et al., 2012).

Given the potentially high sensitivity of this technique for absorbed dose determination, studies have been launched to investigate its performance as an environmental and personal dosemeter for external gamma radiation exposures (e.g., Bernhardsson et al., 2011, 2012; Ekendahl et al., 2016). NaCl is a low-cost detector material that enables fast and straightforward sample preparation as well as calibration. For workers such as first responders in a radiological or nuclear emergency who have to operate in very different radiation fields, a dosemeter of this type would be of great value. Also, since radiation dosemeters are often not a budget priority for many employers when the probability of radiation exposure is low (e.g., for public safety personnel), a simple, cost-effective dosiemeter could allow all workers to have a personal dosemeter.

It is important to know the energy response of the detector material for accurate dose determination. Depending on the radiation detector material's effective atomic number and the type of stimulation, the photon energy response can present as either an under-response or an over-response relative to air in the low-energy range (e.g., Harder and Hermann, 1985). For personal dosimetry, it would be an advantage if the material used has the same (or similar) effective atomic number (Z_{eff}) as soft tissue (Z_{eff} = 7.65) (ICRP) or water (Z_{eff} = 7.51) (Bos, 2001). In theory, such detector materials can exhibit a signal response based on the dose absorbed by tissue that is independent of the photon energy, in the range from about 10 keV to 3 MeV. Lithium fluoride (LiF) has been a standard dosemeter material for prospective dosimetry in the past decades (Bos, 2001; Kortov, 2007). In large part this is due to

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https://doi.org/10.1016/j.radmeas.2018.03.003
Received 28 September 2017; Received in revised form 9 March 2018; Accepted 11 March 2018
Available online 12 March 2018
1350-4487/

its effective atomic number (Z_{eff} = 8.3), which makes its energy dependence more similar to that of soft tissue and thereby makes it suitable for personal dosimetry. Photon energy dependence is less important for materials with a Z_{eff} close to that of soft tissue, especially at energies of a few hundred keV where the photoelectric effect is dominant. However, many detector materials are not tissue-equivalent. Household salt (NaCl) has a significantly higher effective atomic number (Z_{eff} = 15.2) (Murty, 1965) than that of soft tissue, making it more sensitive to photons with low energy (< 400 keV) than to those with high energy. Other well-known detectors with higher effective atomic numbers are Al_2O_3 (Z_{eff} = 11.3) and CaF_2:natural (Z_{eff} = 16). In order to use NaCl for personal dosimetry, it is therefore necessary to investigate the energy dependence of the absorbed dose in relation to that of soft tissue. In a previous study, the OSL signal in NaCl was compared to the TL signal in LiF after exposure to a ^{60}Co beam ($E_{\gamma1}$ = 1173, $E_{\gamma2}$ = 1333 keV) at a depth of 7 mm in a polymethylmethacrylate (PMMA) phantom (Christiansson et al., 2014). The ratio of OSL-NaCl to TL-LiF was determined to be 1.0 ± 0.03, which is expected at photon energies where the Compton scattering interaction is dominant.

The aim of this study is to investigate whether NaCl may be used as an alternative to or in combination with LiF to determine absorbed doses at lower photon energies, down to 20 keV (Malthez et al., 2014). This may practically be tested under both laboratory and *in situ* conditions by determining the ratio of NaCl and LiF dosemeter readings for photon energies ranging from 20 keV to 1.3 MeV. The long-term objective is to find a physical design and read-out procedure to retrieve an OSL signal in irradiated NaCl that is suitable for estimating the dose absorbed by tissue for assessment of radiation exposure.

2. Materials and methods

2.1. Sample preparation

In a previous study, four brands of household salt were investigated to determine both their OSL response to gamma and beta radiation and their OSL signal integrity (Christiansson et al., 2014). In the present study, one of the previously investigated salt brands ("Falksalt fint salt med jod") is used for all OSL measurements in NaCl as it showed a high sensitivity to radiation and is also widely available in Swedish supermarkets. Hereafter, "Falksalt fint salt med jod" will simply be referred to as salt or NaCl.

Special dosemeter kits were constructed for the purpose of testing household salt as a personal dosemeter. Two different types of holders were used for the dosemeter kits. Holder No. 1 (Fig. 1) was previously developed for estimating external effective doses in Russian populations after the Chernobyl accident. This was accomplished by determining the surface absorbed dose and then applying correction factors (Bernhardsson et al., 2012; Thornberg, 2000; Wøhni, 1995). The holder was made of two PMMA plates with dimensions of 58 × 27 × 4 mm^3. Between the PMMA plates, each kit was prepared with about 80 mg of NaCl and two LiF chips of LiF:Mg,Cu,P (MCP-N, Mikrolab, Poland). The salt and the LiF chips were protected from environmental humidity and separated from each other by individual rubber O-rings (in total, four O-rings per dosemeter: two with NaCl and two with LiF chips). In order to optimize the amount of salt in the dosemeter holder, and in accordance with previous sampling procedures for salt (Christiansson et al., 2008), the salt was sieved to grains in the size range from 100 to 400 µm. The thickness of the NaCl portions was approximately 2 mm (see Fig. 2).

Holder No. 2 (Fig. 1) was designed especially for the experiment with the reference X-ray beams due to physical constraints. The thinner salt layer (~1 mm) was used to more accurately measure the absorbed dose from radiation components with lower photon energies. Holder No. 2 was made of two PMMA plates. The top plate had dimensions of 10 × 10 × 5 mm^3, and the bottom plate had dimensions of 10 × 10 × 6 mm^3 (see Fig. 2) Each had four milled holes for NaCl grains (about 50 mg) and two LiF chips. The thickness of the lid of Holder No. 2 was the same as the thickness of the entrance PMMA plate for the calibration phantom used in routine TLD calibrations.

Before preparing the dosemeter kits with NaCl, any remaining OSL signal in the salt was erased by exposing it to light from a fluorescent lamp with an illuminance of 1100 lux (0.16 mW cm^{-2}) and a wavelength range of 300–700 nm for at least 2 h (Christiansson et al., 2014). The dosemeter kits with NaCl and LiF were assembled and then covered with black tape to avoid signal loss in the salt due to optical bleaching.

For ^{60}Co photon energies (1173 and 1333 keV), both the LiF chip (0.9 mm) and salt layers of 1 or 2 mm, respectively, will be relatively accurately approximated as Bragg-Gray cavities positioned at a point with quasi-charged particle equilibrium (provided by the 4 or 5 mm PMMA layer in front of the salt). However, in this study, the design of a 1–2 mm thick NaCl layer was a compromise between the Bragg-Gray cavity conditions and the fixed thickness of the LiF chips used as reference detectors.

2.2. Calibration and readout of OSL in NaCl

The OSL measurements were carried out in an automated TL/OSL reader (TL/OSL-DA-15; Technical University of Denmark, Risø campus, Roskilde, Denmark). After each exposure, salt was distributed on stainless steel cups. Small aliquots of about 5 mg salt per sample cup were portioned in a thin layer during darkroom conditions. These conditions were established by using red plastic film (106 primary red, LEE filters, www.leefilters.com) in front of the lamps in the laboratory

Fig. 1. Left frame: PMMA Holder No. 1 with two rubber O-rings for the NaCl and two for the LiF chips. Two nylon screws were used to tighten the PMMA plates together and to avoid any moisture from entering the dosemeter cavities. Right frame: PMMA Holder No. 2, with two cavities for the NaCl and two for the LiF chips.