Occupational eye lens dose in endoscopic Retrograde Cholangiopancreatography using a dedicated eye lens dosimeter

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Keywords: Occupational Exposure; ERCP; eye lens; radiation protection; cataract

Abstract

Objectives

Increased X-ray exposure to physicians' eye lenses during radiology procedures is a significant concern. In this study, X-ray exposure to the eye was measured using an anthropomorphic head phantom, with and without radiation-protective devices, to examine the dose of X-ray radiation that physicians are exposed to during endoscopic retrograde cholangiopancreatography (ERCP).

Methods

X-ray exposure of the eye was measured using novel dedicated direct eye lens dosimeters that could specifically measure $H_p(3)$ during the ERCP procedure. The spatial dose in the height direction of the physician was measured using an ionization chamber dosimeter. Eye dosimeters were attached inside and outside the lead (Pb) glasses attached to the head of the human phantom to demonstrate its protective effect. Irradiation from the system lasted for 30 min.

Results

When the overcouch X-ray tube system is used, the cumulative radiation dose over the 30-min X-ray fluoroscopy time, without the use of radiation-protective devices, to the left and right eyes was 3.7 and 1.5 mSv, respectively. This dose was estimated to be the dose to the lens per therapeutic ERCP examination. With radiation-protective glasses, the dose reduced to 1.8 and 1.0 mSv for the left and right eye, respectively. The results of our study indicated that radiation exposure to the eye was reduced by up to 80.0% using Pb glasses and by 96.8% using radiation-protective curtains.

Conclusion

Our study indicates that a physician's maximum radiation exposure to the eyes during an ERCP procedure may be above the level recommended by the International Commission on Radiological Protection when the physician does not use radiation-protective devices. The eyewear, which is larger and fitted more closely to the face, provided a better protection effect even with a low lead equivalence, demonstrating that the shape of eyewear is important for protective function.

Introduction

The International Commission on Radiological Protection (ICRP) recommended in 2011 that the dose limit of the eye lens should not exceed 20 mSv on average for 5 years and 50 mSv per year [1]. This is based on the fact that the threshold dose for cataract is estimated at 0.5 Gy, based on recent epidemiological research and other results [2,3]. However, during interventional radiology (IR) and interventional cardiology procedures, physicians may be injured owing to prolonged exposure to X-ray radiation [3-7]. The radiography and fluoroscopy system with an X-ray tube above the patient table causes a higher amount of exposure to the upper body of the physician [8,9]. In Japan, most hospitals use an overcouch X-ray tube system because upper gastrointestinal series using barium is still performed today. The advantage of the overcouch X-ray tube system is that the flat panel detector is positioned under the table, so there is no contact between the patient and the system. Since the X-ray tube is above the table and there are many scattered rays around the upper body, there is concern about the exposure dose to the eye lens. Moreover, this system with an X-ray tube is often used in nonvascular fluoroscopy-guided interventional procedures. Since endoscopic retrograde cholangiopancreatography (ERCP) is often diagnosed and treated, X-ray fluoroscopy time tends to be longer. Therefore, the actual exposure of medical staff during ERCP has been reported in many previous studies. [10,11]. In particular, the overcouch X-ray system may result in a higher occupational lens dose exposure than the undercouch X-ray system [12]. The ICRP operational quantity $H_p(3)$ is used to monitor doses to the lens of the eye [13].In ICRP Publication 139, the undercouch X-ray system is recommended for use as it can reduce the physician's eye lens dose by 2 to 27 times compared to the overcouch X-ray system [14]. The eye dosimeter is a useful solution for estimating $H_p(3)$, and it can be worn behind lead glasses. In addition, this dosimeter has good fundamental characteristics (batch uniformity, dose linearity, energy dependence, and angular dependence) in the diagnostic X-ray energy domain [15]. This dosimeter can evaluate the exposure dose to the lens of the operator in IR based on $H_p(3)$ and can control the threshold dose of cataract in detail [16-18]. Furthermore, scattered X-rays in IR can be reduced using radiological protection equipment, such as lead (Pb) glasses and radiation-protective curtains [19-22]. Typical ceiling-suspended lead screens have only one shielding direction and do not provide any protection if the user is outside the shielded field. Radiation-protective curtains can shield scattered radiation in four directions, thus providing shielding for the entire field. Moreover, since the protection provided by lead glasses depends on the angle at which scatter from the patient is incident on the head, the X-ray beams incident from the side and below the level of the head should be taken into account during assessment of the eye lens dose. The size of the lenses, use of side shields for glasses with flat lenses, and closeness of the fit to the facial contours are all important in determining the extent of protection provided [14].

In this study, we aimed to measure the lens-equivalent dose in nonvascular fluoroscopy using the radiography and fluoroscopy system with the X-ray tube above the patient table, which is considered to be exposed to the lenses in detail, using 3-mm equivalent dosimeters. We also examined whether the use of radiological protection equipment such as Pb glasses and radiation-protective curtains on the X-ray equipment reduced physicians' exposure to scattered X-rays.

Materials and Methods

Experimental design

In this study, we measured the lens-equivalent dose for physicians using a whole-body phantom (PBU – 60; Kyoto Kagaku) and head phantom (Kyoto Kagaku) as a simulated patient and a simulated physician, respectively. The height of the patient's table was set to 85 cm, and the whole-body phantom was laid on the table. The standing position of the physician was 60 cm from the X-ray irradiation center in the direction of the head side at 45° of the simulated patient. This position makes it easy for the physician to insert the endoscope into the patient's mouth. A nonvascular fluoroscopy device (ZEXIA DREX-ZX80; TOSHIBA Co.) was used as the flat-panel imaging system for radiography and fluoroscopy. The air kerma rate was measured with a cylinder Stem Ionization Chamber (Type23361; PTW) and an electrometer (Type520; EMF). The radiation dose to the eye lens was measured with an eye dosimeter (DOSIRIS; Chiyoda-Technol), which specifically measured the eye lens dose [$H_p(3)$]. The eye dosimeter consisted of a thermoluminescent dosimeter sensor (7 LiF:Mg, Ti), plastic capsule, and adjustable headset. The commercial neck personal dosimeter used was a silver-activated phosphate glass dosimeter (Glass Badge; Chiyoda-Technol), which was worn on the left side of the neck.

Scattered X-ray dose at the physician's standing position

The scattered X-ray dose was measured as the cumulative radiation dose for 1 min at the position of the physician at a height of 60–200 cm above the floor at 10-cm intervals using an ionization chamber dosimeter at the same time. The X-ray irradiation condition was set to auto mode, and the field of view (FOV) was set to a square of 28 × 28 cm.

The source-to-image distance (SID) was 114 cm. The X-ray irradiation center was set on the liver of the whole-body phantom.

Measurement of lens-equivalent dose using dosimeters

The physician’s lens-equivalent dose was measured using the eye dosimeter (DOSIRIS) and the neck dosimeter (glass badge). DOSIRIS was attached to the eyes of the head phantom, and the neck dosimeter was attached to the left side of the neck (Figure 1 A). DOSIRIS measurements were compared between the left and right sides. In addition, the extent to which the measured values for DOSIRIS and the neck dosimeter differed was verified. The direction of the head phantom was tilted 45° toward the head side with respect to the patient table. The position of the lens was similar to the previous experiment (160 cm from the floor), whereas the radiography and fluoroscopy system was set to a height of 85 cm from the floor to the bed, an SID of 114 cm, and an FOV of 28 × 28 cm. This position is the home position of this system, and the ERCP procedure is usually performed at this position at our group hospital. Also, the X-ray fluoroscopy time during ERCP at this hospital averaged at 32.8 min in 22 cases. ERCP involves diagnosis, followed by therapy, such as endoscopic nasobiliary drainage and endoscopic lithotripsy. Table 1 shows the exposure conditions of the fluoroscopy program used in this study. The examination model was ERCP, which tends to increase the X-ray irradiation time to develop into treatment. The whole-body phantom was irradiated with X-rays for 30 min. The measurements were repeated five times. New dosimeters were used each time, and the average was calculated.

Reduction effect using radiation-protection devices

Two types of Pb glasses (PT-53 0.75-mm Pb; Maeda and HF-350 0.07-mm Pb; Hoshina) were used to evaluate the effect of radiological protection equipment on eye exposure. Figure 2 shows the shape of each of the Pb glasses. DOSIRIS was set inside the Pb glasses against the left and right eyes to measure the dose to the eyes (Figure 1 B). Furthermore, the effect of radiation-protective curtains (NP 0.25-mm Pb), which could reduce scattered radiation from the phantom, was also evaluated. The curtains were attached to the X-ray tube (as shown in figure 1 C), and the dose to the eyes was measured using the same method. Since the radiation-protective curtains cover only the area just below the X-ray tube, they do not interfere with the ERCP procedure. Furthermore, the curtains have a slit at the bottom; thus, there is little contact between the curtains and the patient.

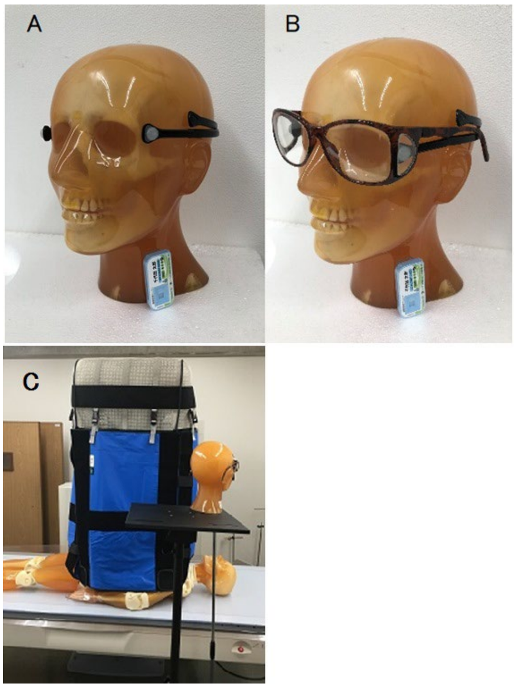

Figure 1 Positions of the dosimeters used during the procedures

A: The eye dosimeter (DOSIRIS) is attached outside to both eyes, and the personal dosimeter is attached on the left side of the neck. B: An additional eye dosimeter (DOSIRIS) is attached outside the Pb glasses, close to both eyes. C: Radiation-protective curtains are attached to the X-ray tube on four sides.

Table 1 Exposure conditions of the fluoroscopy program

KAP (Gy cm^2)	237
ESD (mGy)	547
Voltage (kV)	105
Current (mA)	2.3
Exposure time (min)	30
Total tube current–time product (mAs)	4,140
SID (cm)	115
FOV (cm)	28×28
Table height (cm)	85

KAP: Kerma-Area Product
ESD: Entrance Surface Dose
SID: Source-to-Image Distance
FOV: Field of View

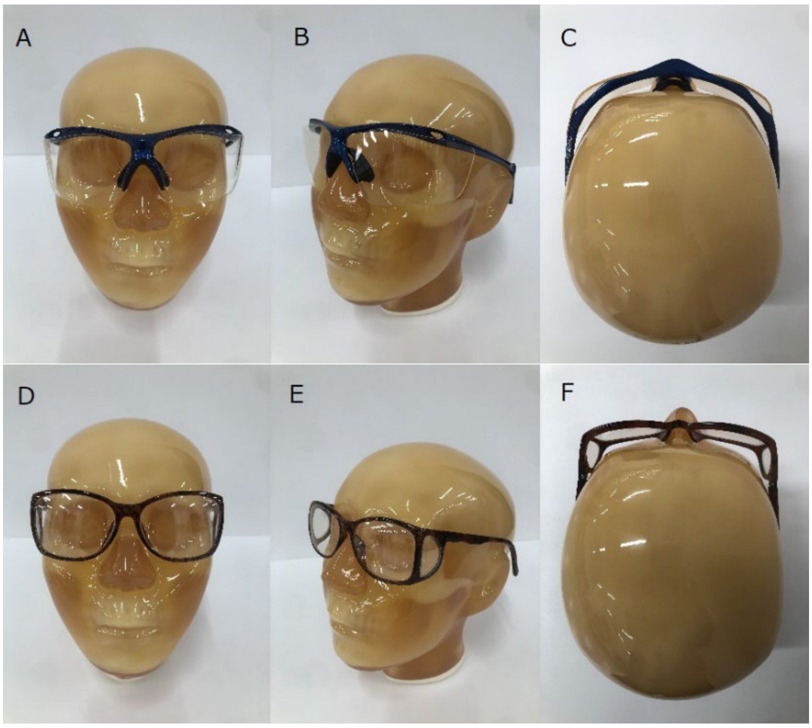

Figure 2 Different shapes of Pb glasses

A–C: 0.07-mm Pb glasses (W 5.5 cm × L 6.0 cm × D 4.5 cm). The shape of the lens of the glasses is curved to match the shape of the face. This shape has almost no gap between the lens and the face.

D–F: 0.75-mm Pb glasses (W 4.5 cm × L 5.5 cm × D 2.0 cm). The shape of the lens and frame of the glasses are straight, and the glasses have a gap between them and the face.

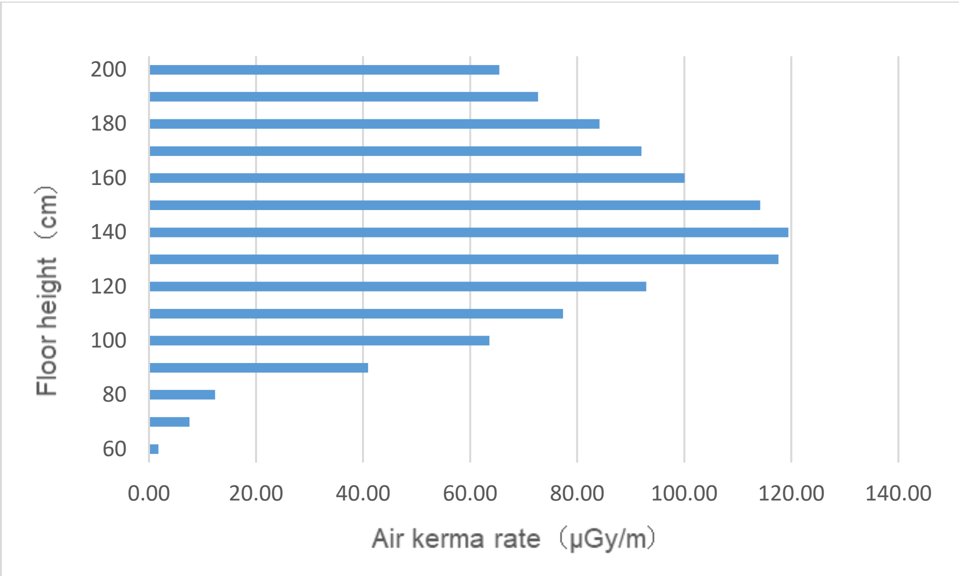

Figure 3 Scattered X-ray dose at the standing position of the physician

A dose of 60–200 cm from the floor was measured as the air kerma rate in the standing position of the physician. The air kerma rate was measured at 10-cm-height intervals for 1 min.

Statistical analysis

Welch's t-test was used to compare the data of the eye dosimeters [$H_p(3)$] of the left and right and the data of the neck badge [$H_p(10)$, $H_p(0.07)$]. Further, the Games–Howell test was used to conduct multiple comparisons between doses to the eye dosimeters and the neck dosimeter. Statistical significance was set at $p < 0.05$. Data processing and statistical analyses were performed using Statistical Package for the Social Sciences, version 19.0.

Results

Scattered X-ray doses at the physician's standing position

Figure 3 shows the scattered X-ray dose in the standing position of the physician. The scattered X-ray dose showed a low value of 12.34 μGy/min at a height of 80 cm from the floor and linearly increased from 90 to 130 cm. Scattered X-ray doses peaked at 140 cm and then linearly decreased.

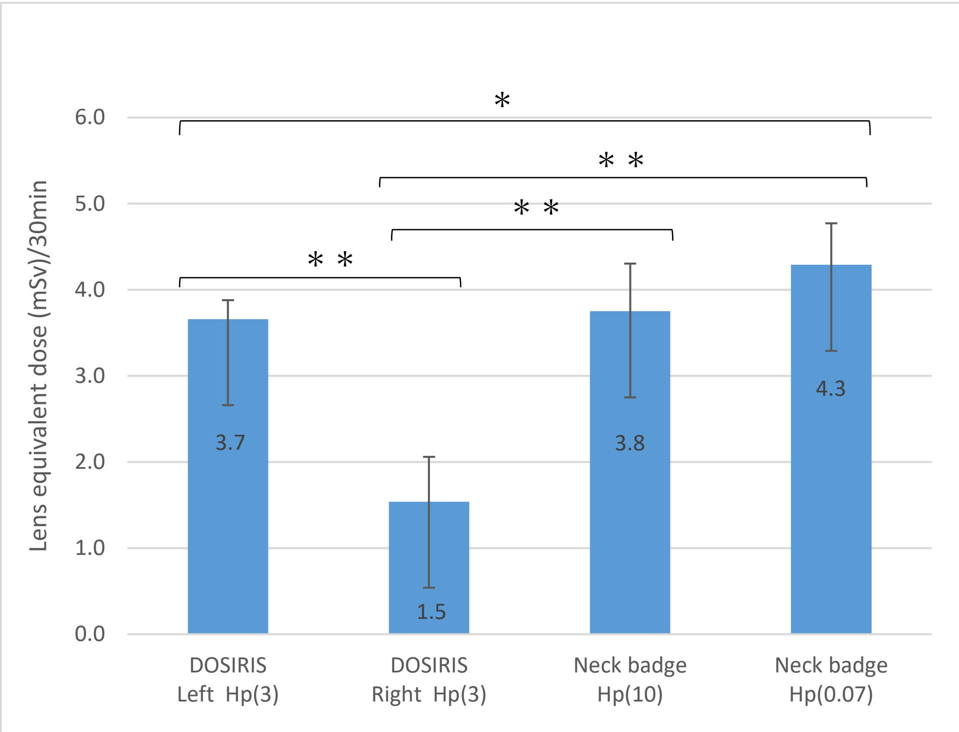

Figure 4 Correlation between DOSIRIS and neck badge

Estimated mean ± SD dose measurements using DOSIRIS and neck badge The neck badge measured $H_p(10)$ and $H_p(0.07)$. DOSIRIS Left $H_p(3)$ is attached closer to the X-ray tube than Right $H_p(3)$. A paired t-test was performed to analyze each dose of DOSIRIS and neck badge. (* $p<005$, ** $P<0.01$)

Table 2 Reduction effect of scattered X-ray doses using two types of Pb glasses

Estimated mean ± SD dose measurements using no lead glasses and attached 0.07-mm Pb and 0.75-mm Pb glasses. The dose reduction rate indicates a reduction in the dose when Pb glasses are donned.

Eye	Glass type	Lens-equivalent dose (mSv)/30 min	Dose reduction rate (%)
Left	No lead glasses	3.7 ± 0.19	-
	0.07-mm Pb glasses	1.6 ± 0.47	56.8
	0.75-mm Pb glasses	1.8 ± 0.40	51.4
Right	No lead glasses	1.5 ± 0.52	-
	0.07-mm Pb glasses	0.3 ± 0.11	80.0
	0.75-mm Pb glasses	1.0 ± 0.23	33.3

Measurement of lens-equivalent doses using dosimeters

Figure 4 shows the average value of the physicians' eye dose when the whole-body phantom was irradiated with X-rays for 30 min during ERCP using the overcouch X-ray tube system. The value of each dosimeter showed the highest value for the neck badge [$H_p(0.07)$]. The dose measured using DOSIRIS for the left eye was not significantly different from the measurements made with the neck dosimeter. However, the dose to the right eye was substantially lower.

Protective effects using radiation-protection devices

Table 2 shows the average value of the eye dose when two types of radiation-protective Pb glasses were donned, indicating that the glasses could attenuate the dose to both eyes. The dose reduction rate in the left eye was higher for the 0.07-mm Pb glasses with a curved lens shape and larger area than for the 0.75-mm Pb glasses with a straight lens shape and smaller area. The 0.07-mm Pb glasses had a much higher dose reduction than the 0.75-mm Pb glasses, even in the right eye.

The eye dose when the radiation-protective curtain was attached to the X-ray tube showed a detection limit of 0.1 mSv for the left eye and was less than the detection limit for the right eye. The reduction in scattered X-rays was 96.8% with the left eye when fitted with the radiation-protective curtain.

Discussion

In this study, there was no significant difference in the measured values when the exposure to the lens was measured using a lens dosimeter or a neck personal dosimeter. It has been shown that radiation-protective devices such as radiation-protective lead glasses and scattered radiation-protective curtains can significantly reduce IR physicians' exposure.

For the examination model as ERCP, the scattered X-ray dose at the position of the physician was the maximum at a height of 140 cm from the floor, probably influenced by backscattered X-rays from the whole-body phantom. It is thought that when a whole-body phantom with a body thickness of 20 cm is irradiated with X-rays, the ratio of back scattering is higher [23]. Scattered X-rays are also generated from the acryl plate of the irradiation window of the X-ray tube [24]. This height corresponds to the thyroid gland because the average height of Japanese men is 171 cm [25]. Our results based on ERCP simulation using the overcouch X-ray tube system may indicate the risk of cataract since the dose to the physician's eyes during the irradiation to the whole-body phantom for 30 min ranged from 1.5 to 3.7 mSv. O'Connor et al. state that the mean equivalent dose to the lens of the eye of a gastroenterologist is 0.01 mSv per ERCP procedure with an undercouch X-ray tube and 0.09 mSv per ERCP procedure with an overcouch X-ray tube. However, the fluoroscopy time for this study was 225 s and 87 s in the two hospitals [10]. Zagorska et al. report that the fluoroscopy time varied from 1.0 min to 28.8 min owing to the different complexities of ERCP procedures [11]. This means that our study estimated the maximum dose to the physician's eyes during an ERCP procedure. However, in our study, KAP was higher than the national diagnostic reference levels for ERCP in Japan, which may have increased the physician's lens dose. The dose to the left eye using the overcouch X-ray tube system (3.7 mSv) corresponded to 7.4% of the maximum annual limit proposed by ICRP (50 mSv); therefore, the total dose can reach the proposed dose if ERCP is performed 14 or more times a year. The reason the dose to the left eye was high could be explained as follows: the left eye was closer to the irradiation center than the right eye in the phantom head setting with 45° rotation in our study (Figure 2). In our study, the lens-equivalent dose was measured using Pb glasses of two kinds of lead equivalent. Pb glasses with a small lead equivalent are advantageous because of their light weight. Originally, the radiation-scattering reduction rate was expected to be higher for Pb glasses with a larger lead equivalence [26]. However, in this study, 0.07-mm Pb glasses showed higher scattered ray reduction rates than 0.75-mm Pb glasses in both eyes. This is related to the difference in the shape of the glasses. Dorey et al. proposed an important observation, i.e., the increased dose rate the clinician's eyes receive despite wearing Pb glasses, as the angle of gaze moves to 45° and 90° from 0° toward the scattering source. The gap between Pb glasses and the skin becomes wider as the angle of gaze increases, allowing more scattered X-rays to enter the eye [27]. The lens and frame of 0.75-mm Pb glasses are flat and straight; therefore, the gap between these glasses and face/eyes is wider than that between the face/eyes and 0.07-mm Pb glasses, which are curved to fit the face, resulting in less gas between the glasses and face/eyes. Our study indicated that the shape of the frame and lens is also critical in reducing the scattered radiation to the eyes, although lead thickness is important for providing better protection. The scattering X-ray reduction rate reduced to 33.3%–80.0% by attaching the Pb glasses in our study. The results of this study are similar to those of previous studies [28-30]. Moreover, 96.8% of the scattered X-rays were reduced when the radiation-protective curtains were attached to the X-ray tube. Our study results were similar to those of Minami et al., who reported similar radiation reduction effects using radiation-protective curtains [31,32]. In fact, radiation-protective curtains were not particularly obstacles in helping physicians perform ERCP examinations, which do not require sterile conditions. Although radiation-protective curtains provide higher protection against scattered X-rays than Pb glasses, they are not very popular because they are expensive.

In this study, the physician's lens-equivalent dose during ERCP was estimated using the overcouch-type X-ray television system, which is said to project more X-ray doses to the physician's upper body. As a result, we clarified that the lens-equivalent dose during each ERCP examination shows a very high proportion to the annual lens-equivalent dose recommended by the IRCP, and we also warned against cataract risk. As a precautionary measure, the use of Pb glasses and especially radiation-protective curtains is highly effective in reducing scattered X-rays; thus, we recommend using these. In addition, since the undercouch X-ray tube system has been shown to reduce the exposure dose to the upper body of the physician, the introduction of these systems is recommended in the future.

Our study had several limitations. First, during an actual examination, the physician needs to turn their face in different directions; however, these effects were not included in this study because the physician will move their face but should, in fact, be looking at the TV monitor during X-ray irradiation. Second, although the size of the X-ray irradiation field changes depending on the situation, this measurement was performed with only a 28 × 28-cm FOV. In the future, we will attempt to verify the effect of the angle of the physician's face on the reduction of the lens dose.

Conclusion

Our study showed that the lens-equivalent dose reduced by up to 80.0% when using Pb glasses and by 96.8% when using radiation-protective curtains. The eyewear that is larger and fitted more closely to the face provided a better protection effect even with a low lead equivalence, demonstrating that the shape of eyewear is important for protective function.

ERCP with the overcouch X-ray tube system is associated with the risk of cataract when performed several times without the use of radiation-protective equipment.

Thus, we recommend using Pb glasses, especially radiation-protective curtains, owing to their extremely high scattered radiation reduction effect.

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Ethical statement

Institutional Review Board approval was not required because this study was a phantom study.

References

1. Commission on Radiological Protection, 2011. Statement on tissue reactions. *ICRP*, *4825*.
2. Nations Scientific Committee on the Effects of Atomic Radiation, 2017. UNSCEAR 2016 Report—Sources, Effects and Risks of Ionizing Radiation. *Report to the General Assembly. Scientific Annexes A, B, C, and D. Available on http://www. unscear. org/unscear/en/publications/2016. html.(accessed 15 Oct 2017)*.
3. Valentin, J., 2000. Avoidance of radiation injuries from medical interventional procedures, ICRP Publication 85. *Annals of the ICRP*, *30*(2), pp.7-7.
4. Haga, Y., Chida, K., Kaga, Y., Sota, M., Meguro, T. and Zuguchi, M., 2017. Occupational eye dose in interventional cardiology procedures. *Scientific Reports*, *7*(1), pp.1-7.
5. Balter, S. and Miller, D.L., 2014. Patient skin reactions from interventional fluoroscopy procedures. *American Journal of Roentgenology*, *202*(4), pp.W335-W342.
6. Chida, K., Inaba, Y., Saito, H., Ishibashi, T., Takahashi, S., Kohzuki, M. and Zuguchi, M., 2009. Radiation dose of interventional radiology system using a flat-panel detector. *American Journal of Roentgenology*, *193*(6), pp.1680-1685.
7. Inaba, Y., Chida, K., Kobayashi, R. and Zuguchi, M., 2016. A cross-sectional study of the radiation dose and image quality of X-ray equipment used in IVR. *Journal of applied clinical medical physics*, *17*(4), pp.391-401.

8. Blanchette, J. and Renaud, L., 1992. Radioexposure levels observed with sub-optimal fluoroscopic systems. *The Canadian journal of medical radiation technology*, *23*(4), pp.187-192.
9. Garg, M.S., Patel, P., Blackwood, M., Munigala, S., Thakkar, P., Field, J., Wallace, D., Agarwal, S., Aoun, E., Kulkarni, A. and Dhawan, M., 2017. Ocular radiation threshold projection based off of fluoroscopy time during ERCP. *American Journal of Gastroenterology*, *112*(5), pp.716-721.
10. Zagorska, A., Romanova, K., Hristova-Popova, J., Vassileva, J., Katzarov, K., 2015. Eye lens exposure to medical staff during endoscopic retrograde cholangiopancreatography. *Physica Medica, 31*(*7)*, pp.781-784.
11. O'Connor, U., Gallagher, A., Malone, L., O'Reilly, G., 2013. Occupational radiation dose to eyes from endoscopic retrograde cholangiopancreatography procedures in light of the revised eye lens dose limit from the International Commission on Radiological Protection. *The British Journal of Radiology, 86*(1022):20120289.
12. Staniszewska, M.A., Kujawski, K., Kopec, R. and Sasak, K., 2017. ERCP procedures as a source of radiation risk to a single gastroenterologist. *Medycyna Pracy*, *68*(6), pp.735-742.
13. International Commission on Radiological Units, 1993. Quantities and units in radiation protection dosimetry. *ICRU Report no. 51*. Bethesda, ICRU.
14. P Ortiz López, L T Dauer, R Loose, C J Martin, D L Miller, E Vañó, M Doruff, R Padovani, G Massera, C Yoder., 2018. ICRP Publication 139: Occupational Radiological Protection in Interventional Procedures. *Ann ICRP,* 47(2), pp.1-118.

15. Ishii, H., Haga, Y., Sota, M., Inaba, Y., Chida, K., 2019. Performance of the DOSIRIS™ eye lens dosimeter. *Journal of Radiological Protection39*(3), N19-26.
16. Barnard, S.G., Ainsbury, E.A., Quinlan, R.A. and Bouffler, S.D., 2016. Radiation protection of the eye lens in medical workers—basis and impact of the ICRP recommendations. *The British journal of radiology*, *89*(1060), p.20151034.
17. Matsubara, K., Lertsuwunseri, V., Srimahachota, S., Krisanachinda, A., Tulvatana, W., Khambhiphant, B., Sudchai, W. and Rehani, M., 2017. Eye lens dosimetry and the study on radiation cataract in interventional cardiologists. *Physica Medica*, *44*, pp.232-235.
18. Guberina, N., Dietrich, U., Forsting, M. and Ringelstein, A., 2018. Comparison of eye-lens doses imparted during interventional and non-interventional neuroimaging techniques for assessment of intracranial aneurysms. *Journal of NeuroInterventional Surgery*, *10*(2), pp.168-170.
19. Tavares, J.B., Sacadura-Leite, E., Matoso, T., Neto, L.L., Biscoito, L., Campos, J. and Sousa-Uva, A., 2016. The importance of protection glasses during neuroangiographies: a study on radiation exposure at the lens of the primary operator. *Interventional Neuroradiology*, *22*(3), pp.368-371.
20. Grabowicz, W., Domienik-Andrzejewska, J., Masiarek, K., Górnik, T., Grycewicz, T., Brodecki, M. and Lubiński, A., 2017. Effectiveness of pelvic lead blanket to reduce the doses to eye lens and hands of interventional cardiologists and assistant nurses. *Journal of Radiological Protection*, *37*(3), p.715.
21. Domienik, J., Bissinger, A., Grabowicz, W., Kręcki, R., Makowski, M., Masiarek, K., Plewka, M., Lubiński, A. and Peruga, J.Z., 2016. The impact of various

protective tools on the dose reduction in the eye lens in an interventional cardiology—clinical study. *Journal of Radiological Protection*, *36*(2), p.309.

22. Bertolini, M., Benecchi, G., Amici, M., Piola, A., Piccagli, V., Giordano, C. and Nocetti, L., 2016. Attenuation assessment of medical protective eyewear: the AVEN experience. *Journal of Radiological Protection*, *36*(2), p.279.
23. Xiong, Z., Vijayan, S., Rudin, S. and Bednarek, D.R., 2017, March. Monte Carlo investigation of backscatter point spread function for x-ray imaging examinations. In *Medical Imaging 2017: Physics of Medical Imaging* (Vol. 10132, p. 1013243). International Society for Optics and Photonics.
24. Tachibana, M., Izumi, T. and Yoshinaka, M., 2002. Absorption and scatter with an acrylic plate attached to the front of an X-ray beam limiting device. *Nihon Hoshasen Gijutsu Gakkai Zasshi*, *58*(7), pp.931-939.
25. Ministry of Health, Labour and Welfare (2017) National Health and Nutrition Survey. https://www.e-stat.go.jp/dbview?sid=0003224177 Accessed 02 Mar 2020
26. da Silva, E.H., Martin, C.J., Vanhavere, F., Buls, N., 2020. A study of the underestimation of eye lens dose with current eye dosimeters for interventional clinicians wearing lead glasses. *Journal of Radiological Protection, 40*(1), pp.215-224.
27. Dorey, S., Gray, L., Tootell, A., Higgins, R., Al-Islam, S., Baxter, H., Dixon, P., Hogg, P., 2019. Radiation protection value to the operator from augmented reality smart glasses in interventional fluoroscopy procedures using phantoms. *Radiography (Lond) 25*(4), pp.301-307.
28. Tavares, J.B., Sacadura-Leite, E., Matoso, T., Neto, L.L., Biscoito, L., Campos, J. and Sousa-Uva, A., 2016. The importance of protection glasses during

neuroangiographies: a study on radiation exposure at the lens of the primary operator. *Interventional Neuroradiology*, *22*(3), pp.368-371.

29. Martin, C.J., Magee, J.S., Sandblom, V., Almén, A. and Lundh, C., 2015. Eye dosimetry and protective eyewear for interventional clinicians. *Radiation Protection Dosimetry*, *165*(1-4), pp.284-288.
30. Thornton, R.H., Dauer, L.T., Altamirano, J.P., Alvarado, K.J., Germain, J.S. and Solomon, S.B., 2010. Comparing strategies for operator eye protection in the interventional radiology suite. *Journal of Vascular and Interventional Radiology*, *21*(11), pp.1703-1707.
31. Inoue, T., Komemushi, A., Murota, T., Yoshida, T., Taguchi, M., Kinoshita, H. and Matsuda, T., 2017. Effect of protective lead curtains on scattered radiation exposure to the operator during ureteroscopy for stone disease: a controlled trial. *Urology*, *109*, pp.60-66.
32. Minami, T., Sasaki, T., Serikawa, M., Kamigaki, M., Yukutake, M., Ishigaki, T., Ishii, Y., Mouri, T., Yoshimi, S., Shimizu, A. and Tsuboi, T., 2014. Occupational radiation exposure during endoscopic retrograde cholangiopancreatography and usefulness of radiation protective curtains. *Gastroenterology Research and Practice*, *2014*.