Radiation Measurements xxx (2017) 1–7

Contents lists available at ScienceDirect

Radiation Measurements

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

Dosimetric properties of a personal dosimetry system based on radio-photoluminescence of silver doped phosphate glass

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HIGHLIGHTS

- Dose response of a radio-photoluminescence based personal dosimetry system was determined.
- Various dose levels, photon and beta radiation energies, incident angles and combinations were tested.
- Dosimetric requirements of the Swiss radiation protection legislation are fulfilled.

ARTICLE INFO

Article history:
Received 12 September 2016
Received in revised form
28 April 2017
Accepted 20 June 2017
Available online xxx

Keywords:
Radio-photoluminescence
Silver doped/activated phosphate glass
Individual monitoring
Dose equivalent response
Photon radiation
Beta radiation

ABSTRACT

In the presented study, the relative response of a commercially available RPL glass dosemeter system, developed for individual monitoring of external ionizing radiation, was determined for different photon and beta radiation qualities, varying angle of incidence of photon radiation, and for combined photon irradiations. For ^{137}Cs radiation quality the $H_p(10)$ and $H_p(0.07)$ relative responses vary between 90% and 100% from 0.1 mSv up to 5 Sv. In the photon energy range from 33 keV to 1250 keV the $H_p(10)$ variation is less than 10%. The $H_p(0.07)$ variation is less than 10% for photon energies higher than 12 keV. The response of both dose quantities varies less than 15% for angle of incidence up to 60° for ^{137}Cs and N-80 photon radiation qualities. For beta radiation the relative response of $H_p(0.07)$ was determined to be 1.03 for ^{90}Sr+^{90}Y, 0.98 for ^{85}Kr, and 0.48 for ^{147}Pm. Under combined irradiation conditions with differing radiation qualities and angles of incidence, the dose accuracy was within ±50%. The precision of the RPL dosimetry system in $H_p(0.07)$ and $H_p(10)$ is better than 2% for radiation quality ^{137}Cs and doses greater than 0.5 mSv.

1. Introduction

Silver doped phosphate glass exposed to ionizing radiation shows radio-photoluminescence (RPL) when excited by ultraviolet light. Combined with suitable materials for filtering ionizing radiation and a dose calculation algorithm, silver doped phosphate glass can be used for the measurement of the personal dose equivalent quantities $H_p(10)$ and $H_p(0.07)$. The RPL in silver doped phosphate glass is based on the creation of color centers by ionizing radiation, and the emission of light in the visible region after optical excitation of the color centers e.g. by a UV light source with a wavelength of 365 nm (Yamamoto et al., 2011). The RPL signal is proportional to the concentration of color centers created by ionizing radiation, which in turn is proportional to the amount of absorbed radiation energy. The color centers do not fade over time and remain stable under optical excitation. Therefore, the RPL measurement of an exposed phosphate glass detector can be repeated many times with identical results. Annealing at high temperatures at about 400 °C restores the original silver dopant concentration, allowing the material to be used again with the same dose response. The RPL emission mechanism in this type of glass has been investigated recently by Miyamoto et al. (2011, 2010), and Kurobori et al. (2010), and its energy dependence was reported by Hocine et al. (2011) and Juto (2002). A historical overview on RPL and its applications can be found in Perry (1987).

Because silver doped phosphate glass is an integrating, passive solid state detector, it is suitable for individual monitoring in radiation protection, and automated dosimetry systems have been developed (Burgkhardt et al., 1990; Ikegami, 1991; Nomura et al., 2002; Piesch and Burgkhardt, 1994). CHIYODA TECHNOL CORP., Tokyo, designed two similar, state-of-the-art versions of RPL

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http://dx.doi.org/10.1016/j.radmeas.2017.06.008

Please cite this article in press as: Assenmacher, F., et al., Dosimetric properties of a personal dosimetry system based on radio-photoluminescence of silver doped phosphate glass, Radiation Measurements (2017), http://dx.doi.org/10.1016/j.radmeas.2017.06.008

dosemeter badges and reading systems. The GBFJ-01 dosemeter badge version was first used at the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) in France since 2008 (Hocine, 2012; Hocine et al., 2011). Maki et al. (2015) present the test results and dosimetric properties of the second version, so called *New Glass Badge* (GB), which is used since 2014 only in Japan. Both RPL dosemeter designs differ slightly in glass detector dimensions and badge construction.

At the Paul Scherrer Institut (PSI), the TLD personal dosimetry system for individual monitoring was replaced in 2016 by the GBFJ-01 based RPL dosimetry system. Therefore, the objective of this study was to determine its dosimetric properties and demonstrate that it fulfills the Swiss Federal Legislation (Swiss Federal Council, 2013), which differs partially from the international standard (IEC 62387, 2012). To the best of our knowledge, such data on this type of RPL dosimetry system has not been published yet.

2. Materials and methods

2.1. The RPL dosimetry system

The RPL dosimetry system at PSI consists of the dosemeter badge type GBFJ-01, the reader type FGD-660, and the dose calculation software CDEC-Easy (CHIYODA TECHNOL CORP., Tokyo). The dosemeter badge has dimensions 61 × 30 × 8 mm^3, and houses the glass detector formed in the shape of a slab with dimensions 35 × 7 × 1.5 mm^3. The dosemeter badge is equipped with radiation absorbers made from aluminium, copper, tin, and two kinds of plastic materials, forming five differently filtered areas of the glass detector. The dosemeter design and the internal construction are shown in detail in Hocine et al. (2011). The detector material, Ag^+-doped phosphate glass (P_4O_{10}), named FD-7, was produced by AGC TECHNO GLASS CO., LTD., Shizuoka, with a weight composition of 31.55% P, 51.16% O, 6.12% Al, 11% Na, and 0.17% Ag (Yamamoto et al., 2011).

Each glass detector is measured at five distinct positions, corresponding to the five differently filtered areas. The FGD-660 device uses 365 nm laser pulses of approx. 1 ns for optical excitation, and a photomultiplier tube for time-resolved detection of the RPL signal. By integrating the luminescence signal in two delayed time windows, the RPL signal due to radiation-induced color centers can be distinguished from the zero-signal due to intrinsic bulk luminescence (Huang and Hsu, 2011). For preparation of glass detectors before use, the pre-dose signals are measured at all five positions and later subtracted from the measured RPL signals of the irradiated detectors.

Before measurement the glass detectors were heated at 100 °C for 1 h to establish a complete RPL signal build-up (Perry, 1987). The dosemeters were measured with two FGD-660 readers, calibrated with the same set of reference dosemeters, and the data was combined to one data set without device specific adjustments.

2.2. Irradiations

The irradiations with photon radiation qualities were performed according to ISO norms 4037–1 and 4037–3 (ISO, 1999a,b) by the secondary standard dosimetry laboratory (SSDL) at PSI. The radiation fields are traceable to the primary standards of the Physikalisch-Technische Bundesanstalt (PTB), Germany. For the radiation qualities ^{137}Cs and ^{60}Co radionuclide sources inside an OB20 irradiation device (Buchler GmbH, Braunschweig) were used, and for X-ray radiation qualities of the narrow series an ISOVOLT Titan TI320 device (GE General Electric Inspection Technologies). The relative uncertainties (coverage factor $k = 2$) of the irradiated dose values were in the range from 3.4% to 3.9% for the OB20 device, and from 2.3% to 2.6% for the TI320, and include 2% uncertainty of the conversion factors from air kerma K_a to $H_\text{p}(10)$ (ISO, 1999b). In the commissioning tests $H_\text{p}(10)$ or $H_\text{p}(0.07)$ were chosen as reference values and the corresponding values K_a were determined according to the relation $H_\text{p}(d) = h_\text{p}(d, E, \alpha) \times K_\text{a}$ with dose conversion factors $h_\text{p}(d, E, \alpha)$ for varying photon energies or radiation quality E, angle of incidence α and depth in tissue d given by ISO 4037–3 (1999b). For angle $\alpha = 15°$, the conversion factors were given by ICRP Publication 74 (ICRP, 1996). For radiation quality N-15 the value h_p (10, N-15, 15°) = 0.06 was determined by linear interpolation between h_p (10, N-15, 0°) and h_p (10, N-15, 30°). A 30 × 30 × 15 cm^3 ISO water slab phantom with 10-mm thick side and rear walls made of polymethyl methacrylate (PMMA), and 2.5-mm thick PMMA front wall was used in all irradiations (ISO, 1999b). To establish secondary particle equilibrium for ^{137}Cs and ^{60}Co radiation qualities, an additional PMMA sheet 2-mm thick for ^{137}Cs and 4-mm thick for ^{60}Co was placed in front of the dosemeters. For quality assurance, constancy checks and *in situ* monitoring of the irradiations were performed with calibrated ionization chambers, especially when irradiations of a group of dosemeters had to be split into several runs due to the limited space on the ISO water phantom. The reference point for the distance from the source to the dosemeters was defined on the surface of the ISO water phantom. Typical source-surface distances were 2 m for the ISOVOLT TI320 device and from 2 m to 6 m for the OB20 device.

The irradiations with beta radiation qualities ^{90}Sr+^{90}Y, ^{85}Kr, and ^{147}Pm were performed by the SSDL at the Institut universitaire de radiophysique appliquée (IRA) in Lausanne, Switzerland. Each group consisted of six dosemeters, and the distance from the source to the ISO water phantom surface was 30 cm for ^{90}Sr+^{90}Y and ^{85}Kr, and 20 cm for ^{147}Pm. The 95%-confidence interval of $H_\text{p}(0.07)$ was 4% for ^{90}Sr+^{90}Y, 4.4% for ^{85} Kr, and 9.8% for the ^{147}Pm source. Control dosemeters were used to correct for transport and natural radiation background dose.

2.3. Dose calculation

The dose calculation algorithms implemented in CDEC-Easy for determining the personal dose equivalents $H_\text{p}(10)$ and $H_\text{p}(0.07)$ from the five measured RPL signals of a glass detector were described by Juto (2002). Due to the filter design, distinction between photon and electron radiation qualities and estimation of the mean energy are possible. However, the metallic filters absorb beta radiation and very low energy X-rays almost completely, the distinction between beta and X-ray radiation is subject to higher uncertainty and ambiguity. Because the conversion factors from air kerma to dose equivalent for photon radiation and from absorbed dose to dose equivalent for beta radiation are usually different, small changes in the RPL signals may lead to an increased inaccuracy in personal dose determination.

For a few detectors of the dosemeter groups which were exposed to radiation quality N-15 with a mean photon energy of 12 keV, or radiation quality N-80 with an angle $\alpha = +60°$, the RPL signals were falsely identified as originating from beta radiation. In such cases, the dose calculation by CDEC-Easy was corrected to exclude contributions from beta radiation. For the purpose of determining the dosimetric properties of the RPL dosimetry system this approach is justified. In the general case, when the specific radiation fields in routine are not known, additional information is required when a dose contribution by beta radiation was identified.

For the duration of the commissioning tests of approx. 3 months the dosemeters were stored in a shielded environment. The residual natural radiation background dose was determined from 24 dosemeters to be (0.14 ± 0.02) mSv (k = 2) for $H_\text{p}(10)$ and $H_\text{p}(0.07)$, and was subtracted from the measured dose values.

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