Master of Science dissertation:

Dosimetry for the Lens of the Eye, Applications for Medical Staff Involved in Interventional Radiology Procedures

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Abstract

Background: Cataract (opacity of the lens of the eye) has always been thought of as a deterministic effect. That is, that there is a threshold dose below which damage does not occur. However, recent studies suggest a lower threshold and the question whether there is any threshold at all has been raised. One situation that leads to special concern, if this turns out to be the case, is during interventional radiology (IR) and cardiology procedures where the medical staff, being exposed to scattered radiation from the patient, can receive relatively high absorbed doses to their eyes.

Aim: When the dose to eye is measured it is usually done by placing a dosimeter at the side of the head near the eye. The aim of this study is to investigate how good an approximation this is by means of experimental studies and Monte Carlo calculations. Another aim is to study the distribution of absorbed dose inside the skull including that to the lens, and to investigate if there is any relationship between the output from the x-ray tube and the absorbed dose to the lens.

Material & Methods: Measurements were carried out with a thorax phantom placed on an operating table and a head phantom placed where a physician would be expected to stand. The head phantom contained TLDs and Gafchromic film. The measurements were performed both with and without protective goggles. Measurements were also performed on two senior physicians wearing headbands with TLDs during procedures. The simulations were made in the Monte Carlo program PENELOPE. The geometry contained a detailed head, and eyes, and a patient lying on the operating table.

Results and Discussion: The phantom measurements show that the absorbed dose to the lens is higher than that at the forehead for both eyes. This means that a dosimeter at the forehead underestimates the lens dose. A clear relationship between lens dose and DAP value could also be seen. This is not as pronounced in the measurements on the physicians although there is still a relation. When protective goggles were used in the phantom measurements a reduction of the absorbed dose to the lens could be seen for the right eye. However, film measurements show that radiation can slip through the goggles in some angles. The simulations show that the absorbed dose in the lens is lower compared to the absorbed dose at the forehead, i.e. a dosimeter at the forehead would overestimate the lens dose. From the simulations there could be seen that the energy of the radiation reaching the lens have a small but pronounced shift towards lower energies, compared to the energy leaving the x-ray tube.

Conclusions: Dosimeters used for measuring the dose to the lens of the eye may underestimate the dose with up to 25 %. This indicates that a better way of estimating the dose to the lens may have to be found. It seems to be a relationship between dose to the patient and dose to the physicians' eyes and perhaps a factor could be found so that estimations can be made without specific point dose measurements. The film measurements show that the design of protective goggles has to be improved, so that no radiation can slip through at any angle.

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Abbreviations & Acronyms

CZ	Central Zone
DAP	Dose-Area Product
EVAR	EndoVascular Aneurysm Repair
GZ	Germinative Zone
ICRP	International Commission on Radiological Protection
IPEM	Institute of Physics and Engineering in Medicine
IR	Interventional Radiology
MR	Meridional Rows
NCRP	National Council on Radiation Protection and measurements
PE	Polyethylene
PENELOPE	PENetration and Energy Loss Of Positrons and Electrons (Monte Carlo simulation program)
PSC	Posterior SubCapsular
ROI	Region Of Interest
SSD	Solid State Detector
TLD	Thermo Luminescent Dosimetry
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UV	Ultra Violet

Contents

Introduction

Cataract, which is an opacity of the lens of the eye, accounts for the majority of cases of blindness worldwide[1]. Cataract may arise from a number of causes, such as trauma, chronic uveitis (inflammation of the eye) and age[2]. It has long been known[3] that also exposure of ionizing radiation may produce cataract. The development of radiation induced cataract has been thought of as a deterministic effect, i.e. a threshold dose exists below which damage does not occur[2-6]. This threshold dose is currently set to 2 Gy for a single exposure and present ocular guidelines are based on this[6]. However, recent studies, where populations have been exposed to far lower absorbed doses suggest a lower threshold and the question whether there is any threshold at all has been raised. The recent studies include investigations of radiologic technologists[7], radiotherapy patients[8 9], atomic bomb survivors[10-12], Chernobyl "liquidators"[13] and astronauts[14]. This is of considerable interest to the risk assessment community since protection measures have to be optimized and a reduction of current dose limits, both occupational and public, may be necessary in the future. The ICRP stated in their publication 103[6] that a thorough review of the radio sensitivity of the lens of the eye was needed and that there should be particular emphasis on optimisation in situations of exposure of the eyes due to the uncertainty concerning the risk, and that they had formed a task group to review the matter[6]. The reason why the lower threshold or, possibly, stochastic nature of radiation induced cataracts have been overseen until now is assumed to be the generally short follow-up periods in many of the early studies[13 15], on which most risk estimates are based and where they failed to take into account the increasing latency period as dose decreases, and that relatively few subjects had been exposed to absorbed doses below a few Gy[16].

Aims

The fact that the lens of the eye may be more radiosensitive than previously thought raises a number of questions. One situation that leads to special concern is during interventional radiology (IR) and cardiology procedures where the medical staff, being exposed to scattered radiation from the patient, can receive relatively high absorbed doses to their eyes. It is necessary to find better ways of assessing and reducing the exposure to this medical staff. If the absorbed dose to the lens of the eye is measured at all during medical procedures today it is usually done by placing a dosimeter at the side of the head near the eye or at the forehead[17 18]. The aim of this investigation is to investigate how good an approximation this is of the absorbed dose to the lens of the eye. In other words it is desired to find out what the relation between the dose to the lens and the dose to a measuring point at the side of the head looks like. This is done by means of experimental studies and Monte Carlo calculations. Another aim is to visualize the distribution of absorbed dose inside the skull and thus increase understanding of the radiation geometry and the effect of protective goggles. If dose limits for the eye is to be reduced it will be of even more importance to keep track of the dose received by the staff to make sure these are not exceeded. Since measurements are very consuming it would be desirable to be able to estimate the dose to the lens of the eye without performing measurements and therefore in this study it is also investigated if there is any relationship between the output from the x-ray tube and the absorbed dose to the lens.

Description of the lens of the eye and the development of cataract

The eye

The eye is an organ that allows us to see and create an image of the surrounding world by its ability of detecting light. It can distinguish between different colours and shapes and also give a perception of depth.

Anatomy

The anatomy of the eye is complex and focus on its details is outside the framework of this study. However, an overview of the major components, especially of the lens, is given below.

When light hits the eye an image is produced at the retina due to refraction in the cornea and the lens. To get a clear image at different distances the lens can accommodate through muscles attached to the ciliary body that changes the lens radii of curvature. The space between the lens and the retina is known as the vitreous body and the space between the lens and the cornea is known as the anterior chamber. [19]

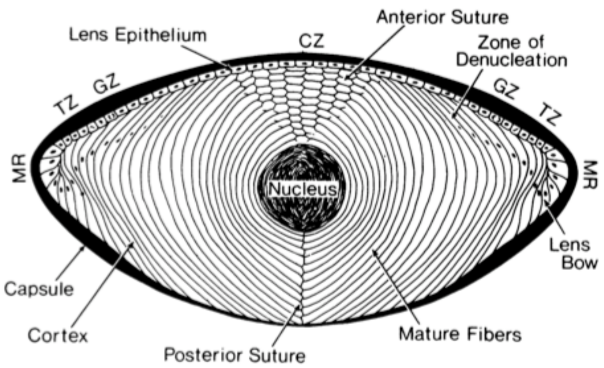

Figure 1. A sagital section of a human lens illustrating the various relationships in that tissue. [2]

The lens is a transparent, elastic structure that consists of mainly three parts, the capsule, the epithelium and the lens fiber, figure 1. The lens has a biconvex form and the connection between the two surfaces is called the equator. The capsule is highly elastic and constitutes the outer part of the lens, therefore the lens is isolated and lacks blood supply. Beneath the anterior part of the capsule there is a single layer of cuboidal cells, the epithelium, and the central part of the lens consists of lens fiber. There is no epithelium at the posterior part of the lens. Mitosis takes place at the epithelium, termed the germinative zone (GZ), near the equatorial region where the cells differentiate to lens fiber and adds to the outer cortex (cortex is the name for the younger lens fiber between the nucleus and the epithelium). The cells in the central zone (CZ) proliferate very slowly and play little role in the lens growth[16]. After cell division in the GZ the cells migrate towards the equator and line up in a precise manner known as meridional rows (MR) where they mature into lens fiber cells. Lens fiber are long and thin transparent cells that extends from the posterior part to the anterior part of the lens. Mature lens fiber have no organelles and no nuclei. Throughout life the lens continues to grow, though no mechanism for removal of old cells exists, figure 2.

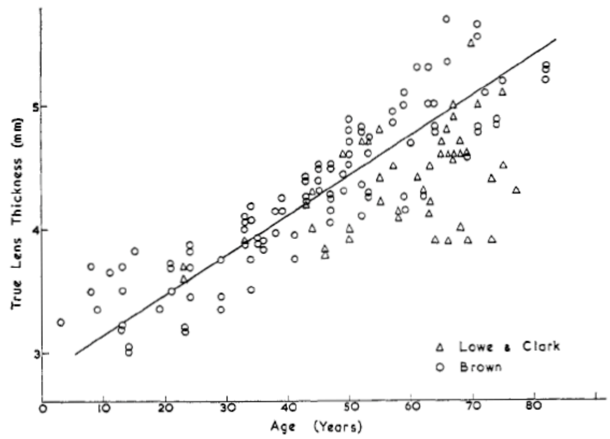

Figure 2. Lens sagital thickness as a function of age. [19]

Cataract

The lens of the eye is optically clear, so that light can pass through it. The fact that the lens continues to be transparent depends on the proper morphogenesis of lens fibre cells, i.e. the cells without nuclei and organelles that are a progeny of the cells in the epithelium[16]. However, due to many different causes the lens of the eye may obtain opacities. This phenomenon is known as cataract. Possible causes may for example be trauma, age, UV radiation, certain steroids, diabetes or ionizing radiation[2]. There are three predominant forms of cataract: nuclear; involving the inner lens fibre cells, cortical; initializing in the outer, more recently formed lens fibre cells and posterior subcapsular (PSC); developing in the epithelial cells and leads to opacity at the posterior pole[20]. Radiation cataract is generally associated with PSC although other causes also can lead to this type of cataract[2]. The mechanism of radiation induced cataract formation is not fully understood but genomic damage is considered to be the salient injury, rather than cell killing[16 21]. For a long time it has been recognized that dividing cells are more radiosensitive and it has been shown that cell division is required for cataract to develop and thereby that the opacification process is primarily the result of changes in the epithelial cells[2 19]. Radiation cataract is believed to develop in the following manner: the epithelial cells are injured and when they continue to undergo mitosis their progeny are displaced to the meridional rows where the damage is expressed in form of disorganization of the rows. Abnormally shaped fibres gather beneath the posterior capsule where these cells take on a rounded appearance and are known as Wedl cells. The opacities initially appear as small circles and may at times have a relatively clear centre, giving it a doughnut shape[2]. Since the lens does not have a mechanism for cell removal any given injury to the cells will always be present.

Threshold dose

The development of radiation induced cataract has long been thought of as a deterministic effect, i.e. a threshold exists below which damage does not occur[2-6], figure 3. This assumption is based largely on animal studies and clinical studies of Merriam *et al.*[2 3]. The guidelines set by the risk assessment communities (ICRP[5 6], NCRP[21] and UNSCEAR[22]) are all predicted on this assumption. A dose delivered within a certain time that falls below the lower line of figure 3 is not assumed to produce damage to the lens while a dose that falls over the upper line is assumed to produce cataract, usually with visual loss[3]. In the zone between the lines cataract may or may not occur and within this zone the probability increases with increasing dose. The current threshold is believed to be about 0.5-2 Gy for acute exposure and 5 Gy for fractionated exposures[3 5 6 21 22]. The latency period for radiation induced cataract is believed to be inversely related to the dose, i.e. the latency period increase when the dose decrease[2].

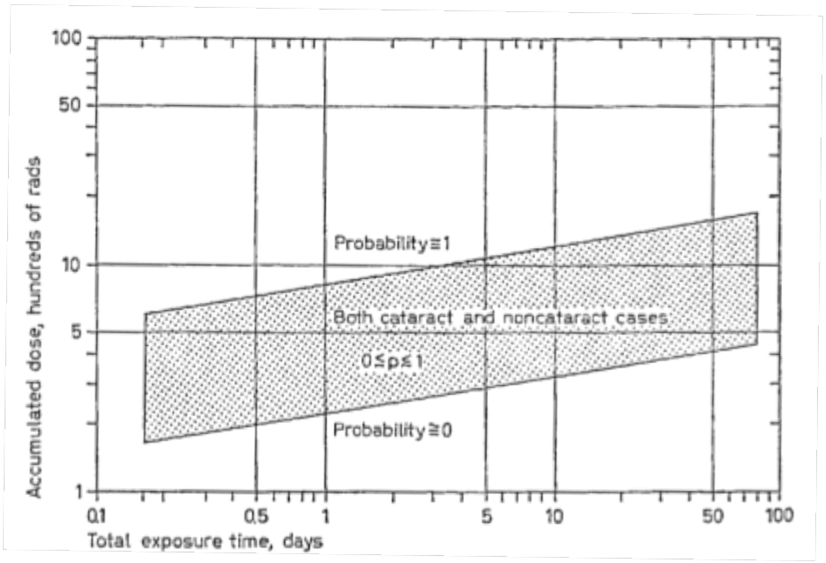

Figure 3. Time-dose relationship indicating dosage for cataract production with a probability between zero and one.[3]

In recent years, however, new studies have been published which suggest that the threshold in fact is much lower or even not exist at all, i.e. that cataract is a stochastic effect. In these studies populations that have been exposed to far lower doses than the threshold dose have shown lens opacifications, including radiologic technologists[7], radiotherapy patients[8 9], atomic bomb survivors[10-12], Chernobyl "liquidators"[13] and astronauts[14]. Before this can be adopted with certainty further studies have to be made, both IAEA[23] and ICRP[6] are currently investigating the issue. If this turns out to be the case current guidelines may need to be revised. In the meantime the recommendations given from ICRP[6] is that there should be particular emphasis on optimisation in situations of exposure of the eyes due to the uncertainty concerning the risk.

The reason why the lower threshold or, possibly, stochastic nature of radiation induced cataracts have been overseen until now is assumed to be the generally short follow-up periods in many of the early studies[13 15] and where they failed to take into account the increasing latency period as dose decreases, and that relatively few subjects had been exposed to absorbed doses below a few Gy[16].

Dosimetry

Current dose limits given from the ICRP[6] for the lens of the eye is 150 mSv for workers. Since the protective quantities are impossible to measure directly operational quantities are used and the ICRU[24] recommends the personal dose equivalent Hp(3) for eye lens dosimetry. In many cases though, dosimeters calibrated in terms of Hp(0.07) have been seen as sufficient for monitoring the dose to the lens of the eye[25]. If guidelines are to be revised, protection measures have to be optimized and the question of which personal dose equivalent quantity that is appropriate for monitoring the dose to the lens of the eye has to be considered. This have recently been and is currently being investigated by several researchers[26-28]. For doses near a dose limit, which could possibly be the case in interventional radiology if limits are reduced, it is necessary to confirm that the operational quantities provide a good estimate of the protection quantities[25]. This requires good knowledge of the radiation geometry and the position of the dosimeter is of great importance. Position and design of a suitable dosimeter for eye lens dosimetry is a hot topic at present time[28].

Material & Methods

A head phantom was used for the absorbed dose measurements and a thorax phantom was used as scattering material, i.e. to simulate a patient.

Head phantom

The head phantom is an anthropomorphic Alderson phantom constructed around natural human bone, divided in discs with a thickness of 2.5 cm, figure 4. It is constructed to resemble a natural human head. Teeth and nasal cavities (sinuses) are also incorporated. To be able to place TLDs inside the head and not destroying the phantom, the disc where the eyes are located was replaced with a disc of polyethylene (PE) that has density and atomic number close to that of tissue. Small holes where made for the TLDs at the positions of the lenses and also in a cross pattern to get information about absorbed dose distributions, figure 6. The holes have a diameter of 4.2 mm and a depth of 13 mm to accommodate the square-shaped dosimeters of 3x3 mm^2 and positioning the TLDs in the middle of the "eye disc".

Figure 4. Head phantom

Figure 5. Thorax phantom

Figure 6. Polyethylene disc, used in the head phantom, with holes to fit TLDs.

Thorax phantom

The thorax phantom (model PBU-X-21, Kyoto Kagaku CO. Ltd, Kyoto, Japan, www.kyotokagaku.com) is an anthropomorphic phantom that closely resembles a real human chest, figure 5. The phantom consists of materials that interact with radiation in the same manner as do a real human being.

Phantom measurements

During measurements the thorax phantom was placed on the operating table and the head phantom placed where a physician would be expected to stand, figure 7. The chosen distance between the head phantom and the thorax phantom is in agreement with the distance between a physician's head and a patient, based on the physicians participating in measurements described later.

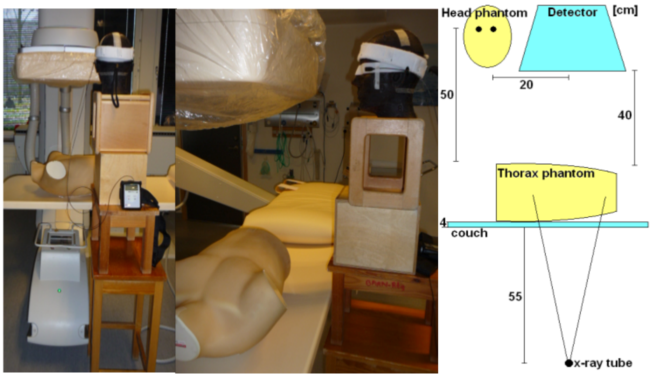

Figure 7. Position of thorax and head phantom during measurements.

A headband with pockets for TLDs in seven different positions, figure 8, was produced and placed on the head phantom. In each pocket on the headband were two TLDs. TLDs were also placed in the polyethylene disc, at the positions of the lenses and at the various other positions. The TLDs used were square chips made of LiF:Mg,Ti, TLD-100 (Thermo, Ohio, USA). The TLDs were calibrated individually, to determine the absorbed dose to water, in a ^{60}Co-field at a position with well known absorbed dose rate at a depth of 0.5 cm in a polymethylmethacrylate phantom of 7.5 cm thickness. The TLDs were heated for 10 minutes in an oven holding 400°C to clear the TLDs before use. Since the TLDs are irradiated in a different radiation quality during measurements than ^{60}Co this is accounted for by multiplying with an energy correction factor of 0.8. After measurements they were read out in a reader (Harshaw Automatic Dosimeter Reader, model 5500, Thermo Scientific, Germany, www.thermo.com). The TLDs are divided into groups, with 20 TLDs in each group, and for each measurement four of the TLDs were used for standard calibration and two for measuring the background. The remaining 14 TLDs were used for measurements.

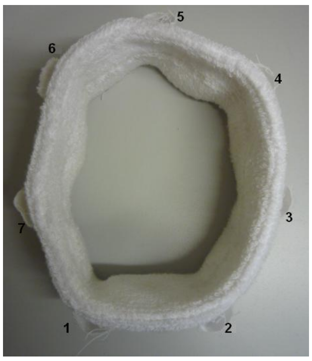

Figure 8. Headband with TLDs. Position one and two is located just above the right and left lens respectively, and position five is located at the centre of the back of the head.

A Solid State Detector, SSD, (Unfors EDD-30, model 8181010-C, Unfors Instrument, Billdal, Sweden, www.unfors.com) was also placed at the side of the head phantom. This detector is customized to be able to measure eye doses from scattered radiation in this kind of situations and has a clip so that it can be attached on for example the side of a pair of glasses during the clinical procedures. The SSD is calibrated to measure the operational quantity Hp(0.07) and to change between the dose in Sv and Gy a factor 1 is used.

The phantom measurements were performed on a clinically used x-ray unit (Philips MultiDiagnost Eleva, Philips Medical Systems, Stockholm, Sweden, www.healthcare.philips.com/se). To be able to easily repeat the measurements, the automatic exposure control was turned off and the exposure parameters set to 77 kV, 500 mA and 200 ms (100 mAs). No additional filter was used and the field size was set to it's maximum (about 13 x 16 cm^2 at a distance of 55 cm from focus). The phantom was then exposed repeatedly between 85 and 105 times. The SSD, that gives the dose in Gy, was read after the last exposure and the dose-area product, DAP, (from the control panel of the x-ray unit) was noted. TLDs and Gafchromic film (described below) were read out separately.

Measurements were carried out both with and without protective goggles, figure 9. The goggles used in this investigation were a pair with 0.75±0.05mm Pb equivalent leaded glass (Ultralite 9941, ProTech leaded eyewear Inc., Florida, USA, www.protecheyewear.com) fitted for scattered x-ray radiation.

Figure 9. Head phantom with headband and SSD, and with and without protective goggles respectively.

Radiochromic film

Gafchromic film XR-QA is a radiochromic film that is self-developing and designed to measure absorbed dose of low energy photons, between 20 kVp and 200 kVp (www.gafchromic.com). The film is not sensitive to visual light and can therefore be handled in ambient light. It is also possible to cut the film in any desired size and shape. The dose range is between 1 mGy and 200 mGy. The film was cut to fit between the discs of the head phantom, one film underneath the PE disc and one above.

To be able to translate the blackening of the film to absorbed dose the film had to be calibrated. Since the output of most x-ray tubes is not completely constant for repeated exposures this had to be accounted for first. This was done by placing a monitor detector (Unfors Xi, model

8201011-C, Unfors Instrument, Billdal, Sweden, www.unfors.com) a couple of centimetres from where the film was to be located but within the radiation field, and an ion chamber (Radcal Accu-Dose, model 2186, Radcal Corporation, Monrovia, USA, www.radcal.com) where the film was to be located to measure the output (mGy/mAs). The relation between the measurement results from the two detectors was noted and later used to correct the absorbed dose to the film. The ion chamber was then removed and replaced with a small square of film (the monitor detector still in place). Repeated exposures with increasing dose were then made while exchanging films, giving darker and darker films. To scan the film an EPSON 4900 flatbed scanner was used and the images were then read with the program ImageJ (http://rsbweb.nih.gov/ij/). There they were inverted (to get higher pixel values where there have been more radiation) and transformed to an 8-bit image. The mean pixel values were measured in each film square using rectangular ROIs. One film square that had not been exposed at all was used to obtain the background pixel value. The values were then used to draw a dose-response diagram, figure 10. A third degree polynomial was fitted to the measurement points. This equation was later used to convert net pixel value distributions into absorbed dose distributions in the film used in the head phantom. Most of the measuring points were performed at very low doses since it is in this dose region that measurements will be performed. In the program ImageJ it is also possible to use a plugin called Contour Plotter, this draws contour lines at user-defined levels in different colours. This was used to obtain "isodose curves" in the images.

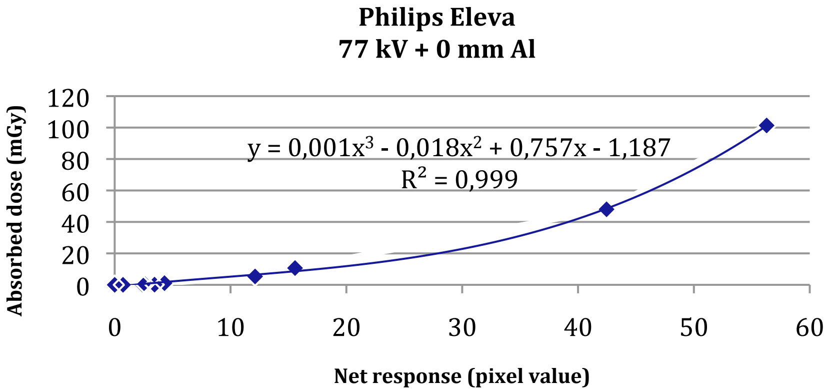

Figure 10. Function for calibration of Gafchromic film.

Simulations

The Monte Carlo simulations made in this study were performed using the code system PENELOPE. PENELOPE is an acronym for PENetration and Energy Loss Of Positrons and Electrons (photons were introduced later). PENELOPE is a Monte Carlo algorithm and computer code for simulation of coupled electron-photon transport in different materials for a wide range of energy, from a few hundred eV to 1 GeV [29]. Also included is a Fortran subroutine geometry package, called PENGEOM, which allows generation of random electron-photon showers in homogeneous bodies such as spheres, cylinders and planes.

The geometry simulated was based partly on the existing example of the human body included in PENELOPE, partly on the anthropomorphic Alderson phantom used in measurements and partly on dimensions from the ICRP Reference Man[30]. The geometry includes brain, cranium, facial skeleton, soft tissue, sinuses, skin and eyes, as seen in figure 11. The eyes are composed of a lens, an anterior and a vitreous chamber and a cornea, and the geometry is based on information in Behrens et al.[26] and in the ICRP Reference Man[30]. Also included are two small discs placed above the eyes, representing TLDs as in position 1 and 2 on the headband used on the physicians and on the phantom. For the different bodies predefined materials were used, which are given in table 1. The material for the parts of the eye, except the lens, was chosen to be water. This because no other eye material was predefined in the program and according to ICRPs Reference Man[30] their properties is very near those of water. Since only the lens is of interest this small difference for the other parts of the eye have minimal impact on the results. A "patient" lying on an operating table was also included in the geometry and represented by an ellipsoid of water, figure 12. The head and the patient were then placed in a box of air since the program otherwise will assume that the geometry is surrounded by vacuum. The x-ray source was placed underneath the patient, as in interventional procedures, at a distance of 60 cm. In relation to the left lens the source was moved 20 cm to the left and 25 cm forward. The aperture of the source was chosen to 10°, corresponding to a circular field size of about 20 cm in diameter.

The x-ray spectrum used as input was calculated by using a Spectrum Processor program from the Institute of Physics and Engineering in Medicine (IPEM, Catalogue of Diagnostic X-Ray Spectra & Other Data, Publication report 78, York, England, www.ipem.ac.uk). The tube voltage was set to 77 kVp, the target material to tungsten, anode angle to 12° and filter to 3.4 mm Al, as in the Philips Eleva unit. This gives a very detailed spectrum that would take unnecessary long time for PENELOPE to process and therefore the spectrum was subdivided into larger photon energy intervals, as seen in figure 18 and 19, and this new spectrum was used as input in the simulations.

Simulations were made to obtain energy of the photons striking the lens as well as to obtain the absorbed dose (energy deposition) in the lens relative to the absorbed dose in the "TLD" at the forehead.

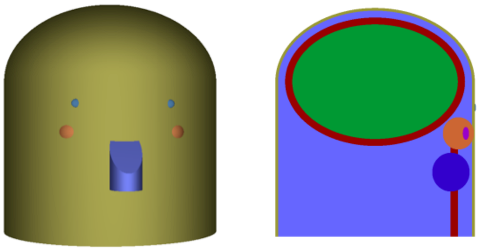

Figure 11. PENELOPE geometry of the physician's head with TLDs at the forehead in 3D and 2D respectively.

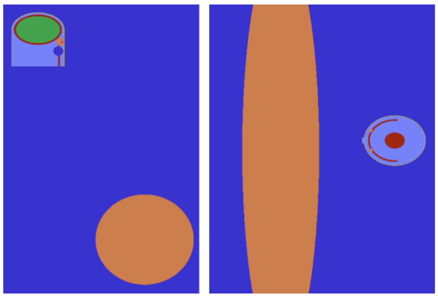

Figure 12. PENELOPE geometry, head and patient, seen from the side and above respectively.

Table 1. List of materials in the PENELOPE geometry, predefined in the program.[29]

Body	Id-number	Compound/ Mixture
Eye lens	156	Eye lens (ICRP)
Eye other, Patient	278	Water, liquid
Sinuses/ Air	104	Air, dry (near sea level)
Brain	123	Brain (ICRP)
Cranium, Facial skeleton	120	Bone, cortical (ICRP)
Tissue	262	Tissue, soft (ICRP)
Skin	251	Skin (ICRP)

Measurements on physicians

Measurements were carried out on senior physicians during a number of interventional procedures, figure 13. They were told to wear the same headband with TLDs as used for the phantom measurements. In contrast to the phantom measurements where the position of the phantom was fix, the physicians were moving around and during the procedure the x-ray tube was in different angles. Mostly however it is directly underneath the patient imaging in a posterior-anterior projection. They also often work in pairs so that only one of them is near the patient while the other stands behind, being slightly shielded from the scattered radiation coming from the patient. How the physicians moved and what tube voltages that were used was studied carefully under a couple of procedures prior to the phantom measurements to learn about the physicians behaviour in the operating room so that the arrangement would be similar.

The measurements were performed during a number of different procedures, mostly EndoVascular Aneurysm Repairs (EVAR). EVAR is a procedure to repair an aneurysm of the aorta by placing a so-called stent in the aorta to keep it open. The x-ray units used during these procedures were a Siemens Axiom Artis TA as well as a Siemens Axiom Artis zee DF (www.medical.siemens.com), x-ray units similar to the earlier used Philips Eleva.

The headband was put on prior to the clinical procedure and then kept on during the whole procedure. Parameters such as DAP value, tube voltage and total time of fluoroscopy was noted after each occasion and the TLDs in the headband were read out.

Figure 13. Physician with headband containing TLDs during an interventional procedure.

Results

Phantom measurements

Figure 14 shows the relation between the DAP values obtained from the x-ray unit and the TLDs in the right and left lens position in the phantom. For both the right and left lens there is a clear linear relationship. If a line were to be fitted to the data points a factor for estimating the eye dose from the DAP value would be obtained. Here, such a factor is 0.070 m^{-2} for the left lens and 0.055 m^{-2} for the right lens, which then is a conversion between the DAP value in $mGym^2$ and the dose in mGy.

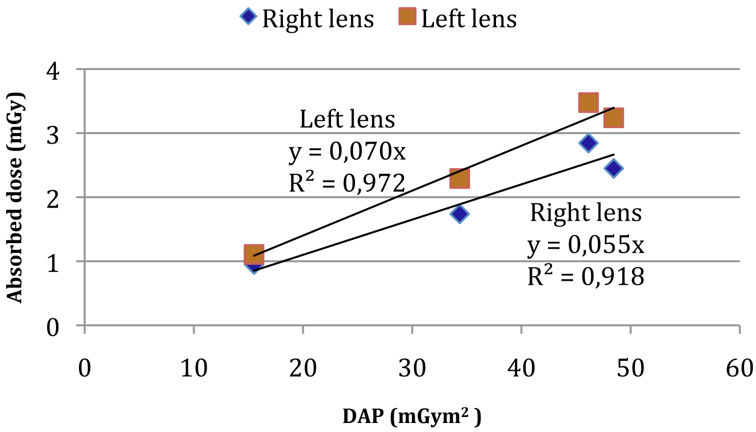

Figure 14. Relation between absorbed dose from TLD measurements in head phantom and DAP value from the x-ray unit.

The relative absorbed dose in the headband for the TLD positions (percentage of the sum of the absorbed dose in all dosimeters in the headband), according to figure 8, show that most of the radiation is deposited in the anterior left part of the head, position 2 and 3, while the lowest doses are obtained in the posterior right part, position 5 and 6, as seen in figure 15. This is not unexpected since the radiation strikes from the left.

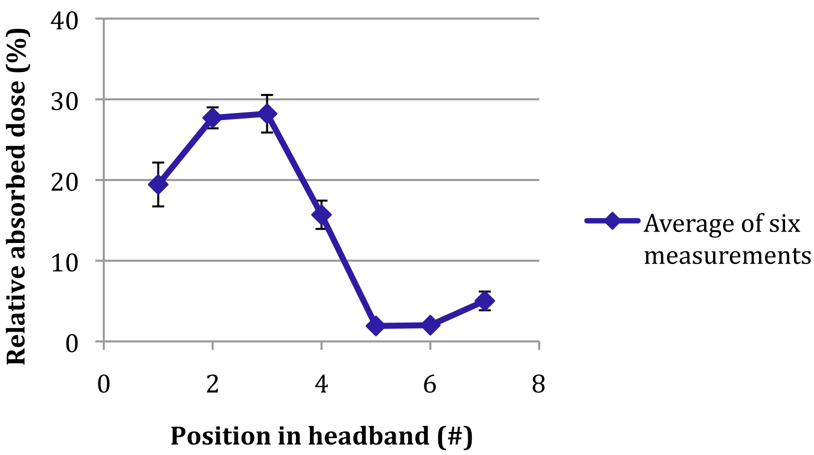

Figure 15. Average relative absorbed dose in the headband for all phantom measurements, with error bars of one standard deviation. Percentage of the sum of the absorbed dose in all dosimeters in the headband.

When the absorbed dose to the TLDs at the lens positions were compared with the absorbed dose to the TLDs at the forehead (in the headband) for measurements without protective goggles it could be seen that the TLDs in the headband underestimates the lens dose for both the right and left lens, as seen in table 2. For both eyes the absorbed dose is about 25 % higher in the lenses than at the forehead. When the absorbed dose in the lens positions were compared to the dose given from the SSD the situation was different. For the right lens the SSD overestimates the lens dose with about 16 % while for the left lens it underestimates the lens dose with about 5 %.

Table 2. The absorbed dose to the TLD in the lens position related to the dose to the TLD at the corresponding position in the headband (at the forehead), and the dose to the TLD in the lens position related to the dose from the SSD, without protective goggles.

	Lens/Headband, without protective goggles	Lens/SSD, without protective goggles
Right eye	+25 %	-16 %
Left eye	+25 %	+5.1 %

When protective goggles were used the absorbed dose to the left lens was decreased with about 21 % compared with the measurements without protective goggles while for the left lens the dose increased with almost 6 %. When the SSD was snapped on at the left side of the protective goggles it overestimated the lens dose for both eyes with over 20 %, see table 3.

Table 3. The absorbed dose to the TLD in the lens position with protective goggles related to the dose to the TLD in the lens position without protective goggles, and the dose to the TLD in the lens position with protective goggles related to the dose from the SSD.

	Lens with protective goggles/ Lens without protective goggles	Lens/SSD with protective goggles
Right eye	+5.6 %	-21 %
Left eye	-21 %	-25 %

The film measurements show a dose distribution that is consistent with the TLD measurements in the headband, i.e. most radiation is deposited in the anterior left part, only a small amount in the posterior right part. Without protective goggles a large part of the dose is distributed in the left lens area, but interestingly a relatively large part is also distributed in the area of the right lens, figure 16. When protective goggles were used it could be seen that the doses are reduced in the lens position in the film sheet located above the polyethylene disc while little difference could be seen for the film sheet that was located under the PE disc, figure 17.

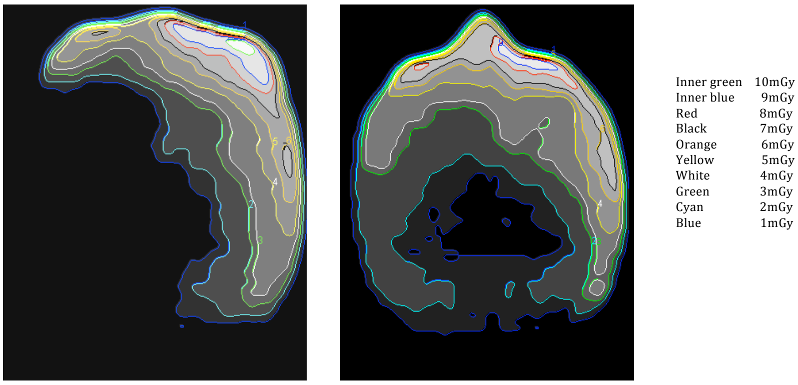

Figure 16. Dose distribution over (left) and under (right) the PE disc in the head phantom without protective goggles. (To be seen as medical images)

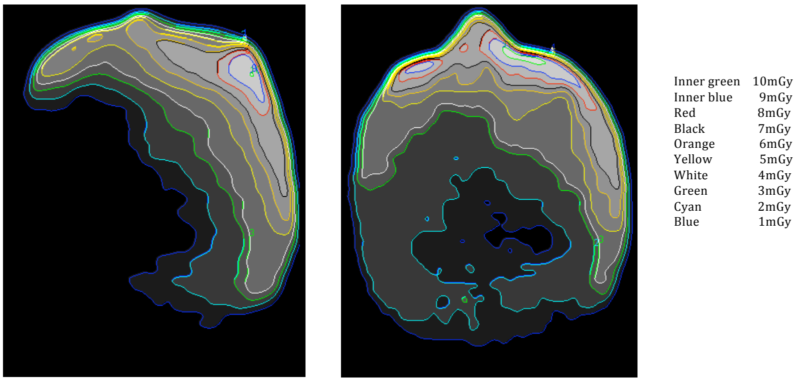

Figure 17. Dose distribution over (left) and under (right) the PE disc in the head phantom with protective goggles. (To be seen as medical images)

Simulations

The spectrum from a 77 kVp tungsten target calculated using a Spectrum Processor program could be seen in figure 18. To make simulations more effective the spectrum was subdivided into larger intervals (primary spectrum in figure 19), which was used as input in PENELOPE. Simulations then showed that the energy spectrum reaching the left lens of the eye (secondary spectrum in figure 19) had been shifted a little bit towards lower energies. The two spectra have been plotted as a percentage of the maximum value of each spectrum, so that they can be compared. In fact the secondary spectrum is naturally of much lower intensity.

When the absorbed dose to the lens was compared to the absorbed dose in a measuring point at the forehead, just above the eye, it turned out that the measuring point at the forehead showed a higher dose with about 21 %, table 4.

Table 4. The absorbed dose to the lens related to the absorbed dose in a measuring point at the forehead, just above the eye.

	Lens/Measure point at forehead
Left eye	-21 %

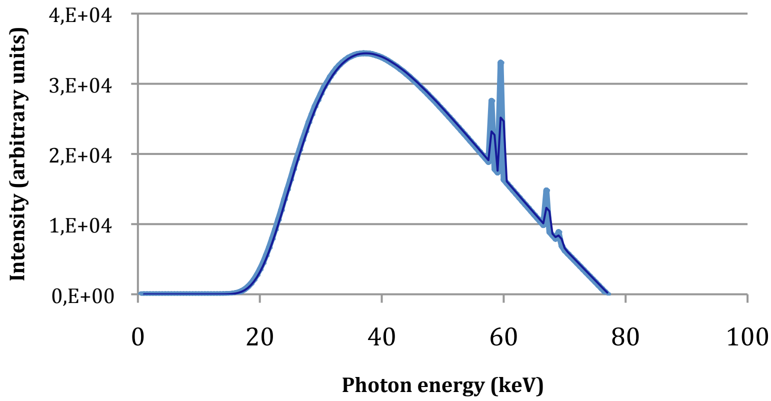

Figure 18. Spectrum of 77 kVp, tungsten target, 12° anode angle and 3.4 mm Al calculated with a Spectrum Processor program.

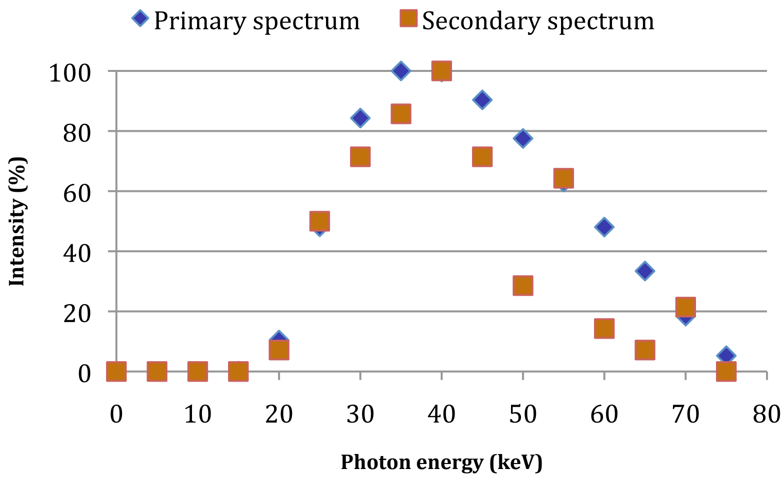

Figure 19. Primary spectrum leaving the x-ray tube, used as input in simulations, and secondary spectrum that strike the lens, given from the simulation.

Measurements on physicians

The linear relationship between DAP value and absorbed dose to the lenses are not as pronounced as it is for the phantom measurements, figure 20. However, if a line were to be fitted to the data points here as well, the factor for estimating the eye dose from the DAP value would be about 0.010 m^{-2} for the left lens and 0.007 m^{-2} for the right. The relative absorbed dose in the headband for the TLD positions (percentage of the sum of the absorbed dose in all dosimeters in the headband), according to figure 8, show that most of the radiation is deposited in the anterior left part of the head, position 2, while the lowest doses are obtained in the posterior right part, position 5 and 6, seen in figure 21, as in the phantom measurements. A comparison between the phantom measurements and the measurements on the physicians show good correlation, figure 22.

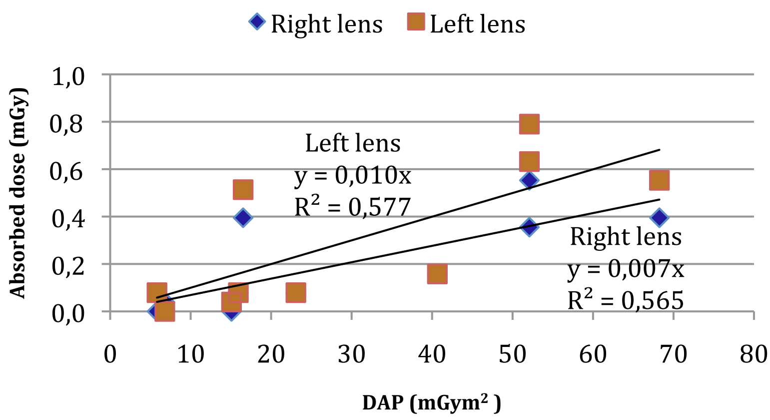

Figure 20. Relation between absorbed dose from TLD measurements on physicians and DAP value from the control panel.

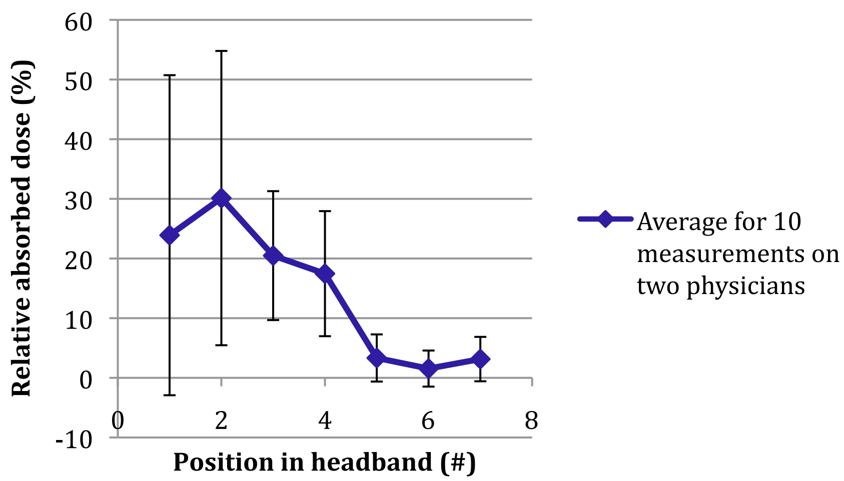

Figure 21. Average relative absorbed dose for all measurements on physicians for the different positions around the head, with error bars of one standard deviation. Percentage of the sum of the absorbed dose in all dosimeters in the headband.

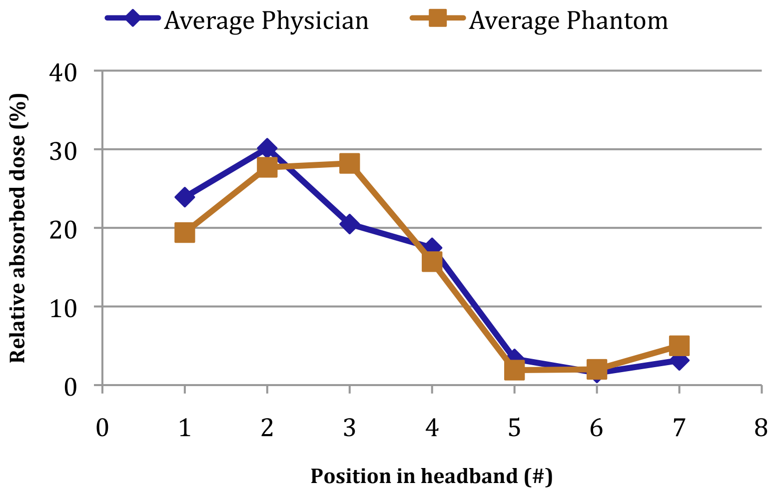

Figure 22. Average relative absorbed dose for all measurements on physicians for the different positions around the head compared with the average relative absorbed dose for all phantom measurements. Percentage of the sum of the absorbed dose in all dosimeters in the headband.

Discussion

Phantom measurements

The clear correlation between DAP value and absorbed dose to the right and left lens, respectively, indicates the possibility of estimating the dose to the lenses without performing specific point dose measurements, for a given procedure, i.e. that a factor between DAP value and dose to the lens could be found. This would be of great use since it means that time consuming measurements would not be needed at all times and yet an estimation of the dose to the physicians' eyes would be obtained. In this case such a factor for the left lens would be 0.070 m^{-2} and 0.055 m^{-2} for the right lens, which is a conversion between the DAP value in $mGym^2$ and the dose in mGy. The correlation between scattered dose to the eye (in μSv) and the DAP value (in $Gycm^2$) have been studied before[31], which also showed good linearity and a ratio of 7 μSv/$Gycm^2$. For the detector used the relation between the dose in Sv and the dose in Gy is one and thus 7 μSv/$Gycm^2$ corresponds to 0.070 mGy/$mGym^2$, which is consistent with the result from this study. However, the dose that is termed eye dose in the article[31] is measured with a SSD at a position typical of that of a cardiologists eyes during working conditions, i.e. no phantom was used. Consequently, this does not take scatter inside the head into account and do not correspond to the absorbed dose in the lens but rather that at the side of the head.

The achieved relative absorbed dose in the headband is as expected, with the highest doses at the anterior left part, from where the radiation strikes, and the lowest doses at the posterior right part, that is the most shielded. The TLDs in positions 1 and 2 corresponds to the lens doses in the right and left eye respectively. Comparing the dose to the TLD at the forehead with the TLD at the lens position, the dose in the lens is about 25 % higher than that of the forehead for both the right and left lens. Thus, a TLD positioned at the forehead would underestimate the dose to the lens of the eye with 25 %. The results of the Monte Carlo simulations differ and a reason for this could be that no image intensifier is present in the simulation geometry, and perhaps this is a significant source of scattered radiation. There are all reasons to believe in the experimental results. To underestimate the dose to the lens for the physicians could lead to serious consequences, especially if the threshold dose turns out to be lower than previously thought.

When protective goggle were used the absorbed dose to the left lens decreased with 21 % compared to when protective goggles were not used. However, the right lens dose increase with 5 % when protective goggles are put on. This is not expected, and the question is whether this is due to an actual increase of radiation reaching the lens, perhaps scattered from the goggles in some way, or if it is just the small difference of scattered radiation from the thorax phantom between the different measurements that give rise to this. This needs to be further investigated.

The SSD overestimates the dose if protective goggles are used with up to 25 % for both lenses. If protective goggles were not used however, the dose to the left lens was underestimated while the dose to the right lens was still overestimated. The large difference between the dose given from the SSD and the right and left lens respectively is due to the SSD being positioned at the left side of the head. The natural idea would be that the SSD therefore should give a more correct dose value for the left lens than for the right lens. However, in this case the SSD underestimates the lens dose to the left lens with 5 %, which is not desirable for a dosimeter. However, if protective goggles are not used this does not seem to be the case for the left lens.

The images from the film measurements reveal the dose distribution inside the head, and since the head phantom include both skull and sinuses it reflect the distribution in a human head well. Without protective goggles the highest absorbed dose is found at the left lens but there also seems to be a hot spot at the right lens. In a retrospective study the fact that the left lens receives a higher absorbed dose would show as a greater frequency of damage in the left lens than in the right, which would be interesting to investigate. Otherwise, the dose distributions inside the head look more or less as expected with higher doses at the anterior left part and lower at the posterior right part. The doses also are consistent with those from the headband.

When protective goggles were used the doses at the lens position in the film sheet located above the polyethylene disc were reduced but not for the film sheet located under the polyethylene disc. This effect is also shown in the position of the left lens. This is believed to be due to a suboptimal construction of the protective glasses. Radiation can slip through in the gap created between the glasses and the cheek and also at the nose, since the radiation strikes oblique from underneath. The design of protective goggles is especially important in situations were the radiation does not strikes direct from the front, such as this case. During interventional procedures the physicians are looking straight forward, on a screen, while the source, i.e. the patient, is underneath the physicians' head.

Not much can be said about comparisons with other studies since no one have investigated the absorbed dose to the lens in relation to the absorbed dose at the side of the head before now.

Simulations

The energy of the photons reaching the left lens is only slightly lower than the energy leaving the x-ray tube, so in other words not much energy is lost on the way towards the eye even though the photons have been scattered in the patient. This could be due to the position of the head relative to the position of the patient. In other words, the head is in such an angle that photons that get there will only have been scattered in a small angle, i.e. not lost very much energy. The measuring point at the forehead shows a greater absorbed dose than that in the lens, i.e. a TLD at the forehead would overestimate the dose to the lens. However, here the measuring point, that is supposed to simulate a TLD, consists of the same material as the lens so potential effects from the material are not accounted for. The simulations have been time consuming and it has not been possible to carry out as many simulations as desired during the time of this project. However, the impact of different positions of the lenses (depths) and the TLDs on the dose relationship are planned to be investigated. In difference to the phantom measurements no image intensifier is present and so also the significance of this should be investigated.

Measurements on physicians

The linear correlation between absorbed dose to the eye and DAP value for the clinical measurements are not as clear as it is for the phantom measurements. This could be due to the movement of the physicians or to the fact that the physicians are working in pairs during most procedures resulting in the dose to the TLDs does not correspond to the whole procedure. Alternately, one of them is working closest the patient while the other is standing behind, shielded from the radiation.

The relative absorbed dose in the headband correlates well with the phantom measurements, indicating that the individual movements of the physicians are not of major importance for the achieved dose distribution. Observations of the physicians during procedures also show that their heads are more or less in the same position during fluoroscopy since they are looking at the imaging screen, and the movement is foremost between the fluoroscopy sessions. One aspect that could potentially affect the outcome is the patient size since a large patient generates more scattered radiation than does a small. The thorax phantom used in the phantom measurements represents an average Asian male and is perhaps not comparable with the patients who underwent surgery during the measurement on the physicians. This has not been accounted for in this study.

Interconnection summary

The relation between lens dose and dose at a measuring point at either the forehead or the side of the head is not consistent between the different methods. The phantom measurements show a 25 % higher dose in the lens than at the forehead while the simulations show a 21 % lower dose in the lens than at the forehead. As mentioned the phantom measurements are considered as more credible. The SSD measurements show a 5 % higher dose in the lens than at the side of the head for the left eye but a 16 % lower dose in the lens for the right eye. Compared to the TLD at the forehead the underestimation of the dose to the right lens is lower which would mean that a SSD would be preferable for measuring the lens dose. However, if the limitations for a TLD at the forehead are known this could be accounted for at the readout. Regardless of what dosimeter that is selected it is important to be aware of the limitations of that particular dosimeter. It is also important to be consistent in where the dosimeter is placed.

The dose distributions from headband measurements on phantom as well as on physicians are consistent with the distribution from the film. The largest part of the radiation is deposited in the anterior left part of the head.

The correlation between patient dose and dose to the physicians are inconsistent for the phantom measurements and the measurements on physicians. This is as mentioned probably due to that the physicians work in pairs but perhaps measurements with only one physician participating would result in a better agreement. Regardless, a conversion factor based on phantom measurements would not underestimate the lens dose.

Conclusions

When the absorbed dose to the lens of the eye is measured today it is usually done by placing a dosimeter at the side of the head or at the forehead and the assumption is made that this corresponds to the dose in the lens. When an approximation is made it is important to know in which order the errors are introduced, in order to justify the approximation. This has most likely not been the case so far. This study shows that the dosimeters at the forehead underestimate the dose to the lens by 25 %. Consequently, the approximation that a TLD at the forehead corresponds to the lens dose is not good. This has to be considered when estimating the absorbed dose to the lens of the eye.

It seems to be a clear relationship between DAP value and dose to the physicians' eyes. This relationship is most clear for phantom measurements but it is possible that a factor that correlates well even for physicians could be found. The meaning of such a factor would be that a lot of time could be saved since an approximation of the lens dose could be made from the patient dose, given after each procedure, and therefore tedious measurements would not always be required. Perhaps measurements could be performed only for those who after this kind of approximation lie over a threshold level. This would be a very good tool to keep track of the dose received by the staff, which will be particularly important if dose limits for the eye is reduced.

The images given from the radiochromic film clearly visualizes the distribution of absorbed dose in the skull, which is focused on the front left side of the head, and thence the effect of protective goggles. They also show that the design of protective goggles is decisive, so that no radiation can slip through at any angle. In this study only one pair of goggles were tested but it would be interesting to compare several different models of various design.

To sum up

- a dosimeter at the forehead could underestimate the dose to the lens of the eye with as much as 25 %
- it is possible that a relation between patient dose (DAP) and absorbed dose to the physicians eyes could be found, which would mean that estimations of lens dose could be made without measurements
- the front left side of the head receives the largest part of the radiation in interventional radiology
- there are deficiencies in the design of protective goggles since radiation may slip through at several places

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