Experimentally determined and Monte Carlo–calculated energy dependence of NaCl pellets read by optically stimulated luminescence for photon beams in the energy range 30 keV to 1.25 MeV

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Abstract
Ordinary salt, NaCl, has many properties suitable for dosimetry and has been suggested for both retrospective and prospective optically stimulated luminescence (OSL) dosimetry. Lately, the focus has been on NaCl that is compressed into solid pellets, as this improves both its handling and dosimetric properties. In this project, the energy dependence of NaCl pellets produced in-house was investigated for photon energies between 30 and 1.25 MeV. The NaCl pellets were first exposed to free-in-air conditions, and the estimated absorbed dose to the NaCl pellets was compared to the air kerma, $K_{air}$, at the point of exposure. Second, a backscatter medium of polymethyl methacrylate (PMMA) was added, and NaCl pellets were exposed when positioned on an ISO slab phantom to relate the response in the NaCl to the personal dose equivalent, $H_p(10)$. The results show a significant energy dependence for exposure to low-energy photons with a peak over-response compared to $K_{air}$ and $H_p(10)$ of up to 18. Comparisons with Monte Carlo simulations show good agreement, even though the simulations cannot account for properties related to the intrinsic
luminescence effects of the NaCl pellets or the readout and calibration process. The finite thickness of the NaCl pellet makes it an imperfect Bragg-Grey cavity, which complicates the behaviour of the energy dependence. The results presented here may serve as an important basis for further experimental and theoretical modelling of a build-up layer and filters in efforts to develop a passive personal dosemeter based on NaCl.

Keywords: energy dependence, OSL, NaCl pellets, dosimetry

(Some figures may appear in colour only in the online journal)

1. Introduction

Common household salt, based on NaCl, has been proven to be sensitive to ionising radiation. Through optically stimulated luminescence (OSL), a radiation-induced signal can be obtained from the NaCl and the corresponding radiation exposure quantified. Several potential applications in retrospective OSL dosimetry (mainly blue LED continuous wave stimulation) have been described [1–5]. NaCl in various forms has also been studied as a potential prospective dosemeter [6, 7], and more recently, it has been used in the form of pellets [8–11] to widen and improve its applicability as a dosemeter. To assess the suitability of NaCl pellets for prospective dosimetry and to optimise the detector design, it is necessary to study the energy dependence of NaCl in physical pellet configurations that are relevant for prospective dosimetry.

A NaCl pellet-based dosemeter for individual dosimetry in applications with a wide photon energy range should have a reasonably small $H_p(d)$ energy dependence over that energy range. The first step towards a NaCl pellet OSL dosemeter, described in [9] for prospective dosimetry, is to investigate how the OSL signal varies for different photon energies. In this work, blue 470 nm continuous wave light is used to stimulate the luminescence from photon exposures of NaCl pellets in the energy range 30 keV to 1.25 MeV.

The photon energy dependence of NaCl in grain form has previously been studied for a fixed build-up layer of polymethyl methacrylate (PMMA) or polyactide acid plastic [7, 12]. However, by first establishing the energy dependence without any build-up or filters, it is possible to further develop configurations of the build-up and filter layers that are customised and optimised for various applications and relevant quantities, such as air kerma and personal dose equivalent. The aim of this study is to determine the NaCl pellets’ energy dependence for different photon energies when exposed free in air and with backscatter on a phantom. These two geometries form a basis for further experimental and theoretical modelling of an optimal personal dosemeter configuration in terms of build-up layer and filters.

As the geometries chosen for this investigation are not investigated under conditions in which charge-particle equilibrium (CPE) reigns for all energies, the established energy dependence is not only compared to the ratio of attenuation coefficients for NaCl and tissue but also to the energy dependence obtained using Monte Carlo simulations.

2. Method

2.1. NaCl pellets

The salt used for producing the NaCl pellets was a rock salt (Falksalt Finkornigt hushålssalt, Hanson & Möhring, Sweden) bought in a Swedish supermarket, containing NaCl (>99.6%),
Figure 1. Example of the light-shielded package containing eight NaCl pellets during irradiation and until readout. The package is made from aluminium, which is opaque to visible light.

KI (0.005%), and anti-caking agents (E535, E3536). This brand of salt was chosen as it has previously been thoroughly investigated and used for dosimetry purposes [2, 9, 13]. About 100 mg of NaCl was compressed using about 3 tons of mechanical pressure (according to the press manometer), forming 5 NaCl pellets at a time. Experience from earlier investigations showed that, by using sieved salt with grain sizes between 100 µm and 400 µm, the pellets become more homogenous and mechanically stable. A specially manufactured tool (Promech Lab, Sweden) was used together with a hydraulic press (Hamron, Sweden) to compress the NaCl to a pellet that was 4 mm in diameter and 0.8 mm thick, similar in shape and size to commercially available dosemeters such as LiF chips [9]. The thickness of 0.8 mm was required for the pellet to be mechanically stable.

Like other OSL-sensitive materials, the NaCl pellets need to be stored in darkness during and after irradiation to maintain the signal. Otherwise, if exposed to visible light, the OSL signal will become depleted. Darkness during and after irradiation was ensured by using an adhesive aluminium tape (0.1 mm thick) that is opaque to visible light (Etab, Sweden). The influence of the tape was not accounted for but resulted in an attenuation of 0.1% for primary photons at 1250 keV and an attenuation of 3% at 30 keV. For the exposures, dosemeter packages (figure 1) were assembled by putting eight pellets (side by side) in plastic wrap and then sealing them from light by the aluminium tape. Plastic wrap was added to allow removal of the pellets for readout after irradiation. The influence of the plastic wrap on the signal was assumed to be negligible. One package was irradiated for each radiation quality for each exposure geometry.

2.2. Radiation qualities

X-ray exposures by means of standard reference X-ray beam spectra (SS-ISO 4037-1:2011 and IEC 61267:2005) were used for low-energy photon exposures (table 1). For higher photon energies, $^{137}$Cs- ($E_γ = 661.7$ keV) and $^{60}$Co- ($E_{γ,1} = 1173$ keV, $E_{γ,2} = 1332$ keV) point sources were used.

2.3. Setup and exposure

Two calibration geometries were studied: (i) beam irradiation with NaCl packages suspended at a point free in air (figures 2 and 3) and (ii) corresponding irradiation with the NaCl dosemeter attached to a backscatter medium (figure 4) consisting of an ISO slab phantom [14] behind the dosemeter in the beam direction.
Table 1. X-ray qualities used for exposures of NaCl pellets that are free in air and with backscatter. ISO or IEC codes are taken from SS-ISO 4037-1:2011 and IEC 61267:2005.

| ISO Code | Mean energy [keV] | IEC code | Mean energy [keV] |
|----------|-------------------|----------|-------------------|
| L-35     | 30                | RQR 2    | 28.4              |
| N-40     | 33.3              | RQR 3    | 32.5              |
| N-60     | 47.9              | RQR 4    | 36.5              |
| N-80     | 65.0              | RQR 5    | 40.3              |
| N-100    | 83.1              | RQR 6    | 44.0              |
| N-120    | 100.0             | RQR 7    | 47.6              |
| N-150    | 117.7             | RQR 8    | 50.8              |
| N-200    | 164.0             | RQR 9    | 56.6              |
| N-250    | 207.5             | RQR 10   | 64.5              |
| N-300    | 248.9             | RQT 8    | 58.2              |
|          |                   | RQT 9    | 65.3              |
|          |                   | RQT 10   | 74.3              |

Figure 2. Left: An overview of the setup for X-ray irradiation free in air at RTI. Right: The reference detector (red) is seen together with the NaCl package (grey).

2.3.1. Exposures free in air. All RQR and RQT X-ray irradiations were performed at the dosimetry and calibration laboratory at RTI Group in Mölndal, Sweden, with calibrations traceable to the primary standard at the Physikalisch-Technische Bundesanstalt (PTB). The NaCl pellets were configured to be free in air by placing the dosemeter packages on a sheet of plastic wrap placed 80 cm under the X-ray tube (figure 2). The X-ray generator used at RTI is a model Sedecal SHF 535 s/n G-37563 with an X-ray tube Varian RAD 14 s/n 76924-S0 with a Wolfram anode. An R100B silicon diode detector (RTI Group, Mölndal, Sweden) was used for reference measurements. The NaCl pellets were placed close to the R100B during the X-ray exposures and the irradiation continued until the reference detector measured around 1 mGy. The RQR and RQT filtrations shown in table 1 were used for the X-ray exposures.

The N-300 X-ray beam, $^{60}$Co, and $^{137}$Cs irradiations were performed at the National Metrology Laboratory at the Swedish Radiation Safety Authority (SSM) in Stockholm. A setup with the NaCl pellet package placed on a phantom made from plastic film and Styrofoam was used for the irradiations (figure 3). The Styrofoam and plastic were used to simulate an exposure situation as close as possible to free-in-air conditions.
Figure 3. The experimental setup used for irradiation in free-in-air conditions at the National Metrology Laboratory in Stockholm. The setup consists of a plastic sheet on a frame made from Styrofoam.

Figure 4. Exposure setup for irradiations with an ISO slab phantom at the National Metrology Laboratory in Stockholm.

$^{60}$Co irradiations were performed with the NaCl pellets placed 3 m from the source. The air kerma rate at that position was $1.41 \pm 0.03 (2\sigma)$ mGy/s at the time of irradiation. Three irradiations were performed on three separate NaCl dosemeter packages. The air kerma from the
beam was 1.96 ± 0.04 (2σ) mGy, 11.2 ± 0.3 (2σ) mGy, and 99.6 ± 2.1 (2σ) mGy, respectively, at the point in air where the NaCl packages were positioned. 137Cs irradiations were performed 2 m from the source. The air kerma rate at that position was 4.40 ± 0.10 (2σ) µGy s⁻¹ at the time of irradiation. Air kerma of 1.00 ± 0.02 (2σ) mGy, 10.0 ± 0.2 (2σ) mGy, and 30.0 ± 0.7 (2σ) mGy were given to three separate NaCl dosemeter packages, respectively. Multiple irradiations were performed for 60Co and 137Cs to reduce uncertainties in air kerma at the point where the NaCl was positioned.

The X-ray equipment used at SSM is a 320 kV Yxlon (model MG 325/4.5–320 kV, Hudson, USA), with a Yxlon X-ray tube (model Y.TU 320-D03) and internal filtration of 3 mm Be. The N-300 exposure was performed at a distance of 2.5 m with an air kerma rate of 2.22 ± 0.05 (2σ) µGy s⁻¹ at the time of irradiation. A single irradiation of 1.00 ± 0.02 (2σ) mGy was performed for the exposure of the NaCl pellet packages.

2.3.2. Exposures on an ICRU slab phantom. To investigate the absorbed dose energy dependence of the NaCl pellets when used for personal dosimetry, the NaCl pellets were positioned on a water-filled ISO slab phantom during irradiation (figure 4). An H_p(10) of 1.00 ± 0.04 (2σ) mSv was given to the NaCl for L35, N-40 to N-300 (table 1), and 137Cs. H_p(10) values of 49.8 ± 2.2 (2σ) mSv and 100.1 ± 4.5 (2σ) mSv, respectively, were given for the 60Co irradiations. These irradiations were performed at SSM, using the same equipment as described in the previous section.

The distance between the X-ray source and the NaCl in both exposure configurations creates a build-up region large enough to ensure CPE for the lower photon energies, as the range in air for secondary electrons below 250 keV is at most 60 cm.

2.4. Description of the Monte Carlo calculations

Monte Carlo calculations for the exposure geometries of a NaCl pellet were performed with the transport code MCNP6.2 [15], using the nuclear cross-section data set ENDF/B-VII.0 [16]. Among other processes, it accounts for photon creation and loss through relevant mechanisms such as bremsstrahlung, fluorescence, Compton scattering, photon capture, pair production, and p-annihilation.

The code allows for the definition of complex 3-dimensional geometries through a combinatorial geometry technique. The definition of the geometry of a NaCl pellet with and without the ISO slab phantom is based on the physical measurements of the real pellets and the real slab phantom dimensions. The regions in space were constructed by a logical combination (union, intersection, difference) of elementary geometric bodies and surfaces. As input for the different parts of the geometry, data from a material compendium [17] were used to assign the material specifications with definite atomic compositions and densities, as summarised in table 2. To determine the energy dependence of the NaCl pellets compared to K_air or H_p(10), reference calculations were performed by replacing the NaCl pellets with air.

The software SpekCalc [18, 19] was used to create a spectrum for each radiation quality for the MCNP simulation, which enabled more accurate simulations than the use of monoenergies. Spectra were created for RQR2–RQR10, L-35, and N40–N200 and employed as the sources in the Monte Carlo calculations. As the software does not include the option of lead filters, no spectra were created for N250 or N300, and instead, the mean fluence energies (table 1) were employed for these calculations. In addition to the created spectra, a few monoenergies were simulated to obtain an idea of the simulated energy dependence. For the free-in-air configuration, mono-energetic simulations were performed at 100 keV, 150 keV, 200 keV,
Table 2. Material specifications with definite atomic compositions and densities used for the Monte Carlo calculations.

| Material | Atomic composition | Density in g cm$^{-3}$ |
|----------|--------------------|------------------------|
| Air      | 0.02% C; 78.44% N; 21.07% O; 0.47% Ar | 0.001205               |
| Aluminium| 100% Al            | 2.70                   |
| NaCl     | 50% Na; 50% Cl      | 2.17                   |
| PMMA     | 53.33% H; 33.33% C; 13.33% O | 1.19                   |

and 300 keV in addition to the photon energies of the radionuclides. For the backscatter configuration, mono-energetic simulations were performed at 250 keV and 450 keV in addition to the photon energies of the radionuclides.

The source region was defined as a flat circle with a diameter of 15 cm, and its distance from the pellet was set according to the distance in the experiment. For the additional mono-energetic simulations, a distance of 2.5 m was chosen. The photons emitted from this source area were modelled to be monodirectional towards the position of the pellet.

The detector region was defined by the cell of the NaCl pellet that is defined by its geometrical dimensions. In this cell, the numbers and energies of the gamma photons and electrons passing through were scored and the energy deposition was determined. In the calculations for the reference values, the fluence was determined at the same point where the pellet was centred. The determined fluences were converted to $K_{air}$ or $H_p(10)$ by applying conversion coefficients [20, 21].

2.5. OSL signal readout

OSL readout of the NaCl pellets was performed using a Risø TL/OSL reader (TL/OSL-DA-15, DTU Nutech, Denmark), described in detail in Thomsen 2004 [22]. The reader is equipped with an internal irradiation source (20 MBq (2009-04-09) $^{90}$Sr/$^{90}$Y) with an absorbed dose rate to NaCl of $0.72 \pm 0.014$ mGy s$^{-1}$ (1u) (2019-02-01) at the irradiation position. The $^{90}$Sr/$^{90}$Y source was calibrated using Risø calibration quartz [23], and the absorbed dose to NaCl was calculated using the stopping-power ratio between NaCl and quartz at 500 keV. The side of the pellet facing the X-ray unit during exposure was placed up (towards the PMT tube) in the readout unit, although preliminary studies indicated that the orientation does not affect the result. The light stimulation was performed using blue light at 470 nm in the continuous wave mode.

2.6. Calculation of absorbed dose to NaCl

After readout of the unknown signal, $S_u$, each pellet was given a calibration dose, $D_c$, by the internal $^{90}$Sr/$^{90}$Y source. $D_c$ was set to twice the size of the anticipated dose attained in the irradiation experiment [9]. Normalising $S_u$ to the signal from the known calibration dose, $S_c$, results in a calibration that accounts for the radiation sensitivity of each individual pellet. This reduces the variability between pellets and, when multiplied with $D_c$, the OSL signal is recalculated to the absorbed dose to NaCl, $D_{NaCl}$ (equation (1)). For each dosemeter package, the absorbed dose was determined as the arithmetic mean of the estimated absorbed doses to eight NaCl pellets. As previously mentioned, $K_{air}$ and $H_p(10)$ were used as reference quantities for the obtained $D_{NaCl}$. $D_{NaCl}$ will vary with photon energy in relation to $K_{air}$ and $H_p(10)$.
energy dependence is defined as the ratio of the absorbed dose to the NaCl pellet and the reference medium [24], here expressed according to equation (2).

\[
D_{\text{NaCl}} = \frac{S_u \cdot D_e}{S_c}
\]  

\[
\frac{D_{\text{NaCl}}}{H_p(d)} = \frac{S_u \cdot D_e}{S_c \cdot H_p(d)}
\]

\[
\frac{D_{\text{NaCl}}}{K_{air}} = \frac{S_u \cdot D_e}{S_c \cdot K_{air}}
\]

2.7. Calculation of mass energy absorption coefficients

Due to the finite thickness of the pellets, it was anticipated that the photon interaction in the detector would not be negligible for low photon energies. Hence, the experimental results were compared to the ratio of the theoretical mass energy absorption coefficients, \( \mu_{en}/\rho \), for NaCl and air or tissue. The values of \( \mu_{en}/\rho \) for air and tissue (soft, ICRU-44) were taken from the NIST table ‘X-ray Mass Attenuation Coefficients’ [25] which also lists the \( \mu_{en}/\rho \) coefficients. For NaCl, the \( \mu_{en}/\rho \) coefficients were calculated as a mass-weighted mean of the coefficients for sodium and chlorine. As for the energy, the available spectra were normalised, binned into sections of 10 keV, and multiplied by the mass energy absorption coefficient for each energy bin. This sum provided an energy-weighted mass energy absorption coefficient. The anti-caking agent and the potassium iodine were not accounted for as the proportions were not known. Despite its limitations [26] the calculation provided a good estimate and is a feasible estimation method relative to the scope of this work.

2.8. Uncertainty calculations

For every photon energy investigated, the eight NaCl pellets in the light-shielded package (figure 1) were irradiated and read. The standard deviations \( S_u \) and \( S_c \) were estimated to be the standard deviation of the mean of the eight exposed samples. The uncertainty in the calibration dose, \( D_e \), arising from the uncertainty in the source dose rate calibration and uncertainties between calibrations, and the beta source uniformity were also considered. In addition, the uncertainties in the reference doses, \( D_{ref} \), in the irradiation setup, \( K_{air} \) or \( H_p(10) \), were taken into account in the uncertainty propagation. The correction for the influence of the light-shielding tape was considered as an additional source of uncertainty. The uncertainty of the exposure time related to \( D_c \) was not included as it was deemed negligible.

For calculations including the uncertainty contribution from the ratio of \( S_u \) and \( S_c \), it was necessary to account for the covariance of the two correlated variables. Each reference photon beam deposits energy in the NaCl pellets, resulting in a certain \( S_u \). The \( S_u/K_{air} \) or \( S_u/H_p(10) \) will depend on the photon energy and the radiation sensitivity of the specific pellet (this can vary even in pellets of the same weight), but it will be independent of the magnitude of the reference dose, implying that the signal-absorbed dose response is linear. The same is true for the relationship between \( S_u \) and \( D_e \). The correlation between \( S_u \) and \( S_c \) is expressed as the square root of the correlation coefficient (Pearson R² value), obtained from a linear regression of the experimental data. Because of this strong covariance, the uncertainty contribution
from the ratio between $S_u$ and $S_c$ becomes very small. Uncertainties were calculated using the propagation of correlated uncertainties (equation (3)),

$$\left(\frac{\sigma D_{NaCl}/K_{air}}{D_{NaCl}/K_{air}}\right)^2 = \left(\frac{\sigma S_u}{S_u}\right)^2 + \left(\frac{\sigma S_c}{S_c}\right)^2 + \left(\frac{\sigma D_c}{D_c}\right)^2$$

$$+ \left(\frac{\sigma D_{ref}}{D_{ref}}\right)^2 - 2 \cdot \frac{\sigma S_u}{S_u} \cdot \frac{\sigma S_c}{S_c}$$

where $\sigma$ denotes the standard deviation of the mean.

3. Results and discussion

3.1. Experimentally determined energy dependence

For the studied exposures, CPE reigns for the lower X-ray energies (<250 keV) due to build-up in the air between the X-ray tube and NaCl pellets. For the higher photon energies, neither the anterior air nor the NaCl pellets have mass thicknesses large enough to enable CPE conditions. The 0.1 mm Al layer of the packaging of the NaCl pellets does not provide a proper build-up (solely intended to protect against ambient light from depleting the stored OSL signal). No correction is made for the attenuation in the aluminium tape, as it is considered in the Monte Carlo simulation.

Figure 5 shows the $K_{air}$ energy dependence of the NaCl pellets when placed free in air. The experimentally determined energy dependence shows an over-response in NaCl compared to air, which peaks at about 35 keV. Assuming CPE reigns for low photon energies, the experimental energy dependence should agree with the theoretical ratio of the $\mu_{en}/\rho$ coefficients, but the results differ by more than a factor of 1.5. The Monte Carlo–simulated energy dependence better follows the experimental results, although these results differ in magnitude by up to a factor of 1.2 in the low-energy region. For higher photon energies, above 200 keV, the energy dependence converges towards a ratio of 0.9, which is the theoretical stopping-power ratio between NaCl and air, $S_{NaCl}/S_{air}$, for photon energies above 200 keV. For these energies, the range of the secondary electrons becomes larger compared with the 0.8 mm thick NaCl pellet, and for even higher energies, the NaCl pellet will act as a Bragg-Grey cavity if the condition of delta particle equilibrium can be assumed. This seemed to be true only for the $^{60}$Co result in figure 5.

Figure 6 shows the corresponding energy dependence of the NaCl pellets when irradiated on an ISO slab phantom. The shape of the curve is somewhat different from the free-in-air geometry, as the experimental data are normalised to $H_{d}(10)$ instead of $K_{air}$. Assuming CPE for low-energy photons, the agreement between the experimentally determined values and the theoretical values of the $\mu_{en}/\rho$ coefficients should be good, but the corresponding graphs in figure 6 differ by almost a factor of 2 for the lowest energies. However, the experimental values agree reasonably well with the Monte Carlo simulations. With increasing energy, the energy dependence converges towards a ratio of 0.8, which corresponds to the theoretical stopping-power ratio between NaCl and tissue, $S_{NaCl}/S_{Tissue}$, for photon energies above 200 keV for a small detector with delta particle equilibrium. Again, this seems to be true only for the $^{60}$Co exposure.

The results in figures 5 and 6 thus show that the NaCl pellet with a fixed thickness of 0.8 mm behaves as a large (photon) detector for low photon energies, a small (electron) detector for high energies, and a Burlin cavity for intermediate photon energies. Hence, for low photon energies, the energy dependence is dependent on the attenuation coefficients, and for higher
energies, it is dependent on the stopping-power ratio, $S_{NaCl}^{Tissue}$. This, again, assumes CPE for low energies and delta ray equilibrium for higher photon energies.

For a potential dosemeter based on NaCl pellets, adding a build-up layer in front of the NaCl pellets will slightly flatten the energy dependence for low-energy photons by attenuation. For higher energies, a build-up layer will increase the signal. A combination of filters might be needed to accurately flatten the energy dependence over a wide energy range. Moreover, other filter combinations may be used to distinguish doses from photons, electrons, and even neutrons (as previously suggested [27]). This will be of importance in the development of a dedicated NaCl pellet badge for personal dosimetry.
3.2. Comparison of the two geometries

To compare the experimental results of the different geometries, the $H_p(10)$ reference values from the backscatter geometry were converted to $K_{air}$ values. The result of this is shown in figure 7. When normalising the results from both exposure geometries to $K_{air}$, the curves appear very similar. As expected, the backscatter geometry gives somewhat higher absorbed doses to the NaCl than does the free-in-air geometry due to the backscattering component. Different radiation facilities were used for the two exposure geometries and there were no common reference spectra available. As a results of this, as can be seen in figures 5–7, the photon energies and range do not completely overlap for the two exposure geometries. On the whole however, this should not have an impact on the energy dependence.

3.3. Discrepancy between simulated, experimental, and theoretically determined energy dependence

The experimentally observed energy dependence for low photon energies can be divided into two parts: one is related mainly to the relative difference in $\mu_{en}/\rho$ coefficients between the detector medium (NaCl) and the reference medium (air or tissue), referred to as the absorbed-dose energy dependence, and the second is referred to as the intrinsic energy dependence [24]. The intrinsic energy dependence is related to the measured value from a detector in relation the actual absorbed dose. This would, for example, account for the radiation-induced luminescence processes in the dosemeter material until the registration of a luminescence signal in the photomultiplier tube. Depending on the size of the intrinsic energy dependence and the accuracy of the theoretical and simulated absorbed-dose energy dependence, there will be a discrepancy between the theoretical, simulated, and experimental energy dependency.

3.3.1. Absorbed-dose energy dependence. In the simulated NaCl pellet, only sodium and chlorine are considered. The potassium iodine, anti-caking agent (sodium ferrocyanide and potassium ferrocyanide), and trace amounts of other substances in the actual salt are not considered. Although these amounts are very small, these additives contain high Z components.
that could alter the average attenuation coefficient of household salt. The Monte Carlo simulations could also be further improved if spectra could be used to simulate all radiation qualities. However, the use of extra mono-energetic simulations provides an idea of the energy dependence.

The $\mu_{en}/\rho$ coefficients have all been estimated using the whole energy spectrum when possible. The spectra were binned in a way that made it possible to account for the mass energy absorption coefficients for the whole range of photon energies in each spectrum. Using the full spectra is preferable for a more accurate comparison with the experimental energy dependence. Because each spectrum includes a wide range of photon energies, it could also be that CPE reigns for only part of a spectrum, which makes a comparison more complex. The mass weighting of the coefficients themselves also contributes to the uncertainty. The $\mu_{en}/\rho$ coefficients of sodium and chlorine are based on an atomic number dependency (usually $Z^{3-4}$), which might be different from that of NaCl. If the Z dependency of the compound differs from that of the components, the curve would be different. It is difficult to estimate the true effective atomic number dependency of NaCl with the available data, especially as it may vary for different photon energies. The mass weighted $\mu_{en}/\rho$ should provide a good enough estimate to give an idea of the theoretical absorbed-dose energy dependence for low photon energies, but it should not be considered as exact.

3.3.2. Intrinsic energy dependence. The stopping power of electrons in NaCl is slightly higher for low electron energies than higher ones. If the luminescence process is energy dependent or dependent on the stopping power, this may lead to a higher luminescence yield per unit absorbed dose, depending on electron energy. This in turn will lead to an overestimate of the absorbed dose in NaCl for low photon energies when using a $^{90}$Sr/$^{90}$Y source (mean beta energy 0.5 MeV) for calibration. This effect would not be seen in the Monte Carlo simulation, as the luminescence process and influence of the calibration dose had not been considered.

In other dosemeter materials, such as Al$_2$O$_3$, a change in stopping power has been shown to lead to a change in luminescence emission band and a change in the OSL decay curve [28]. The change in OSL decay curve can result in different energy dependences depending on how the signal is defined [29] but this effect was not observed for OSL signals in this study. The change in emission wavelength with varying LET was not considered in this study, and further work into this is desirable.

3.4. Uncertainty calculations

The uncertainties considered in the propagation of uncertainty are presented in table 3. The $^{90}$Sr/$^{90}$Y source calibration contains both the uncertainty in a single calibration and the variation between calibrations. The uncertainties expressed as the coefficient of variation, $C_v$, vary between 5% and 20% for the different radiation qualities. The only sources of uncertainty that vary between radiation qualities are the variations in $S_u$ and $S_c$; all other sources of uncertainty remain the same.

Uncertainties have only been calculated for the experimentally determined energy dependence. For the theoretical and simulated energy dependencies, the uncertainties are presented and discussed, but they have not been explicitly quantified.

No uncertainties related to variation in humidity in places where the NaCl are kept before, during, and after irradiation have been considered. NaCl is highly hygroscopic and the absorption of water could potentially alter the dosimetric properties of the NaCl pellet. Hitherto no such effects have been seen but the hygroscopic effect is a factor which contribution to the
Table 3. Sources of uncertainty for the calculation of the energy dependence of the NaCl pellets used during this study.

| Source                          | Uncertainty |
|--------------------------------|-------------|
| $^{90}$Sr/$^{90}$Y source calibration | 5.4%        |
| Size of calibration dose        | 5%          |
| Beta dose uniformity            | 4%          |
| Reference dose, RTI             | 1.6%        |
| Reference dose, $K_{air}$, SSM   | 1.1%        |
| Reference dose, $H_p(10)$, SSM  | 2.3%        |
| Light-shielding tape            | 1%          |

overall uncertainty needs to be more thoroughly investigated if NaCl is to be used as a personal dosimeter.

4. Summary and conclusion

NaCl pellets have been investigated in terms of the energy dependence of the continuous wave blue light OSL response for air kerma and personal dose equivalent for various photon beam energies ranging from 30 keV to 1.25 MeV. This was done as a first step towards developing a personal passive dosemeter based on NaCl.

- The thickness of the NaCl pellet leads to an imperfect Bragg-Gray cavity:
  - A strong $Z^{1.4}$ dependency of the photon interactions results in a large over-response for low-energy photons.
  - For low-energy photons, the 0.8 mm NaCl pellet will act as a photon detector and depend on the $\mu_{en}/\rho$ coefficients.
  - For high-energy primary photons, the experimental energy dependence is comparable to that of a true Bragg-Gray cavity with a stopping-power ratio between NaCl and the surrounding medium, $S_{NaCl}/S_{Medium}$.
  - For intermediate photon energies, the 0.8 mm NaCl pellet will act as a Burlin cavity dependent on both the $\mu_{en}/\rho$ coefficients and the stopping power.
- When comparing the experimental results from both exposure geometries to air kerma, the energy dependencies agree well with a slightly higher over-response for the backscatter geometry because of the backscatter component.
- There are several uncertainties in comparing the experimental results with simulations and theoretical values, e.g.:
  - CPE is not ensured for all photon energies.
  - Luminescence and readout properties are not considered in simulations or theoretical values.
  - The estimation of theoretical $\mu_{en}/\rho$ values are uncertain for the Na + Cl compound and the radiation qualities approximated by mono energies.
  - The NaCl pellet is simplified to contain only sodium and chloride, excluding potassium iodine and anti-caking and trace agents.
- Based on the results in this study, physical filters or mathematical corrections specific to the studied NaCl pellets configuration can be developed and applied to achieve a dosemeter response approaching the one for tissue, which hence can be used to obtain accurate estimates of $H_p(10)$ or $H_p(0.07)$ for prospective dosimetry.
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