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Real-time eye lens dose monitoring during cerebral angiography procedures

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Real-time eye lens dose monitoring during cerebral angiography procedures

Abstract

Objectives: To develop a real-time dose-monitoring system to measure the patient's eye lens dose during neuro-interventional procedures. **Methods:** Radiation dose received at left outer canthus (LOC) and left eyelid (LE) were measured using Metal-Oxide-Semiconductor Field-Effect Transistor dosimeters on 35 patients who underwent diagnostic or cerebral embolization procedures. **Results:** The radiation dose received at the LOC region was significantly higher than the dose received by the LE. The maximum eye lens dose of 1492 mGy was measured at LOC region for an AVM case, followed by 907 mGy for an aneurysm case and 665 mGy for a diagnostic angiography procedure. Strong correlations (shown as R²) were observed between kerma-area-product and measured eye doses (LOC:0.78, LE: 0.68). Lateral and frontal air-kerma showed strong correlations with measured dose at LOC (AKL:0.93, AKF:0.78) and a weak correlation with measured dose at LE. A moderate correlation was observed between fluoroscopic time and dose measured at LE and LOC regions. **Conclusions:** The MO Skin dose-monitoring system represents a new tool enabling real-time monitoring of eye lens dose during neuro-interventional procedures. This system can provide interventionalists with information needed to adjust the clinical procedure to control the patient's dose. **Key Points** • Real-time patient dose monitoring helps interventionalists to monitor doses. • Strong correlation was observed between kerma-area-product and measured eye doses. • Radiation dose at left outer canthus was higher than at left eyelid

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Real-time eye lens dose monitoring during cerebral angiography procedures

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Abstract Objectives: The purpose of this study was to develop a real-time dose monitoring system to measure the patient's eye lens dose during neuro-interventional procedures. *Methods:* Radiation dose received at left outer canthus (LOC) and left eyelid (LE) were measured using Metal-Oxide-Semiconductor Field-Effect Transistor dosimeters on 35 patients who underwent diagnostic or cerebral embolization procedures. *Results:* The radiation dose received at the LOC region was significantly higher than the dose received by the LE. The maximum eye lens dose of 1492 mGy was measured at LOC region for an AVM case, followed by 907 mGy for an aneurysm case and 665 mGy for a diagnostic angiography procedure. Strong correlations were observed between kerma-area-product and measured eye doses (LOC: 0.78, LE: 0.68). Lateral and frontal air-kerma showed strong correlations with measured dose at LOC (AK_L : 0.93, AK_F : 0.78) and weak correlation with measured dose at LE. A moderate correlation was observed between fluoroscopic time and dose measured at LE and LOC regions. *Conclusions:* The MOSkin dose monitoring system represents a new tool enabling real-time monitoring of patient's eye lens dose during neuro-interventional procedures. This system can provide interventionalists with information needed to adjust the clinical procedure to control the patient's dose.

Keywords:

Interventional radiology, Cerebral angiography, Eye lens, Patient dose, Real-time dose monitoring

Key point:

1. Real-time patient dose monitoring helps interventionalists to monitor patient's dose.
2. Strong correlation was observed between kerma-area-product and measured patients' eye doses
3. Radiation dose at patients' left outer canthus was higher than left eyelid

Abbreviation list:

1. FT= Fluoroscopic time
2. KAP= Kerma-area-product
3. AK= Air kerma
4. IRP= Interventional reference point
5. LE= Left eyelid
6. LOC= Left outer canthus
7. MOSFET= Metal-Oxide-Semiconductor Field-Effect Transistor

I. Introduction

Fluoroscopy-guided interventional radiological procedures provide enormous advantages over invasive surgical procedures. However, long radiation exposure during complicated interventional radiology (IR) procedures remains a concern. Skin injuries are the most frequently encountered tissue reaction effects from IR procedures [1-4]. Different indirect dose evaluation techniques, such as fluoroscopic time (FT), kerma-area-product (KAP), dose level at the interventional reference point (IRP), and peak skin dose, have been established as skin dose indicators for IR procedures [5, 6]. Other than skin dose, the radiation dose to patient's eye lens is also a concern, particularly for patients undergoing long neuro-interventional procedures. Cataract formations are late effects of radiation exposure. Unlike skin reactions, which are visible after about 2 weeks, they usually appear after 10-20 years. To date, different threshold doses have been proposed for cataract formation during acute radiation exposure. The International Commission on Radiological Protection (ICRP) [7], following recent epidemiology studies [8-11], issued a new statement in 2011 on the threshold of 0.5 Gy in absorbed dose to eye lens. Currently, different direct dosimeters have been used as post-processing dose evaluation methods to evaluate the patient's skin dose and eye lens dose during IR procedures [12-17]. To the best of the authors' knowledge, there is no real-

time *in vivo* dosimetry system that has been used for patient dose monitoring during IR procedures.

The purpose of the present study was to: first, demonstrate a new real-time dose monitoring system for determining patient eye lens dose during neuro-interventional procedures; and second, to evaluate correlations of the patient eye lens dose with dose metric parameters, like KAP, FT, and AK of the frontal (AK_F) and lateral tube (AK_L). In this study, our hypothesis was that not all existing dose metric parameters are suitable to indicate patient's eye lens dose.

II. Materials and Methods

II. A. Patients

The real-time monitoring of eye lens dose was carried out on 35 patients, 24 female patients (45 ± 16.9 years) and 11 male patients (age 46 ± 16.8 years), comprising 19 diagnostic angiographies, 8 treatments of cerebral aneurysms, and 8 embolizations of AVMs. The same interventionalist and radiography team performed the neuro-interventional procedures from March 2013 to March 2014.

II. B. X-ray equipment

The neuro-interventional procedures were performed using an Allura Xper

FD20/20[®] biplane system (Philips Healthcare, Best, The Netherlands) at the University of Malaya Medical Centre (UMMC). This suite consists of one ceiling-mounted x-ray tube and one floor-mounted x-ray tube (C-arm) equipped with a 30 cm x 38 cm dynamic flat detector. This machine is equipped with different electronic rectangular field-of-views (FOVs), which change the sensitive image detector area from 15 cm to 48 cm while the exposure tube potential varies between 40 and 125 kVp. This machine can generate five frame rate ranges for vascular procedures (0.5fps, 2fps, 3fps, 4fps, and 6fps) and two frame rate ranges for cardiac procedures (15fps and 30fps). The tube voltage is controlled by an automatic brightness control system (ABC). The Allura Xper FD20/20 machine can apply different filtrations, 0.2 mm, 0.5, and 1.0 mm copper equivalent, which are specified to different types of exposures.

II. C. MOSkin Dosimetry system and measurement setup

MOSkin detector is a new type of Metal Oxide Semiconductor Field Effect Transistor (MOSFET) detector designed by the Centre for Medical Radiation Physics (CMRP), University of Wollongong, Australia. This detector was specially designed for skin dose measurement and has previously been used for patient skin dose measurement during radiotherapy procedures [18-22].

This detector is composed of a hermitically sealed MOSFET detector in a kapton strip using “drop-in” packaging technology [18]. A layer of polyamide film protects and encapsulates the radiosensitive MOSFET sensor, as well as provides a reproducible build-up layer with water equivalent depth of 0.07 mm [Figure 1]. The principle of operation of the MOSkin detector is based on the change of the threshold voltage (ΔV_{th}), which is proportional to the irradiation dose [19, ("Characterization of MOSkin detector for *in vivo* skin dose measurement during interventional radiology procedures" by Safari MJ, Wong JHD, Ng KH et al, submitted in September 2014, Medical Physics Journal)].

The MOSkin detector was characterized under Radiation Qualities in Radiation beams emerging from the x-ray tube assembly (RQR) standard beam. This detector proved to be reliable when exposed to different dose rates ($\pm 3\%$), frame rates ($\pm 3\%$), radiation incident angles ($\pm 5\%$), and exposure energies ($\pm 5\%$) ("Characterization of MOSkin detector for *in vivo* skin dose measurement during interventional radiology procedures" by Safari MJ, Wong JHD, Ng KH et al, submitted in September 2014, Medical Physics Journal).

The MOSkin detector response (ΔV_{th}) can be recorded either manually from the reader or automatically via computer software. In this study, a graphic user interface, FETch, was designed to present the dose values in a more visual form. This interface displays the accumulated dose in column bar charts and

numeric form [Figure 2 (b)]. Dose measurements can be performed at user-defined readout frequencies (maximum temporal frequency is 1 Hz). With this interface, the operators are able to monitor the radiation dose received by the patient in a more intuitive and direct manner, providing valuable information with minimal or no distraction to the interventionalist during a clinical procedure.

II. B. Data acquisition

For all the neuro-interventional procedures, the lateral x-ray tube was positioned on the left side of the patients' heads throughout the treatments. A study of the exposure parameters during 53 neuro-interventional procedures showed that, in 73.7% of the projection times, the frontal tube projections were acquired in the posterior-anterior direction (10° RAO-10° LAO) and in 93% of the time the lateral tube direction was changed from 70° RAO to 90° RAO. ("An investigation of the contribution of routine radiological exposure parameters to patient's dose during neuro-interventional radiology procedures: A phantom study" by Safari MJ, Wong JHD, Jong WL et al, submitted in March 2015, European Radiology). Therefore, the lenses of the left eyes were constantly exposed to the primary x-ray beam from the lateral x-ray tube. The difference between the radiation doses received in the left and right eyes during

cerebral angiography procedures were studied in a pilot study on two patients, which revealed that the radiation dose delivered to the left eye region is significantly higher (~5 times) than the dose delivered to the right eye. For this reason, in this study we focused on the measurement of the dose delivered to patients' left eye. The study of the patients' eye lens dose was implemented using *MOSkin* detectors. The patients were asked to keep their eyes closed during the treatment procedure. Two *MOSkin* detectors were positioned on the patient's left outer canthus (LOC) and left eyelid (LE) [Figure 3(a)]. This detector is not visible on the displayed image and does not interfere with the treatment procedure [Figure 3(b)]. The *MOSkin* detectors were placed on the patient's body for at least 5 minutes to allow the detectors to equilibrate with the patient's body temperature before commencing the measurement. The *MOSkin* dosimetry system equipped with acquisition laptop using FETch software was placed in front of the interventionalist and the radiographer during the treatment procedures [Figure 2(a)]. Exposure parameters were recorded from the console. Measured doses were compared with exposure parameters such as FT, KAP, AK_F and AK_L .

II. C. Statistical analysis

Regression correlation tests were carried out to determine the relationships

between the MOSkin response and total fluoroscopic time, KAP, AK_L as well as AK_F . All analyses were carried out using SPSS (version 16, SPSS, Chicago, IL).

III. Results

II. A. Patient's eye lens dose

The average dose received at the outer canthus and eyelid regions showed that the radiation dose received at the outer canthus region was significantly higher than the dose received at the eyelid region [Table 1]. The range of the AK for each tube and, consequently, KAP for AVM procedures, was higher than for other procedures. Due to higher dose delivery in AVM procedures, patients received higher dose at the outer canthus and eyelid locations [Table 1 and Figure 4].

Figure 5 shows the correlation between the exposure parameters and received dose at LE and LOC. There is a strong correlation between accumulative KAP and dose values at LE and LOC regions (LOC: $R^2=0.78$ and LE: $R^2=0.68$) [Figure 5 (a)]. Moderate correlations were observed between total fluoroscopic time and dose at LE and LOC (LOC: $R^2=0.52$ and LE: $R^2=0.40$) [Figure 5 (b)]. The accumulative AK for lateral and frontal tubes shows a strong correlation with measured dose at LOC (AK_L : 0.93 and AK_F : 0.78) [Figure 5 (c, d)] but a

weak correlation with measured dose at LE (AK_L : 0.28 and AK_F : 0.10) [Figure 5 (c, d)].

II. B. Study of exposure parameters

Figure 6 shows the accumulated dose trend at LOC for a particular AVM case, highlighting the unique capability of the *MOSkin* dosimetry system. Using the *MOSkin* detector, we can study the trend of the patient's accumulated dose during an interventional procedure. By matching the *MOSkin* detector response and exposure time from the console, we can correlate the dose measured by the *MOSkin* detectors with the machine exposure parameters, thereby understanding their contribution to the patient's received dose. The system not only enables us to record real-time patient dose, but also enables us to investigate the contribution of each exposure to patient's dose in terms of exposure parameters (kV, mAs, exposure angulation and rotation and number of frames) [Figure 6] or exposure types (Fluoroscopy, DSA, cine and road mapping) [Figure 7]. From Figure 6, it was found that the sharp increments in the detector threshold voltage were due to high dose rate DSA acquisition technique. For this particular AVM procedure, the DSA contributed 94% of the total dose to eye lens followed by road mapping (4.7%), cine trace (0.5%) and fluoroscopy (0.8%). This information [Figure 6& Figure 7] is important in

post-procedure analysis for future dose minimization strategies and can be utilized for the interventionalists' training.

IV. Discussion

Different techniques have been recommended to reduce radiation dose during IR procedures, such as using pulsed mode fluoroscopy exposure, shortening the exposure time, increasing distance between x-ray source and patient, reducing distance between image receptor and patient, minimizing the magnification, maximizing collimation, using last image hold technique, changing C-arm angles and using low frame rate exposure[23, 24].

Applying these strategies and using a direct dosimetry system can significantly improve patient radiation safety during IR procedures. Direct dose measurement is not feasible for all IR procedures; for this reason, the dose metric parameters (FT, KAP, AK_{IRP}) are regularly monitored and recorded. To prevent skin injuries, a certain threshold level has been suggested for each parameter, for instance FT 40-60 min, KAP 500 Gy.cm², IRP 5 Gy and peak skin dose 3 Gy [25]. While these parameters are mostly recorded after each IR procedure as a rough estimate of the radiation dose received by patients, some studies have shown that they do not provide sufficient information during a procedure to control local skin dose to a given patient [5, 6, 26, 27]. The actual

patient's entrance skin dose can be calculated from exposure air kerma at reference point by incorporating table attenuation, backscatter factor, correction of actual source skin distance (Inverse square law) of reference point to actual skin point and correction of mass energy absorption coefficients of skin to air [28]. Recently, automatic skin dose simulation tools were used to estimate the entrance skin dose from the geometrical and exposure information extracted from DICOM tags and system parameters. These software are able to map the estimated skin dose distribution on standard and anatomical patient model phantoms [28, 29].

In this study, KAP values showed strong correlation with doses received at LE and LOC regions. For the cerebral angiography procedure, the patient's eyes are frequently exposed to primary radiation beams. This may be the main reason that this strong correlation was observed between KAP and measured dose at LE and LOC regions. In our center, the lateral tube was always placed at the left side of the patient's head, therefore AK_L and measured doses at LE and LOC showed strong correlation, unlike the frontal tube, which showed a weak correlation with the measured doses.

For all cases measured dose at LOC was higher than LE. This difference can be explained by two reasons: first, the closer proximity of the LOC detector to the lateral x-ray tube compared to the LE detector; and second, collimation of

the radiation field. The radiography team was well trained to minimize the irradiation dose to the left eye lens by collimating the radiation field of the lateral tube. With proper collimation of the radiation field, the detector on the eyelid would be out of direct radiation from the lateral tube, while the detector on the outer canthus would still be within the direct beam. The collimation effect would be significant for embolization procedures at the posterior region of the skull, which can completely place the patient's eyes outside of the primary beam. This finding clearly shows the importance of choosing the right location for the point dose measurement during a non-homogenous dose distribution procedure. The maximum eye lens dose of 1492 mGy was measured at LOC region for an AVM case, followed by 907 mGy for an aneurysm case and 665 mGy for a diagnostic angiography procedure.

This study showed that among the 35 patients, LOC regions of 8 patients and LE region of 1 patient were found to receive higher doses than the assumed threshold dose for cataract formation (500 mGy). Recent studies have reported the average and maximum patient eye doses for neuro-interventional radiology procedures [Table 2]. Generally, therapeutic procedures are more complicated than diagnostic procedures, which lead to longer exposure time and higher dose delivery to patients' bodies (KAP). The results of our study are in good agreement with previous studies. As shown, the detectors positioned at the

lateral margin received higher doses in comparison to those placed on the eyelids or inferior and superior margins (I-S margins).

As a high frame rate and high quality imaging technique, DSA plays a major role in contributing to patient's dose. Some studies have tried to evaluate the effect of DSA exposure on patient dose [30, 31]. The *MOSkin* detector enables us to study the contribution of various exposure parameters on patient's dose during a clinical procedure. However, the main objective of the patient dosimetry is to monitor the total dose delivered to the patient's body as well as the dose delivered to the sensitive organs. A real-time dose monitoring system can provide real-time information for each particular exposure. This information can be used to study the techniques to optimize patient's radiation safety during IR procedures, such as changing the exposure angulation, adjusting the exposure collimation, and shortening the exposure time when the dose at detector position reaches a critical level.

In summary, indirect dose measurements using machine available dose metrics such as KAP, FT and air kerma are not accurate indicators of the actual dose received by patients undergoing interventional radiological procedures. This information can only be obtained via actual *in-vivo* dose measurements. In this work, we demonstrated the feasibility of using the *MOSkin* dose monitoring system as a real time, *in-vivo* dose measurement system. The system was

successfully used to measure patient eye lens dose during neuro-interventional procedures. This system enables interventionalists to have better awareness of the patient's eye lens dose during clinical procedures.

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List of figures:

Figure 1 (a) MOSkin dosimetry system (b) MOSkin detector and (c) MOSkin detector components.

Figure 2 (a) MOSkin dosimetry system was placed at treatment room and accumulated dose values were displayed using the FETch software in front of the interventionalist and the radiographer during treatment procedures. (b) FETch display showing the accumulated dose values.

Figure 3 (a) The MOSkin detectors were positioned on the left eyelid and left outer canthus regions during interventional procedures. (b) This detector is almost invisible on the displayed image.

Figure 4 The boxplot shows the median and distribution of the dose delivered to the outer canthus and eyelid areas for each treatment procedure for the 35 participating patients, comprising 19 diagnostic angiographies, 8 treatments of cerebral aneurysms, and 8 embolizations of AVMs.

Figure 5 Correlation between the measured dose to left outer canthus and left eyelid regions to (a) KAP, (b) FT, (c) AK_L and (d) AK_F.

Figure 6 The accumulated dose trend line at LOC for an AVM procedure. From the real-time response pattern of the *MOSkin* detector, it is possible to investigate the dose delivered to the patients. The temporal dose pattern allows us to evaluate the contribution of each exposure to dose delivery to the patient's eye. Two particular exposures were labeled in this graph, d_1 is dose before exposure and d_2 is the dose after exposure. The increment dose (Δd) indicates the absorbed

Figure 7 The dose delivered to the patient's LOC depicted as contribution of different types of exposure (e.g. fluoroscopy, road mapping, DSA and Cine Trace).

List of Tables:

Table 1 Exposure parameters and dose delivered to LE and LOC areas, averages, medians, and 95th percentiles.

	KAP (Gy.cm ²)	AK _r (mGy)	AK _l (mGy)	FT (min)	LE Dose (mGy)	LOC Dose (mGy)
Angiography						
Average	178.8	512.1	302.3	7.2	155.0	267.8
Median	154.9	430.9	264.0	6.5	137.9	218.2
95%	385.5	893.5	716.9	12.4	353.4	648.8
Aneurysm						
Average	211.7	1060.5	516.0	18.2	168.4	393.0
Median	196.6	997.5	388.8	12.4	157.1	294.9
95%	342.1	2139.2	1125.6	44.6	268.8	809.4
AVM						
Average	314.8	1513.5	705.3	13.7	308.4	612.3
Median	238.6	855.4	439.4	8.4	278.6	374.9
95%	649.8	4193.3	1664.2	32.2	524.7	1441.4

KAP indicates kerma area-product; AK_r, air-kerma for frontal tube; AK_l, air-kerma for lateral tube; FT, total fluoroscopic time; LE, left eyelid; LOC, left outer canthus.

Table 2 Comparison of published data on eye doses for neuro-interventional radiology procedure.

Ref. & Year	Interventional procedure	Patient number	Detector type	Mean KAP (Gy.cm ²)	Mean Fluoroscopy time (min)	Detector position	Eye lens dose (mGy)	
							Maximum	Average
[32] (1991)	Embolization	5	TLD ¹	-	59.8	Lateral margin	139	90
[13] (1998)	Diagnostic	15	TLD	-	0.4	I-S margins ²	2	1.1
						Lateral margin	150	99
	LDS ³	10	TLD	-	5.6	I-S margins	66	38
						Lateral margin	294	176
[15] (2000)	DSP ⁴	10	TLD	-	3.9	I-S margins	68	38
[12] (2003)	Embolization	30	TLD	106.0	14.0	-	500	60
[17] (2008)	Therapeutic interventional radiology	28	PLD ⁵	-	55.6	Lateral margin	2079	380
[16] (2010)	Diagnostic	19	TLD	54.7	6.9	Left Eyelid	-	7.8
	Coiling	27	TLD	121.0	32.0	Left Eyelid	515	51
	Embolization	25	TLD	189.0	39.8	Left Eyelid	289	71
This study	Diagnostic	19	MOSkin	178.8	7.2	Left Eyelid	394	155
						Lateral margin (LOC ⁶)	665	268
	Embolization	16	MOSkin	314.7	15.9	Left Eyelid	563	238
						Lateral margin (LOC)	1492	502

¹ Thermoluminescent detector

² Inferior and superior margins

³ Lachrymal drainage system

⁴ Balloon dacryocystoplasty

⁵ Photoluminescence glass dosimeter

⁶ Left Outer Canthus