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OVERVIEW OF DOUBLE DOSIMETRY PROCEDURES FOR THE DETERMINATION OF THE EFFECTIVE DOSE TO THE INTERVENTIONAL RADIOLOGY STAFF

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In interventional radiology, for an accurate determination of effective dose to the staff, measurements with two dosemeters have been recommended, one located above and one under the protective apron. Such 'double dosimetry' practices and the algorithms used for the determination of effective dose were reviewed in this study by circulating a questionnaire and by an extensive literature search. The results indicated that regulations for double dosimetry almost do not exist and there is no firm consensus on the most suitable calculation algorithms. The calculation of effective dose is mainly based on the single dosemeter measurements, in which either personal dose equivalent, directly, (dosemeter below the apron) or a fraction of personal dose equivalent (dosemeter above the apron) is taken as an assessment of effective dose. The most recent studies suggest that there might not be just one double dosimetry algorithm that would be optimum for all interventional radiology procedures. Further investigations in several critical configurations of interventional radiology procedures are needed to assess the suitability of the proposed algorithms.

INTRODUCTION

Interventional radiological procedures can lead to significant radiation doses to patients and to staff members. In order to evaluate the personal doses with respect to the regulatory dose limits, doses measured by dosemeters have to be converted to effective doses (E)[1,2].

Measurement of personal dose equivalent $H_p(10)$ using a single unshielded dosemeter above the lead apron can lead to significant overestimation of the effective dose, while the measurement with dosemeter under the apron can lead to underestimation. To improve the accuracy, measurements with two dosemeters, one above and the other under the apron, have been suggested ('double dosimetry'). The ICRP has recommended that the interventional radiology departments develop a policy that staff should wear two dosemeters[3].

The aim of this study was to review the double dosimetry practices and algorithms for the calculation of effective dose in high-dose interventional radiology procedures. The results will be used to develop general guidelines for personal dosimetry in interventional radiology procedures. This work has been carried out by Working Group 9 (Radiation protection dosimetry of medical staff) of the CONRAD project, which is a Coordination Action supported by the European Commission within its sixth Framework Program[4].

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METHODS

The practices relevant for double dosimetry were reviewed by circulating a questionnaire in a few countries participating in the CONRAD project. The questionnaire concerned regulations, position of dosemeter(s), measured dose quantity and the dose calculation algorithms. In addition, a comprehensive literature search was conducted on the current algorithms for the determination of effective dose. Finally, the accuracy of selected most recent algorithms was tested by calculations based on published studies of dosemeter data with corresponding effective doses.

RESULTS AND DISCUSSION

Dosimetry regulations and practices

The questionnaire on dosimetry practices covered 13 dosimetry services in 13 European countries. All countries used personal dose equivalent $H_p(10)$ as the measured quantity for effective dose calculations.

In five countries, the dosemeter was recommended to be worn above the apron, in seven countries under the apron and in one country above and under the apron. The position of the dosemeter was mostly specified on the chest, but arms and thyroid were also indicated.

There is no harmonization between the national regulations or recommendations for use of *double dosimetry.* Double dosimetry for interventional radiology is foreseen by legislation or regulatory guide only in two countries: one country requires regular use of double dosimetry, while the other country only for some cases. In three countries an expert of the authority or the medical staff can judge on the need for the second dosemeter. In the remaining eight countries, there are no national recommendations for double dosimetry; however, several pilot studies or occasionally also routine measurements have been carried out.

Effective dose is not evaluated and reported routinely but only when needed in specific cases, accounting for radiation environment and personal protective devices. The calculation of effective dose is mainly based on the single dosemeter measurement, where either $H_p(10)$ (when the dosemeter is used below the apron) or a fraction of $H_p(10)$ (dosemeter above the apron) is taken as an assessment of effective dose. In one service, the effect of the lead apron is taken into account by dividing $H_p(10)$ by various factors depending on the case. In two dosimetry services $H_p(10)$ is the measured value and qualified expert is responsible for the calculation of E. In one of these services the assessment of E is done by the radiation protection officers of the hospitals according to the NCRP Report 122[5].

Only three of the services reported their algorithm for double dosimetry. Two of them calculate the effective dose by algorithm (6) of Table 1, where $H_p(10)$ is accepted as E[6]. In Switzerland, this algorithm has been introduced in the regulations[7]. The third service applies the method described by Niklason *et al.*[8].

Double dosimetry algorithms

The literature search on double dosimetry covered altogether about 140 publications, describing a total of 14 different algorithms. The 11 most recent ones are summarized in Table 1. The estimated over- or underestimations of effective dose by these algorithms, as given in the original publications or in other papers, are summarized in Table 2.

Early algorithms without considerations for thyroid shield

The early double dosimetry algorithms given by Gill *et al.*[9], Webster[10] and Balter *et al.*[11] were based on the determination of 'effective dose equivalent' (*EDE*) as defined in ICRP Publication 26[12]. The effect of thyroid shield was not considered. In 1991, ICRP Publication 60[13] issued a new set of weighting factors and in addition, the name 'EDE' was replaced by the term 'effective dose' (E).

Faulkner and Marshall[14] used new weighting factors in their study of the staff exposure and concluded that *no single dosemeter can accurately monitor effective dose* for all irradiation conditions in fluoroscopy. The algorithm introduced by Wambersie and Delhove[15] was based on the two dosemeters and was fully conservative. Rosenstein and Webster[16] used the experimental data from Faulkner and Marshall[14] for their new algorithm. Huyskens *et al.*[17] defined two correction factors, divider (D) and multiplier (M). The divider is the number by which the over apron reading should be divided to yield effective dose and the multiplier is the number by which the under apron reading should be multiplied to yield effective dose. For fluoroscopic interventional practice, they recommended $D = 5$ and $M = 3$ (Table 1). They also emphasized that *single badge monitoring is often not sufficient* when occupational doses may reach recommended dose limits. Based on the analysis of the papers published until 1993, NCRP Report No. 122[5] recommended a divider $D = 21$ for a single personal dosemeter worn on the neck above apron, and for double dosimetry the formula given by Rosenstein and Webster[16].

Algorithm to cover also thyroid shields

Niklason *et al.*[8] concluded that the algorithms by Gill *et al.*[9] and Webster[10] would result in substantial errors because of *different weighting factors associated with EDE* and because the *use of thyroid shields were not considered*. Further, they noted the possibility of large errors when using a single dosemeter[14,18]. They proposed a new algorithm, which was *independent of lead apron thickness and also accounted for the use of a thyroid shield.* The accuracy of the Rosenstein–Webster and Niklason algorithms was checked experimentally by Mateya and Claycamp[19] and by Monte Carlo (MC) calculations by Kicken *et al.*[20]. Their results did not support the Rosenstein–Webster algorithm but found a better agreement with Niklason *et al.*[8]. Padovani *et al.*[21] concluded that the Niklason algorithm performs within the recommended uncertainty range given in NCRP Report 122[5], which accepts an overestimation of E by a factor of 3 when a single dosemeter is worn and a factor of 2 when two personal monitors are used.

Table 1. Algorithms for the calculations of effective dose (E).

	Authors	Algorithm	Place of dosemeters	Remarks
1	Wambersie and Delhove[15]	$E = H_u + 0.1H_o$	H_u: chest H_o: neck or shoulders	
2	Rosenstein and Webster[16]	$E = 0.5H_u + 0.025H_o$	H_u: waist H_o: neck	Based on Faulkner and Marshall[14]
3	NCRP Report No. 122[5]	Single: $E = H_o/21$ Double: same as No. 2	H_o: neck	Based on data published until (including) 1993
4	Huyskens *et al.*[17]	Single: $E = H_o/D$ or $E = H_uM$		$D = 5$ and $M = 3$ for fluoroscopic interventional practice
5	Niklason *et al.*[8]	(a) Without TS, double: $E = 0.06(H_{os} - H_u) + H_u$ Single*: $E = 0.07H_{os}$ (b) With TS, double: $E = 0.02(H_{os} - H_u) + H_u$ Single*: $E = 0.03H_{os}$	H_u: waist H_{os}: collar	*Recommended by Padovani *et al.*[21]; assuming $H_u \sim 0.01H_{os}$ Tested by Mateya and Claycamp[19] and Kicken *et al.*[20]
6	Swiss ordinance[7]	$H_p(10) = H_u + \alpha H_o$ $\alpha = 0.1$ without TS $\alpha = 0.05$ with TS $H_p(0.07) = H_u + H_o$	Not defined	Without TS same as No.4.
	McEwan[22]	Double: $E = 0.71H_u + 0.05H_o$ Single: (a) $E = 0.08H_o$; (b) $E = 2H_u$	H_u: trunk H_o: collar	Without thyroid shield. Based on $E/H_p(10)$ ratios for AP exposures published by NRPB[30]
8	Franken and Huyskens[23]	Single: $E \leq H_o/5$ (a) Double without TS: $E \leq H_u + H_o/10$ (b) Double with TS: $E \leq H_u + H_o/30$	H_o: mid front (1) H_u: mid front (2) H_o: mid front (3) See →	Lead apron: at least 0.25 mm lead (1) At collar or chest level (2) At waist level (3) At collar level
9	Sherbini and DeCicco[24]	$E = 1.0H_u + 0.07H_o$	H_u: waist H_o: neck	
10	von Boetticher *et al.*[25] and Lachmund[26]	(a) Double without TS: $E = 0.65H_u + 0.074H_o$ (b) Double with TS: $E = 0.65H_u + 0.017H_o$	H_u: anterior thorax H_o: neck	
11	Clerinx *et al.*[29]	$E = 1.64H_u + 0.075H_o$	H_u: thorax H_o: neck	Estimation within a 10% underestimation margin

Symbols: H_u: under apron dose, H_o: over apron dose, E: effective dose[13], H_{os}: overcollar shallow dose, i.e. $H_p(0.07)$, TS: thyroid shield.

Further development

A Swiss ordinance on personal dosimetry[7] requires the use of double dosimetry for work involving high doses and introduces an algorithm for effective dose calculation. McEwan[22] derived algorithms for two dosemeters worn at collar and trunk (under apron) and also for a single dosemeter. McEwan assumed no thyroid shielding and that H_{collar} is a good measure of thyroid dose. Franken and Huyskens[23] performed model calculations for a variety of practical situations, with and without a lead apron, and for many apron models, fits and lead thickness. They concluded that the apron *model and fit are often more important than the lead thickness.* Their simple expressions in Table 1 were constructed in such a way that effective dose is estimated as accurately as possible, but never underestimated.

Sherbini and DeCicco[24] used MC dose calculations in an anthropomorphic mathematical phantom to estimate *EDE*, E and $H_p(10)$ under a variety of irradiation conditions. Their algorithms were adjusted from Webster[10] and Rosenstein–Webster[16]. von Boetticher *et al.*[25] and Lachmund[26] based their algorithms on measurements of the occupational radiation exposures at the relevant places in diagnostic radiography. Schultz and Zoetelief[27] carried out dose calculations by MC method in mathematical phantoms for cardiologist

Table 2. Accuracy of the algorithms.

Algorithm (authors)	Estimated maximum overestimation of *E by a factor of…*			Estimated maximum underestimation of *E by a factor of…*	
	Estimation taken from the given reference (when available)	Testing by Schultz and Zoetelief [27]	Testing by data from Siiskonen *et al.*[28] (this work)	Estimation taken from the given reference (when available)	Testing by Schultz and Zoetelief [27]
Single dosemeter above apron, no correction	2–60[14]				
Single dosemeter under apron, waist or chest level, no correction				1.2–7[14]	
Rosenstein and Webster[16]	Up to 1.89[16]	2.25		1.01[16] Up to 3.3[19]	1.2
NCRP Report 122[5]	Up to 3.4[5] (S) Up to 2.03[5] (D)	3.0 (S)	12.3 (S)		
Niklason *et al.*[8]	Less than 2[8]	2			1.3
Padovani *et al.*[21]		2 (S)	2 (S)		1.4 (S)
Franken and Huyskens[22]	Up to 1.5[23]	12.5 (S) 3 (D)			
Swiss ordinance[7]		4.5	3.5		

S: single dosimetry, D: double dosimetry, TS: thyroid shield.

and patient, for cardiac catheterization procedure and applied the results to various published algorithms. They concluded that almost all algorithms overestimate the effective dose and there was no firm indication on the preference of the double dosimetry over single dosimetry. However, they emphasized that the results cannot be generalized. Siiskonen *et al.*[28] carried out similar type of MC simulations for eight cardiac and two cerebral exposure conditions. Their results revealed that the effective dose varied significantly with irradiation conditions and with the location of the dosemeter. They concluded that the data were not sufficient to establish a generally applicable accurate relationship between the dosemeter reading(s) and E. Clerinx *et al.*[29] also performed MC simulations for typical scatter field geometries of interventional radiology procedures. Their results showed that the dosemeter reading at the neck level and under apron at thorax level gives the best correlation with effective dose, and single dosemeter algorithms in certain cases could result in unacceptable underestimation of E.

Comparisons of the algorithms

Some of the algorithms have been tested based on measurements and/or MC calculations of the relevant dose quantities (see the references in Table 1). In this work, some of the most recent algorithms were tested using the data from the MC calculations by Siiskonen *et al.*[28]. The effective dose E_1 was calculated by the algorithms using MC-calculated dosemeter readings (H_u and H_o), and the result was compared with the MC calculated effective dose E_2 for the similar irradiation conditions. If $E_1 > E_2$, then the ratio E_1/E_2 represents the factor of overestimation. If $E_1 < E_2$, then the algorithm underestimates effective dose.

The readings of H_u and H_o should be chosen in accordance with the specifications for a given algorithm. In the study by Siiskonen *et al.*[28], the readings of H_u and H_o have been calculated for the chest only. Therefore, in this study only the algorithms with H_u corresponding to dosemeter position on chest have been compared. Because H_o is specified on the neck in all of the algorithms, an experimental correction was applied to the MC-calculated H_o values on the chest in order to derive H_o on the neck. This correction was determined in the PA geometry by measuring doses with thermoluminescent dosemeters on a Rando Alderson phantom at the chest and the neck level. The correction (ratio of doses: chest/neck) was ~4.2. This value depends also on the irradiation geometry. Due to using the same correction for all geometries, an uncertainty of H_o within a factor of 2 is introduced, which must be considered when making conclusions on the results.

The results of testing of the algorithms are shown in Figures 1 and 2. For the irradiation geometries used by Siiskonen *et al.*[28] (cardiac and cerebral

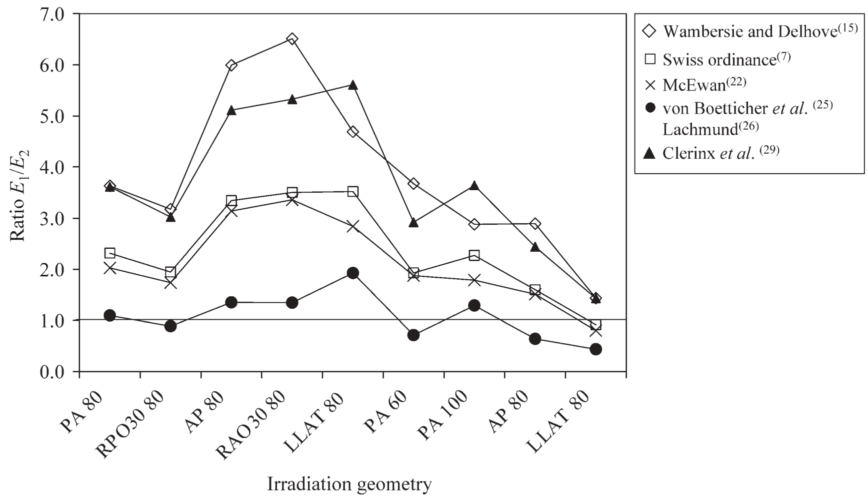

Figure 1. Ratio E_1/E_2, i.e. the effective dose calculated by the algorithm divided by the effective dose obtained from the MC calculation, for the various *double* dosimetry algorithms in the clinical cases considered and calculated by Siiskonen *et al.*[28].

fluoroscopy procedures), the results of calculations indicate overestimation of E by all single and double dosimetry algorithms tested (Figures 1, 2), also when the uncertainty of estimating H_o on the neck is taken into consideration. In Table 2, the maximum over- or underestimations stated by some other workers and that obtained in this work have been compared.

Figures 1 and 2 indicate that the overestimation depends highly on the irradiation geometry. There are significant differences in the overestimation by different algorithms; maximum overestimations are by a factor of ~2–7 with the double dosimetry algorithms, and by a factor of ~2–12 with the single dosimetry algorithms. It should be noted, however, that the geometries where the overestimation is highest (AP, RAO[28]) are not very common in interventional radiology.

The overestimations reported earlier and shown in Table 2 are of the same order of magnitude as the present results for PA geometry (overestimation factor from ~2 to 4). Furthermore, according to Table 2, there can also be significant underestimations of E by some algorithms for certain cases, in particular for the single dosimetry algorithms. However, the results from the cases considered by Schultz and Zoetelief[27] and Siiskonen *et al.*[28] cannot be generalized, because they deal with only a few typical geometries and irradiation conditions.

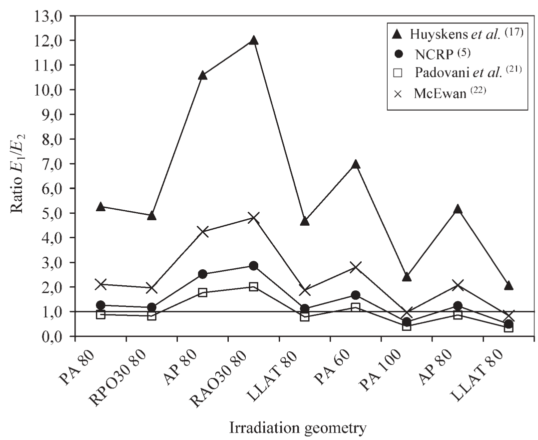

Figure 2. Ratio E_1/E_2, i.e. the effective dose calculated by the algorithm divided by the effective dose obtained from the MC calculation, for the various *single* dosimetry algorithms in the clinical cases considered and calculated by Siiskonen *et al.*[28].

CONCLUSIONS

There are neither harmonized regulations nor consistent practices for double dosimetry and for the calculation of effective dose to the staff in high-dose interventional radiology procedures. Therefore, the effective dose estimations are not fully comparable.

The literature review indicated that a number of algorithms to calculate effective dose have been developed, but there is no firm consensus on the most suitable algorithm. Most algorithms overestimate effective dose significantly, typically by a factor of 2–4, at maximum by over 10 times. The difference between the accuracy of double and single dosimetry algorithms did not appear to be significant in the simulations of this work, but this might not be the case in other clinical conditions where various exposure energies and geometries are applied. Further, the algorithms based on single dosimetry are more prone to underestimate effective dose in certain cases. Therefore, double dosimetry is generally recommended. The most recent studies suggest that there might not be just one double dosimetry algorithm, which would be optimum for all interventional radiology procedures.

Further experimental and numerical intercomparisons in several critical configurations of interventional radiology procedures are needed to evaluate the applicability of the double dosimetry algorithms. The further aim of the EURADOS working group is to work out recommendations on double dosimetry practices and the algorithms for the assessment of effective dose.

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