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Local skin and eye lens equivalent doses in interventional neuroradiology

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Abstract: The aim of this work was to assess patient skin and eye lens doses in interventional neuroradiology and to assess both stochastic and deterministic radiation risks. Kerma-area product, P_{KA} was recorded and skin doses measured using thermoluminescence dosimeters. Estimated dose at interventional reference point, IRP, was compared with measured absorbed doses. The average and maximum fluoroscopy times were 32 and 189 min for coiling and 40 and 144min for embolisation. The average and maximum P_{KA} for coiling were 121 and 436 $Gycm^2$ respectively and 189 and 677 $Gycm^2$ for embolisation. The average and maximum values of the measured maximum absorbed skin doses were 0.72 and 3.0Sv respectively for coiling and 0.79 and 2.1Sv for embolisation. Two out of the 52 patients received skin doses in excess of 2Sv. The average and maximum doses to the eye lens (left eye) were 51 and 51mSv (coiling) and 71 and 289mSv (embolisation). The ratio between the measured dose and the dose at the IRP was $0.44 \pm 0.18 mSv/mGy$ indicating that the dose displayed by the x-ray unit overestimates the maximum skin dose but is still a valuable indication of the dose. The risk in our hospital skin erythema and lens cataract is therefore small.

Keywords: interventional neuroradiology, skin dose, eye lens dose, cerebral aneurysm, cerebral arteriovenous malformation, acute skin exposure.

Introduction

Acute radiation injuries have been reported after radiological interventional procedures [1-2]. It is therefore necessary to assess regularly patient doses, to identify patients at risk and to have proper protocols to minimise local skin doses and skin erythema as a result of these sometimes, lengthy procedures. Operators of interventional radiology should, however, be aware of the potential risk of skin injury following such procedures, particularly for patients with collagen vascular disease, diabetes or previous skin exposure [3]. If proper quality assurance programs including patient dose monitoring, periodic equipment testing, procedure evaluation and training of staff, are established, the risk of skin injuries in interventional cardiology is very low [4]. The Dimond and Sentinel European research projects [5-6] have contributed to the efficacy, safety and good practice of interventional radiology particularly for interventional cardiology, the most common interventional procedure.

Assessing local skin or eye lens doses and particularly their maximum values is difficult as different anatomical areas are exposed and many projections used. In addition, the x-ray beam size, fluence and radiation quality and finally the distances between the skin and the x-ray tube and image receptor vary both during the procedure and from patient to patient. Kosunen et al [7] reviewed methods to estimate patient doses in interventional radiology and give guidance on the accuracy one can expect using different dosimeters. Different dosimeters' photon energy and dose dependences and their clinical usefulness were characterised by Van Dam et al [8].

Estimating maximum dose is facilitated if the dosimeter displays the skin dose in real-time, gives information about the position of the maximum dose and if the dosimeters do not interfere with the examination. Present x-ray imaging systems do not fully comply with these criteria. Fluoroscopy time is always available but is a very poor indicator of maximum skin dose. Balter and Moses [9] state that major interventional procedures using an imaging system equipped only with a fluoroscopic timer are not recommended. Most modern imaging systems for interventional radiology are, however, equipped with a kerma-area product, P_{KA} meter. The air kerma-area product is the integral of the air kerma over the area of the X ray beam in a plane perpendicular to the beam axis and is denoted P_{KA} by ICRU [10] and IAEA [11]. It is the same quantity as that sometimes denoted KAP. As P_{KA} is nowadays readily available, one approach to assessing local skin dose is to measure P_{KA} and correlate its value to the maximum skin dose. Chida et al [12] found a strong correlation between P_{KA} and maximum skin dose in percutaneous coronary interventions (PCI). This is not always the case [13] since the same P_{KA} but different local skin dose can be obtained using a small intense beam or a larger less intense one. When as in some diagnostic procedures, for example in coronary angiography, image projections are known with reasonable accuracy in advance, P_{KA} has been suggested as an appropriate measure [14] particularly for stochastic radiation effects. But it has also been suggested for use in interventional cardiology [15]. Others [16-18] have also suggested using P_{KA} as an indicator for high skin doses.

The dose at the interventional reference point, IRP[19], is available on some modern x-ray units. Skin dose at the IRP, estimated by the imaging system, is updated in real-time but may overestimate the local skin dose as the patient may be positioned further away from the x-ray tube than the reference point. In addition, since x-ray beam projections are not stationary but vary in position and size on the patient's skin, the dose at the IRP may result in a further overestimation of the local skin dose. Rampado and Ropolo [20] have developed a method to map the skin dose in interventional radiology in real time and have estimated that the uncertainty in entrance skin dose is less than 20% (1 standard deviation). This is an important application since the spatial distribution of skin dose is only available with high resolution when radiographic films that require special calibration of their characteristic curves are used. Given the comparably small surface area of the head and the difficulty of fitting a radiographic film on its surface, it is feasible in interventional neuroradiology to place a number of small point dosimeters on the head in order to assess the spatial dose distribution [21]. This work enabled us in this study to identify the locations on the head most likely to receive the highest doses and therefore to place or dosimeters there.

According to Padovani and Quai [22] there are three reasons for dosimetry in interventional radiology: to estimate the risk of stochastic effects that apply mostly to young or middle-aged patients, quality assurance of the imaging equipment and to prevent the deterministic effects of the radiation that are the topic of this study. Risk is highest on the side where the x-rays first interact with the patient's skin, particularly if the beam projection is maintained in a stationary position and not resized. Patients at risk should be counselled and advised to check for skin changes 2-4 weeks after the procedure. Several papers present data on measured absorbed dose to patient skin following interventional neuroradiology [23-26] or energy imparted to the patient [27] in order to correlate with acute and late radiation effects respectively. In this paper, we report on measured local skin doses on the head of patients undergoing diagnostic or therapeutic neuroangiography using thermoluminescence dosimeters, TLD, and compare these with the doses at the IRP as estimated by the x-ray unit in order to provide a method to determine the risk of local overexposure of skin and eye-lenses.

Materials and Methods

Interventional procedures, X-ray equipment and patients

The studies were performed on a biplanar angiography suite (Artis BA, Siemens AG, Erlangen, Germany). The x-ray unit has one floor-mounted (flo) and one ceiling-mounted (cei) x-ray tube each with a 33 cm diameter image intensifier. The floor-mounted x-ray tube is used in posterior-anterior views and the ceiling-mounted x-ray tube for lateral views. Each tube has an air kerma-area product (P_{KA}) meter mounted on the collimator (PTW Diamantor). The unit also presents a calculated dose at the IRP located along the central ray at a distance 150 mm from the isocenter towards the x-ray tube, at 600 mm from the focal spot. The dose at the IRP is displayed and updated continuously and used

as an indicator of local maximum skin dose, D_{IRP} . As the unit has two x-ray tubes, the higher of the two doses $D_{IRP, flo}$ or $D_{IRP, cei}$ is denoted $D_{IRP, max}$. The two x-ray tubes do not directly irradiate the same area of the head.

Cerebral digital subtraction angiography (DSA) was performed in the vascular territories of interest, which may include both internal carotid arteries, both external carotid arteries and the dominant or both vertebral arteries. For each vessel territory low magnification views in the angiographic anterior-posterior view and the lateral view were obtained initially and then magnified oblique views were obtained as necessary to depict the lesion or the anatomy. The routine film rate for each plane was 2 frames/second for the first 3 seconds (or 3 frames/second in the presence of a lesion that includes arteriovenous fistulas), and thereafter 1 frame/second for up to 10 seconds. The field-of-view vary between 22 and 13 cm. The digital matrix was 1024 x 1024 pixels. The distance from the focal spot to the patient's head varied usually between 500 and 600 mm, but was larger in case of extremely angulated working projections. Rotational angiography was performed when necessary (usually for 3D depiction of aneurysms) with 200 frames over 210 degrees.

Endovascular coiling of cerebral aneurysms included a complete DSA study, often including a rotational angiography series. Microcatheterization and coiling of the aneurysm were then performed using vascular road-map at the best beam projections and maximum magnification (FOV=13 cm), and the projections were usually maintained stationary until the end of the procedure. Embolisation of cerebral arteriovenous malformation (AVM), arteriovenous fistulas (AVF) and hypervascular tumours included DSA studies and the procedures were performed using vascular road-map and usually middle value of magnification (FOV=17 cm). These procedures involved often more than one microcatheterization and injection of embolics and the beam projections were often resized. In all kinds of therapy, DSA runs were done when necessary during the procedures and always at the end of the procedures. A discussion of the devices and techniques for endovascular operations falls outside the scope of this article.

During the x-ray unit's period of operation (2004-2008), patient doses were recorded for 1023 procedures, comprising 662 diagnostic angiographies; 226 treatments of cerebral aneurysms (endovascular coiling, in some instances with balloon-assisted technique or including stenting of the parent vessel) and 135 embolisations for cerebral AVMs and AVFs, or for preoperative embolisation of hypervascular tumours. Radiation doses during other endovascular operations (pre-operative embolisation of tumours, pharmacologic or balloon angioplasty of vasospasm, and transarterial trombolysis of ischemic stroke) were recorded but are not included in this study.

Patient dosimetry

Since every intervention is unique and comprises many projections, including both fluoroscopy and digital fluorography, discrepancies between calculated values of D_{IRP} and measured local absorbed doses on the skin are expected. To study this in seventy-one

examinations including interventions (fig. 1) eight pairs of thermoluminescence dosimeters, TLD, ($\text{Li}_2\text{B}_4\text{O}_7$) were positioned on the patient's head using a headband. Dosimeter readout followed a standard protocol for the laboratory using a Rados Dosacus RE-1 reader, i.e. readout at 300°C ; 1.5s preheat, 8.5s heating and pulse counting and 10s post heating. The dosimeters were post annealed at 80°C for 1 h. The TLD were calibrated to measure the superficial personal dose equivalent, $H_p(0.07)$ using the ISO/IEC N-40 spectrum. A selected number of dosimeters have been calibrated at the National Dosimetry Standard laboratory at the Swedish Radiation Safety Authority in Stockholm, where the dosimeters are calibrated for $H_p(10, \alpha)$ and $H_p(0.07, \alpha)$ on a ISO water slab phantom (300 mm x 300 mm x 150 mm, with 2.5 mm thick PMMA walls at the front and 10 mm thick walls) elsewhere [28]. The full set of dosimeters used in the study were calibrated individually at the home laboratory by using a Rados Dosacus calibrator and the $H_p(0.07)$ response established by using the conversion factor between the Dosacus calibrator dosimeter response and the dosimeter response obtained in the ISO water slab phantom calibration. The quantity $H_p(0.07)$ was denoted either entrance skin dose ESD_{skin} or ESD_{eye} if the TLD represented the eye lens. The TLD were positioned as follows: three dosimeters on the left side of the head, two on the back of the head, one on the right side and one on each eye to estimate the dose in the eye lens. The average dose of the two TL dosimeters in the pair was used to represent the skin or eye lens dose at each position. The uncertainty in the calibration procedure was estimated to be less than 15% with a 95% confidence interval.

Figure 1

The measured maximum skin dose value, $\text{ESD}_{\text{skin,max}}$, was compared with the x-ray unit's estimation of the maximum skin dose, $D_{\text{IRP,max}}$, by calculating the conversion factor $\text{ESD}_{\text{skin,max}}/D_{\text{IRP,max}}$ for each patient examination. In addition, conversion factors between $\text{ESD}_{\text{skin,max}}$ and the total P_{KA} value were calculated in each examination. These data are useful for estimating maximum skin dose for situations where the x-ray units provide values of P_{KA} but not of D_{IRP} . The conversion factors, $\text{ESD}_{\text{skin,max}}/P_{\text{KA}}$ for the skin dose and $\text{ESD}_{\text{eye,max}}/P_{\text{KA}}$ for the eye dose, were compared in each examination. The average values of these conversion factors were then used to compute action levels in terms of the kerma-area product P_{KA} for exceeding the threshold doses needed to establish the effects; temporary epilation (3.0 Sv, [1]) and lens cataract with visual impairment (1.5 Sv, [29]).

As a complement to the skin dose assessment, doses to the brain and other organs at risk in the proximity were investigated by dose measurements in an anthropomorphic female phantom (55 kg 160cm, [30], Fig. 1). Twenty-two TLD were inserted in the phantom to measure absorbed doses to the brain (D_{brain}) and nine TLD in the salivary glands (D_{sg}) for simulated coiling and embolisations procedures, respectively. During the two simulations, the interventionist (SR) performed all the relevant fluoroscopy and digital subtraction angiography views typical of both the coiling and embolisation procedures respectively.

During these two sessions, the same type of headband with TL dosimeters, worn by patients, was mounted on the anthropomorphic phantom. The fluoroscopy time, P_{KA} -value and doses at the IRP were recorded so that the mean organ doses in the phantom could be related to organ doses in the patients. These average doses were derived for future reference, since the uncertainty in the relative risk factors for developing late effects (cancer) after irradiation of the brain is high [29].

Statistical analysis was performed using the software package Statistica (v. 6.0) and the Mann-Whitney U-test.

Results

Table 1 summarises the values of P_{KA} and estimated values of D_{IRP} for all 1023 procedures. As expected, the diagnostic angiography procedure results in significantly lower doses than the two interventional procedures, coiling and embolisation. On the average, 68% of the total P_{KA} and D_{IRP} values come from the floor-mounted x-ray tube suggesting that the region of maximum skin dose is located on the back of the patient's head and hence avoids high doses to the eyes. The 95 percentile values of D_{IRP} are 1.0 Gy, 3.0 Gy and 4.7 Gy for angiography, coiling and embolisation respectively. Third quartile (or 75th percentile) values are sometimes used as indicator of reference levels. The corresponding third quartile values of $P_{KA, total}$ in this study are: angiography 72 Gy cm^2 , coiling 157 Gy cm^2 and embolisation 225 Gy cm^2 .

Table 1

Table 2 shows the measured skin and eye doses from the smaller subset (n=71) of measurements using the TL dosimeters. In addition, the P_{KA} values and estimated values of D_{IRP} were also recorded for this smaller subset and shown not to be significantly different ($p>0.05$) from the data given in Table 1 for the larger sample of all patients (n=1023). Hence the large subset can be used to make predictions on estimated maximum doses to the skin and lens of the eye based on the P_{KA} and D_{IRP} data available for all patients.

Table 2

The interventional procedures result in significantly higher patient skin and eye doses than diagnostic angiography. The measured skin and eye dose distributions in coiling and embolisations were not statistically different. The highest doses are found on the back of the head or on the patient's left side. The doses to the patient's left and right eye are much lower than the skin doses; typically less than 5%, 9% and 14% of the maximum measured skin dose for angiography, coiling and embolisations procedures respectively. The maxi-

maximum eye dose of any of the patients measured was 515 mSv following a coiling procedure. The maximum measured skin doses were 2950 mSv and 2100 mSv in coiling and embolisation procedures, respectively, which are lower than the doses at the IRP estimated by the x-ray unit and given in table 1.

Figure 2 shows the average and 95th percentile skin dose in each position for the three procedures. In all procedures, the highest dose is observed on the back right side of the head. The average and 95th percentile maximum measured skin doses per interventional (coiling; embolisation) procedure were 0.72; 0.79 Sv and 1.7; 1.9 Sv, respectively. The corresponding average and 95th percentile maximum absorbed doses to the patient's left eye were comparably lower with averages of 0.05; 0.07 Sv and 0.14; 0.20 Sv. In 85% of the cases, the absorbed dose to the patient's left eye was higher than to the right eye.

Figure 2

Table 3 shows the ratio between the measured values of $ESD_{skin,max}$ and P_{KA} and between the measured values of $ESD_{eye,max}$ and P_{KA} for all three procedures. The ratio $ESD_{eye,max}/P_{KA}$ for the dose to the eye lens is typically lower (average $\pm$ 1SD=0.38 $\pm$ 0.64 mSv/Gycm²) than the corresponding factor $ESD_{skin,max}/P_{KA}$ for the maximum measured skin dose (average $\pm$ 1SD=4.5 $\pm$ 1.6 mSv/Gycm²). In some cases, the ratios are significantly larger than typical, indicating occasionally higher doses to the eye as shown by the 95% and maximum values in table 3. The numerical values above in parentheses are the average and standard deviations for all the 71 dose-measured procedures. The individual data for each type of procedure are given in table 3.

The higher of the average values between the measured maximum dose to the skin or eye lens and the total P_{KA} were in the two interventional procedures 4.9 mSv/Gycm² (skin, coiling) and 0.58 mSv/Gycm² (eye lens, embolisation), respectively (table 3). Corresponding action levels of the kerma-area product for temporary epilation or lens cataract are therefore 612 Gycm² (skin) and 2586 Gycm² (eye lens) respectively, indicating that here the skin is the limiting organ and not the lens of the eye.

Table 3

Table 3 also shows the ratios between the maximum skin doses measured by TL dosimeters for each procedure and the maximum doses as estimated by either of the two x-ray tubes in the interventional reference point, IRP; $ESD_{skin,max}/D_{IRP,max}$. The ratio is in all cases less than one (average $\pm$ 1SD=0.44 $\pm$ 0.18 mSv/mGy) but shows large variations indicating poor agreement but reasonable positive correlation between the two ($r^2=0.77$). The

measured maximum skin dose $ESD_{\text{skin,max}}$ is thus significantly lower than the estimated dose at the IRP indicating that $D_{\text{IRP,max}}$ overestimates the skin dose by approximately a factor of two. Given the data in Tables 1 and 2, the risk of temporary skin epilation ($ESD > 3 \text{ Sv}$) is not as high as initially assumed from the values of $D_{\text{IRP,max}}$ displayed by the x-ray unit.

Table 4 shows the organ dose relative to the kerma-area product, P_{KA} when the two interventional procedures were simulated on an anthropomorphic phantom. Assessing each interventional procedure for itself, the average brain doses are estimated to be 250 mSv and 340 mSv and the salivary gland doses 60 mSv and 110 mSv for the coiling and embolisation procedures respectively.

Table 4

Discussion

Based on the average conversion factor between measured skin dose and P_{KA} 4.9 mSv/Gycm² from table 3, the computed action level for temporary epilation from this work was 612 Gycm². Since 2004 when operations started at our hospital, such a high P_{KA} value has only been observed in three embolisation procedures. These three patients were subject to averages of 88 minutes of fluoroscopy, P_{KA} 640 Gycm² and D_{IRP} 5.5 Gy. The corresponding maximum values are 143 minutes, 676 Gycm² and 7.2 Gy. However, none of these patients were among those 71 measured by the TL dosimeters. To our knowledge, during the study period 2004-2008, only one patient experienced erythema and temporary epilation following the coiling of an aneurysm indicating that our suggested action level is appropriate for our purposes.

In order to obtain representative skin dose mapping with a limited number of TLD, the number of TL dosimeters used and their precise position is important. Nishizawa et al [21] measured the surface dose on two patients' heads with 27 photoluminescent glass dosimeters positioned evenly over the whole surface of the head and neck. After their embolisation treatment of small aneurysms, the maximum skin dose was located on the back of the head behind the right ear. Moritake et al [31] extended the study to 32 patients and found maximum skin dose on the back of the head at the level of the ears. Hence, we conclude that the position of maximum skin dose in their study agrees with the positions of our TLD on our 71 patients.

As obtained by Chida et al [12] for PCI, we also found a correlation between maximum skin dose, $ESD_{\text{skin,max}}$ and kerma-area product, P_{KA} in all three examinations ($r^2=0.94$, 0.74 and 0.85 in angiography, coiling and embolisation respectively), but poorer correlation with fluoroscopy time ($r^2=0.09$, 0.57, 0.57). A reason for the more significant correlation between $ESD_{\text{skin,max}}$ and P_{KA} in our work compared to, for example, Balter et al [17] may be that in our work the large majority of the procedures were performed by one very experienced radiologist. We therefore agree with Balter and Moses [9] who proposed that

both ESD and P_{KA} could be used as key dosimetric quantities to avoid patient over-exposure.

Vano et al [16] found 3rd quartile values of P_{KA} and fluoroscopy time for the diagnostic procedure cerebral angiography of 107 Gy $\cdot$ cm² and 12 minutes. They also suggest preliminary reference levels for this procedure of 120 Gy $\cdot$ cm² and 15 minutes based also on the other five references quoted in their publication. Our corresponding data are 72 Gy $\cdot$ cm² and 7.5 minutes, i.e. 50-60% of the preliminary reference level.

Persliden [32] performed a survey of patient doses in interventional procedures in Sweden, including cranial interventions. His median values of fluoroscopy times and P_{KA} were 53 min and 180 Gy $\cdot$ cm². Our values 26 min and 104 Gy $\cdot$ cm² for coiling and 33 min and 156 Gy $\cdot$ cm² for embolisation are both lower.

Using TLD, Theodorakou and Horrocks [23] measured skin doses and P_{KA} for thirty cerebral embolisations. Their ESD_{TLD} (median 0.6 Sv, max 3.4 Sv) and P_{KA} values (median 40 Gy $\cdot$ cm², max 321 Gy $\cdot$ cm²) agree well with our data and also indicate a good linear correlation between ESD_{TLD} and P_{KA} ($r^2=0.79-0.86$). Bergeron et al [24] also report absorbed doses (median $P_{KA}=166$ Gy $\cdot$ cm² and median ESD=0.61 Gy) lower than ours. Gkanatsios et al [8] estimated the median surface dose in the frontal plane for the diagnostic and interventional procedures to be 1.3 Sv and 2.8 Sv respectively. Our corresponding values in table 2 are much lower. However, the ratio between the dose in the lateral and the frontal views in the diagnostic procedure is the same as in our study, approximately 0.5.

Mooney et al [6] estimated the maximum skin dose in embolisations (AVM) to be 5 Sv, once again higher than those found here. Bergeron et al [24] measured the maximum entrance skin dose in neurovascular interventions to be between 0.13 and 1.3 Sv, whereas our measurement suggest that skin doses as high as 3.0 Sv can be found. Kuwayama et al [26] measured the dose to the patient during 15 endovascular treatments (AVM and AVF). The dose to the dosimeter at the glabella corresponds approximately to those in our dosimeters placed on the patients' left and right eyes. Their eye doses are within the range 3-136 mSv, which is in reasonable agreement with our doses 10-289 mSv in embolisation procedures.

There are many reasons for the dose at the interventional reference point (IRP) to overestimate the skin doses. During the procedure, the beam direction and projection are altered and the beam is not always centred exactly on the same area of the skin. In addition, the patient's skin may be located further away from the x-ray tube than the IRP, because the distance between the isocenter (the point of interest) and the patient surface close to the x-ray tube is less than 150 mm. According to the radiologist, the probability any given skin area being directly irradiated from both x-ray tubes is very low.

The left eye typically absorbed a higher dose than the right eye. This is mainly because the x-ray tube that generates the lateral view is located on the left side of the patient.

Conclusions

The 95th percentile of the maximum local skin dose was 1.7-1.9 Sv, but the corresponding doses to the lens of the eye were significantly lower, being 0.14-0.20 Sv for coiling and embolisation procedures. The average conversion factor between measured skin dose and P_{KA} was 4.5 ± 1.6 mSv/Gy·cm² in interventional neuroradiology. The dose at the interventional reference point estimated by the x-ray unit overestimates the local skin dose by approximately a factor of two but with a large variation. Based on the local skin doses observed here there is no immediate risk of temporary epilation ($ESD > 3$ Sv) for patients in our hospital. For the two interventional procedures, the risk of induction of cataract with visual impairment is not as high as initially expected from the dose at the interventional reference point. Establishing action levels in terms of kerma-area products or dose at the interventional reference point on each procedure and x-ray unit will facilitate identification of individual patients at risk.

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Table 1. Average, median and 95th percentiles of the fluoroscopy time, kerma-area product P_{KA} , and estimated doses at the interventional reference point, D_{IRP} from the floor- and ceiling-mounted x-ray tubes.

Examination	Fluoroscopy time, (min)	$P_{KA, flo}$ (Gycm ²)	$P_{KA, cei}$ (Gycm ²)	$P_{KA, total}$ (Gycm ²)	$D_{IRP, flo}$ (mGy)	$D_{IRP, cei}$ (mGy)
<u>Angiography</u>						
(n=662)						
average	6.9	39.1	15.6	54.7	465	221
median	5.0	33.0	12.8	46.8	393	186
95%	15.7	86.3	37.1	116	992	503
<u>Coiling</u>						
(n=226)						
average	32.0	83.4	38.1	121	1450	789
median	25.8	74.1	33.1	104	1260	665
95%	68.1	166	78.6	243	2960	1750
<u>Embolisation</u>						
(n=135)						
average	39.8	132	56.5	189	1900	968
median	32.8	110	46.9	156	1450	716
95%	85.3	320	134	425	4680	2660

Table 2. Average, median and 95th percentiles of the measured skin equivalent doses ESD_{skin} and eye doses ESD_{eye} in the three types of procedure. The average of the maximum dose for each procedure is also given.

Examination	Left eye (mSv)	Left side 1 (mSv)	Left side 2 (mSv)	Left side 3 (mSv)	Left back (mSv)	Right back (mSv)	Right side (mSv)	Right eye (mSv)	Maximum dose (mSv)
<u>Angiography</u> (n=19)									
average	7.8	66.8	111	146	162	178	20.1	5.9	200
median	5.8	55.0	86.0	89.2	101	107	16.5	5.3	143
95%	14.3	134	258	364	478	487	57.9	11.0	488
<u>Coiling</u> (n=27)									
average	51	296	376	329	516	482	55	18	718
median	24	261	231	209	346	367	38	13	545
95%	143	716	1227	806	1099	1471	134	37	1745
<u>Embolisation</u> (n=25)									
average	71	296	393	402	548	613	42	23	792
median	31	193	223	256	509	504	30	18	652
95%	199	689	931	1344	1288	1595	116	50	1889

Table 3. Average, median, 95th percentile and maximum values of the ratio $ESD_{skin,max}/P_{KA}$, $ESD_{eye,max}/P_{KA}$ and the ratio between the maximum measured skin doses $ESD_{skin,max}$ and the maximum doses at the interventional reference point, $D_{IRP,max}$ for the three procedures.

Examination	$ESD_{skin,max}/P_{KA}$ (mSv/Gycm ²)	$ESD_{eye,max}/P_{KA}$ (mSv/Gycm ²)	$ESD_{skin,max}/D_{IRP,max}$ (mSv/mGy)
<u>Angiography (n=19)</u>			
Average	3.9±0.79	0.18±0.086	0.47±0.19
Median	4.1	0.17	0.51
95%	4.9	0.31	0.67
Maximum	5.0	0.43	0.93
<u>Coiling (n=27)</u>			
Average	4.9±2.20	0.36±0.58	0.42±0.20
Median	4.8	0.18	0.46
95%	8.6	0.88	0.64
Maximum	9.6	2.7	0.79
<u>Embolisation (n=25)</u>			
Average	4.6±1.20	0.58±0.92	0.45±0.14
Median	4.9	0.27	0.50
95%	6.4	1.8	0.61
Maximum	6.7	4.5	0.66

Table 4. Ratios between the measured average brain dose D_{brain} and P_{KA} for simulated coiling and embolisation procedures using the anthropomorphic phantom. Corresponding values of the average salivary gland dose D_{sg} and P_{KA} are also given.

Examination	$D_{\text{brain}} / P_{\text{KA}}$ (mSv/Gycm ²)	$D_{\text{sg}} / P_{\text{KA}}$ (mSv/Gycm ²)
Coiling	2.1	0.50
Embolisation	1.8	0.58

a

b

Figure 1. Images of the white headband with TL dosimeters on a patient (a) and on the anthropomorphic phantom (b).

Angiography: Equivalent doses (mSv)

a

Coiling: Equivalent doses (mSv)

b

Embolisation: Equivalent doses (mSv)

c

Figure 2. Distributions of the means and 95th percentiles of ESD in (a) angiography, (b) coiling and (c) embolisation procedures.