Comparing $H_p(3)$ evaluated from the conversion coefficients from air kerma to personal dose equivalent for eye lens dosimetry calibrated on a new cylindrical PMMA phantom

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Abstract. Based on a new occupational dose limit recommended by ICRP (2011), the annual dose limit for the lens of the eye for workers should be reduced from 150 mSv/y to 20 mSv/y averaged over 5 consecutive years in which no single year exceeding 50 mSv. This new dose limit directly affects radiologists and cardiologists whose work involves high radiation exposure over 20 mSv/y. Eye lens dosimetry ($H_p(3)$) has become increasingly important and should be evaluated directly based on dosimeters that are worn closely to the eye. Normally, $H_p(3)$ dose algorithm was carried out by the combination of $H_p(0.07)$ and $H_p(10)$ values while dosimeters were calibrated on slab PMMA phantom. Recently, there were three reports from European Union that have shown the conversion coefficients from air kerma to $H_p(3)$. These conversion coefficients carried out by ORAMED, PTB and CEA Saclay projects were performed by using a new cylindrical head phantom. In this study, various delivered doses were calculated using those three conversion coefficients while nanoDot, small OSL dosimeters, were used for $H_p(3)$ measurement. These calibrations were performed with a standard X-ray generator at Secondary Standard Dosimetry Laboratory (SSDL). Delivered doses ($H_p(3)$) using those three conversion coefficients were compared with $H_p(3)$ from nanoDot measurements. The results showed that percentage differences between delivered doses evaluated from the conversion coefficient of each project and $H_p(3)$ doses evaluated from the nanoDots were found to be not exceeding -11.48 %, -8.85 % and -8.85 % for ORAMED, PTB and CEA Saclay project, respectively.

1. Introduction
The International Organization for Standardization (ISO) has issued a standard series on photon reference radiation qualities for calibrating dosimeters (ISO 4037) which included conversion coefficients of $H_p(0.07)/K_a$ and $H_p(10)/K_a$ in different types of phantom (slab, pillar, rod) but no conversion coefficients for $H_p(3)$ [1]. Personal dose equivalents are evaluated in terms of $H_p(10)$ and $H_p(0.07)$ by using optically stimulated luminescence (OSL) dosimeters (InLight) placed on a slab phantom (dimension: 30 x 30 x15 cm$^3$). The eye lens dose, $H_p(3)$, can be calculated by a combination of the $H_p(0.07)$ and $H_p(10)$ values and dosimeters worn at the neck. Eye lens dosimetry which can directly evaluated $H_p(3)$ by using dosimeters worn closely to the eye has become increasingly important. In 2011, International Commission on Radiological Protection (ICRP) recommended that the occupational equivalent dose limit for the lens of eye should be reduced from 150 mSv per year to 20 mSv per year, averaged over defined 5 years periods, with no single year exceeding 50 mSv. The dose limit was reduced by more than a factor of 7 due to new findings indicating that the threshold
dose for the lens of the eye to be at risk from radiation is lower than previously concerned. The threshold in absorbed dose was considered to be 0.5 Gy compared with the earlier figure of 5 Gy for chronic and 0.5-2.0 Gy for acute exposures [2]. The new eye lens dose limit will impact interventional radiologists and cardiologists who often receive an annual eye dose of more than 20 mSv due to interventional procedures involving long fluoroscopic time from cine acquisitions to operation of fluoroscopic equipment in high-dose fluoroscopic modes, leading to high worker doses.

In 2009, the Optimization of RAdiation protection for MEDical staff (ORAMED) presented a project which aimed to introduce new elements in the discussion on the quantity \( H_p(3) \) and to propose a more suitable theoretical cylindrical phantom to better approximate the head in which the eyes are placed. A new Monte Carlo approach helped to define the operational quantity of \( H_p(3) \) [3]. Under this project, the Monte Carlo code MCNP4C was proposed by Radiation Protection Institute Bologna team to simulate the photon interactions within an ICRU tissue equivalent cylindrical phantom, 20 cm in diameter and 20 cm in height, which is representative of the mass and shape for a human head [4]. The monoenergetic photons from 10 keV to 10 MeV were simulated for an aligned and expanded field with an angle of 0° and 40°. In the same ORAMED project, the Monte Carlo code PENELOPE was proposed by the French Atomic Energy Commission (CEA Saclay Nuclear Research Centre) to simulate a set of energy and angular dependent also using ICRU cylindrical phantom. The \( H_p(3) \) values have been determined in terms of dose equivalent, according to the definition of this quantity, and also with the kerma approximation as formerly reported in ICRU reports [5]. Conversion coefficients \( (H_p(3)/K_{air}) \) for monoenergetic photons from both projects were also presented. In 2012, Behrens (Physikalisch-Technische Bundesanstalt (PTB)) presented air kerma to \( H_p(3) \) conversion coefficients \( (h_{PK}(3;R,\alpha,\beta)) \) for a new cylinder phantom for X and gamma rays radiation qualities defined in ISO 4037. These conversion coefficients were valid for the total air kerma which calculated using the mass energy transfer coefficient \( (\mu_{ef}/\rho)_{\text{eff}} \) [6]. The purpose of this presentation is to compare the delivered doses \( H_p(3) \) using three different of conversion coefficients to the \( H_p(3) \) from nanoDot dosimeter measurements.

2. Materials and Methods

2.1. Materials

The cylindrical phantom used in this study composes of 40 polymethyl methacrylate (PMMA) slice rings (20 cm in diameter and 0.5 cm in slice thickness) which was designed at Meikai University. There are 10 holes at the depth of 3 mm from the surface of the slice rings. Small dosimeters can be inserted into those holes at position of left and right eyes. The nanoDot dosimeters (Landauer Inc., USA), designed for measuring a small, single point radiation exposure normally worn on a wrist or a finger, were selected in this study. Each dosimeter, 10x10 mm² in size and 2 mm in thickness, composes of aluminum oxide (Al₂O₃: C) crystal, whose thickness is 0.3 mm and diameter is 7 mm, sealed in a thin polyester sheet. Measurements were read out by a microStar mobile reader (Landauer Inc., USA). In the luminescence process which is the same as optically stimulated luminescence (OSL) or InLight dosimeters, the irradiated dosimeters were stimulated by a quantum of visible green light from the light emitting diode (LED). The luminescence time, at the order of 10– several hundred milliseconds, depends on light intensity. During the stimulation, only some fractions of the populated electrons were depopulated. The amount of luminescence was proportional to the absorbed radiation and remained significantly unchanged after the reading. This characteristic enables nanoDots to be read out many times [7].

2.2. Methods

Three nanoDot dosimeters were inserted into the cylindrical phantom holes representing left and right eyes. These dosimeters were irradiated using X-ray beam of qualities N-40, N-60, N80, N-100, N120 and N-150 at Secondary Standard Dosimetry Laboratory (SSDL), Office of Atoms for Peace, Thailand. The delivered air kerma values were 100, 1,000 and 2,000 Gy at 0 degree angle of incidence from the X-ray generator. The air kerma values were traceable to Physikalisch-Technische Bundesanstalt (PTB), Germany. Delivered \( (H_p(3)) \) doses using three conversion coefficients from
ORAMED, PTB and CEA Saclay were calculated. The irradiated nanoDot dosimeters were read out by a microStar reader at Thailand Institute of Nuclear Technology (TINT), Thailand (Figure 1). The microStar reader used at TINT was calibrated with an X-ray generator at 80 kVp which was traceable to National Institute of Standard and Technology (NIST), USA. After reading, \( H_p(3) \) were calculated from the average counts readings multiplied by the calibration factor. The delivered doses (\( H_p(3) \)) based on ORAMED, PTB and CEA Saclay conversion coefficients were compared to the nanoDot measurements.

2.3. Conversion coefficients
The conversion coefficients used in this study are given in Table 1.

![Figure 1. “NanoDot” dosimeters and a mobile reader “microStar”](image1)

![Figure 2. The nanoDot dosimeters were placed in the cylindrical phantom at the depth of 3 mm.](image2)

| Radiation quality | \( \frac{H_p(3)}{K_a} \) ORAMED \( \text{Sv Gy}^{-1} \) | \( \frac{H_p(3)}{K_a} \) PTB \( \text{Sv Gy}^{-1} \) | \( \frac{H_p(3)}{K_a} \) CEA Saclay \( \text{Sv Gy}^{-1} \) |
|------------------|----------------|----------------|----------------|
| N-40             | 1.207          | 1.280          | 1.289          |
| N-60             | 1.469          | 1.540          | 1.553          |
| N-80             | 1.628          | 1.660          | 1.670          |
| N-100            | 1.606          | 1.630          | 1.638          |
| N-120            | 1.567          | 1.580          | 1.580          |
| N-150            | 1.532          | 1.520          | 1.534          |
Table 2. Delivered \( H_p(3) \) doses evaluated from the conversion coefficients of ORAMED, PTB and CEA Saclay compared with \( H_p(3) \) evaluated from nanoDot measurements.

| Radiation quality | ORAMED | PTB | CEA Saclay |
|-------------------|--------|-----|------------|
|                   | Delivered \( \mu \text{Sv} \) | nanoDot \( \mu \text{Sv} \) | % difference | Delivered \( \mu \text{Sv} \) | nanoDot \( \mu \text{Sv} \) | % difference | Delivered \( \mu \text{Sv} \) | nanoDot \( \mu \text{Sv} \) | % difference |
| N-40              | 120.66 | 126.12 | 4.53 | 128.00 | 126.12 | -1.47 | 128.94 | 126.12 | -2.18 |
|                   | 1207.98 | 1272.99 | 5.38 | 1281.46 | 1272.99 | -0.66 | 1290.87 | 1272.99 | -1.39 |
|                   | 2415.96 | 2542.99 | 5.26 | 2562.92 | 2542.99 | -0.78 | 2581.74 | 2542.99 | -1.50 |
| N-60              | 146.91 | 141.57 | -3.63 | 154.00 | 141.57 | -8.07 | 155.26 | 141.57 | -8.82 |
|                   | 1467.88 | 1565.51 | 6.65 | 1538.73 | 1565.51 | 1.74 | 1551.32 | 1565.51 | 0.91 |
|                   | 2935.77 | 3155.46 | 7.48 | 3077.45 | 3155.46 | 2.53 | 3102.63 | 3155.46 | 1.70 |
| N-80              | 162.80 | 173.90 | 6.82 | 166.00 | 173.90 | 4.76 | 166.95 | 173.90 | 4.17 |
|                   | 1628.08 | 1660.74 | 2.01 | 1660.08 | 1660.74 | 0.04 | 1669.58 | 1660.74 | -0.53 |
|                   | 3256.16 | 3272.38 | 0.50 | 3320.17 | 3272.38 | -1.44 | 3339.17 | 3272.38 | -2.00 |
| N-100             | 161.30 | 152.33 | -5.56 | 163.75 | 152.33 | -6.97 | 164.50 | 152.33 | -7.40 |
|                   | 1604.89 | 1673.13 | 4.25 | 1629.28 | 1673.13 | 2.69 | 1636.77 | 1673.13 | 2.22 |
|                   | 3209.77 | 3255.55 | 1.43 | 3258.55 | 3255.55 | -0.09 | 3273.55 | 3255.55 | -0.55 |
| N-120             | 156.70 | 138.69 | -11.49 | 158.00 | 144.01 | -8.85 | 158.00 | 144.01 | -8.85 |
|                   | 1569.07 | 1468.87 | -6.39 | 1582.09 | 1468.87 | -7.16 | 1582.09 | 1468.87 | -7.16 |
|                   | 3134.73 | 3004.37 | -4.16 | 3160.74 | 3004.37 | -4.95 | 3160.74 | 3004.37 | -4.95 |
| N-150             | 153.20 | 141.82 | -7.43 | 152.00 | 141.82 | -6.70 | 153.40 | 141.82 | -7.55 |
|                   | 1529.14 | 1495.11 | -2.23 | 1517.16 | 1495.11 | -1.45 | 1531.11 | 1495.11 | -2.35 |
|                   | 3063.24 | 2995.71 | -2.20 | 3039.25 | 2995.71 | -1.43 | 3067.19 | 2995.71 | -2.33 |

3. Results

Table 2 gives an overview in order to compare the conversion coefficients of ORAMED, PTB and CEA Saclay. The delivered doses which were corrected using three conversion coefficients were compared with evaluated \( H_p(3) \) doses from nanoDot dosimeters at the depth of 3 mm.

The comparison results showed that the percentage differences between \( H_p(3) \) delivered dose calculated using the conversion coefficients of each project and \( H_p(3) \) evaluated from the nanoDot did not exceed -11.48 %, -8.85 % and -8.85 % deviation from ORAMED, PTB and CEA Saclay project, respectively. The expanded uncertainty of the reader measurements was 13.10 % (k = 2).

4. Discussion and Conclusion

From this study, \( H_p(3) \) evaluation by nanoDots of TINT’s Personal Radiation Monitoring Services laboratory appeared slightly different from \( H_p(3) \) calculated by using the conversion coefficients from the three pilot projects. NanoDot dosimeters are small which can be attached on lead glasses and can be calibrated directly at the depth of 3 mm in the cylindrical phantom. This new method should be better than the old method which uses only one personal dosimeter attached at the chest position or uses an additional dosimeter attached on the lead collar. The old method has to use the correction factor, which cannot be calibrated directly due to the size of the dosimeter. For the next study, \( H_p(3) \) at an angle of 40° on the cylindrical axis will be evaluated. Measurements at this angle is better for interventional radiology application because it is in the direction of scattered radiation from the patient.
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