Accepted Manuscript online: 2023-01-30 Article published online: 2023-03-08

Occupational radiation dose from gastrointestinal endoscopy procedures with special emphasis on eye lens doses in endoscopic retrograde cholangiopancreatography

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submitted 12.1.2023
accepted after revision 25.1.2023
published online 30.1.2023

Bibliography
Endosc Int Open 2023; 11: E237–E246
DOI 10.1055/a-2022-2663
ISSN 2364-3722

Georg Thieme Verlag KG, Rüdigerstraße 14,
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Supplementary material is available under https://doi.org/10.1055/a-2022-2663

ABSTRACT

Background and study aims Endoscopic retrograde cholangiopancreatography (ERCP) procedures may result in remarkable radiation doses to patients and staff. The aim of this prospective study was to determine occupational exposures in gastrointestinal endoscopy procedures, with a special emphasis on eye lens dose in ERCP.

Methods Altogether 604 fluoroscopy-guided procedures, of which 560 were ERCPs belonging to four American Society for Gastrointestinal Endoscopy procedural complexity levels, were performed using two fluoroscopy systems. Personal deep-dose equivalent $H_p(10)$, shallow-dose equivalent $H_p(0.07)$, and eye lens dose equivalent $H_p(3)$ of eight interventionists and $H_p(3)$ for two nurse dosimeters were measured. Thereafter, conversion coefficients from kerma-area product (KAP) for $H_p(10)$, $H_p(0.07)$, and $H_p(3)$ were determined and dose equivalents per procedure to an operator and assisting staff were estimated. Further, mean conversion factors from $H_p(10)$ and $H_p(0.07)$ to $H_p(3)$ were calculated.

Results The median KAP in ERCP was 1.0 Gy·cm^2, with mobile c-arm yielding higher doses than a floor-mounted device ($P<0.001$). The median $H_p(3)$ per ERCP was estimated to be 0.6 µSv (max. 12.5 µSv) and 0.4 µSv (max. 12.2 µSv) for operators and assisting staff, respectively. The median $H_p(10)$ and $H_p(0.07)$ per procedure ranged from 0.6 to 1.8 µSv. ERCP procedural complexity level ($P\leq0.002$) and interventionist ($P<0.001$) affected dose equivalents.

Conclusions Occupational dose limits are unlikely to be exceeded in gastrointestinal endoscopy practice when following radiation-hygienic working methods and focusing on dose optimization. The eye lens dose equivalent $H_p(3)$ may be estimated with sufficient agreement from the $H_p(10)$ and $H_p(0.07)$.

Introduction

Endoscopic retrograde cholangiopancreatography (ERCP) is a common interventional procedure used for examination and treatment of the pancreatic and bile ducts. In addition to endoscopy, ERCP utilizes ionizing radiation, which is harmful to health. Therefore, various dose-optimization methods to reduce radiation burden both to the patient and personnel are required. The risk of stochastic effects (e. g., cancer) is assumed to increase linearly with radiation dose [1–3].

Ionizing radiation may also cause cataract, a clouding of the normally clear lens of the eye. Due to recently updated radiosensitivity knowledge of various tissues, the dose limit for the lens of the eye for occupational exposure in planned exposure settings was reduced from 150 mSv/year to 20 mSv/year, averaged over 5 years, with no annual dose in a single year exceeding 50 mSv [4–6]. Some of the most recent epidemiological studies have indicated that the radiation-induced cataract has a lower threshold dose than previously expected or could, similarly to radiation-induced cancer, even be a stochastic harmful effect of ionizing radiation and follow the linear no-threshold model [7–11]. There is a higher prevalence of radiation-induced cataract among staff working with higher radiation levels, such as cardiologists and interventional radiologists, than in normal population and reference groups [10, 12, 13]. Previous studies have shown occupational radiation dose to eyes to vary in ERCP from 10 to >100 µSv, depending especially on operator, the fluoroscopy system used, and x-ray tube position during the procedure [14–16]. Some studies have also anticipated that the annual dose limits for eye lenses could be exceeded in medical staff who frequently perform ERCP procedures [15–17].

The aim of this prospective study was to determine occupational radiation doses in gastrointestinal endoscopy procedures, with special emphasis on eye lens doses in ERCP. The study also produced mean conversion coefficients from kerma-area product (KAP) to $H_p(10)$, KAP to $H_p(0.07)$, and KAP to $H_p(3)$ and further from personal dose equivalents $H_p(10)$ and $H_p(0.07)$ to $H_p(3)$. These conversion coefficients were determined for the purpose of possibly estimating e. g., eye lens dose without a dedicated eye dosimeter.

Methods

Study design and population

This prospective observational study to determine occupational radiation doses was performed at the Helsinki University Hospital Endoscopy department between March 2021 and July 2021. The COVID-19 pandemic did not affect the number or type of performed procedures. Altogether 604 consecutive fluoroscopy-guided procedures to patients were included in the study. From these interventions, 560 were ERCPs and 44 were other gastrointestinal endoscopy procedures, such as duodenal stentings or dilatations of anastomotic strictures. Personal dose equivalents $H_p(10)$, $H_p(0.07)$, and $H_p(3)$ for four gastrointestinal surgeons (S1-S4) and four gastroenterologists (G1-G4) and for assisting nurses (N_Zee and N_Cios) were measured using thermoluminescent dosimeters (TLD) and direct-ion storage dosimeters (DIS). Details of dosimetry practices and dose uncertainty estimation are provided as supplementary material. In the endoscopy department, ERCPs for diagnosis and follow up of primary sclerosing cholangitis (PSC) and dilatations and stentings for these patients are performed by gastroenterologists; surgeons perform all other ERCP procedures. Distributions of the performed and assisted procedures by endoscopist and assisting nurse are given in Table 1 s (supplementary materials). The study was approved by the Institutional Review Board and no patient informed consent was required.

Endoscopy suite

All procedures were performed using CO_2 insufflation with the patient in prone or left lateral decubitus position under conscious sedation controlled by an anesthesiologist and a nurse. The study procedures were performed using a floor-mounted Siemens Artis zee multi-purpose (MP) fluoroscopy system (Siemens Healthcare, Erlangen, Germany) or a mobile Siemens Cios Alpha c-arm device (Siemens Healthcare, Erlangen, Germany). Fixed, mobile, and ceiling-mounted radiation shields and personal protective equipment, such as protective aprons, thyroid shields, and leaded eyewear were used during all the procedures. A more detailed description of the imaging protocols and radiation protection tools implemented is provided as supplementary material.

Other data collected for each procedure included patient characteristics (age, height, weight, and body mass index [BMI]), fluoroscopy time, KAP, and air-kerma at reference point ($K_{a,r}$). Moreover, the procedural complexity of each ERCP was determined and collected based on the 4-point American Society for Gastrointestinal Endoscopy (ASGE) complexity-grading system [18, 19]. The radiation doses in ERCP and other gastrointestinal endoscopy procedures were compared. ERCPs performed for diagnosis and follow up of PSC included a significantly larger number of single image exposures compared to other ERCPs and were thus categorized separately. The effect of ERCP procedural complexity level and fluoroscopy system on radiation doses was then analyzed.

Statistical analysis

The data are presented as median (interquartile range [IQR], i. e., first quartile – third quartile). To compare categorical and continuous variables between patient characteristics, procedure types, fluoroscopy systems, ERCP procedural complexity levels, and interventionists, either Fisher's Exact test or Mann-Whitney *U*-test and Kruskal-Wallis test were used, respectively. All statistical tests were two-sided, and a $P<0.05$ was considered significant. Statistical analysis was performed with SPSS statistical software (IBM, Armonk, New York, United States, version 25.0).

▶ **Table 1** Selected patient characteristics provided as medians (IQR, i. e. first quartile – third quartile) unless otherwise indicated.

Variable	Patients in ERCP w/o PSC (n = 424)	Patients in ERCP PSC (n = 136)	Patients in other GE procedures (n = 44)	*P* value
Age, years	65 (54–75)	37 (30–47)	69 (54–76)	< 0.001
Sex, male; n (%)	225 (53.1)	81 (59.6)	29 (65.9)	0.146
Height, cm	170 (162–178)	176 (169–182)	170 (165–178)	< 0.001
Weight, kg	74 (63–86)	77 (68–86)	73 (57–80)	0.049
BMI, kg/m^2	25.5 (22.2–28.3)	24.7 (22.6–28.6)	23.6 (21.5–27.7)	0.156

BMI: body mass index; ERCP: endoscopic retrograde cholangiopancreatography; GE: gastrointestinal endoscopy; PSC: primary sclerosing cholangitis

Results

Clinical features of patients

Patient characteristics are summarized in ▶ **Table 1**. Patient age ranged from 0 to 97 years and BMI from 14.5 to 48.1 kg/m^2. Patients in the PSC ERCP group were significantly younger (P< 0.001), taller (P<0.001), and somewhat heavier (P=0.049) than patients in other groups. No other statistically significant differences in patient characteristics were observed between the procedure types.

Radiation dose indices and fluoroscopy times of the procedures

▶ **Table 2** (and Fig. 1s in supplementary materials) summarizes the radiation dose indices and fluoroscopy times of the procedures. The accumulated KAP varied from 0.01 to 22.89 Gy·cm^2 in non-PSC ERCPs, from 0.26 to 12.04 Gy·cm^2 in PSC ERCPs, and from 0.01 to 6.57 Gy·cm^2 in other gastrointestinal endoscopic x-ray interventions. The PSC ERCPs resulted in significantly higher KAP, $K_{a,r}$, and fluoroscopy times and contained more single image acquisitions compared to other interventions (P< 0.001). The study $K_{a,r}$ was higher in non-PSC ERCPs compared to other gastrointestinal endoscopy interventions (P=0.043), while no differences in KAP (P=1.000) or fluoroscopy time (P= 0.238) were detected. The floor-mounted system produced remarkably lower patient doses than the mobile c-arm. The ASGE complexity level 3 ERCP procedures typically yielded highest doses and fluoroscopy times.

Occupational radiation exposure

The calculated mean conversion coefficients from KAP to H_p (10) over all DIS and TLD-100 readings were 0.86 ± 0.76 µSv/Gy·cm^{-2} (min-max: 0.03–2.24 µSv/Gy·cm^{-2}) and 1.55 ± 1.05 µSv/Gy·cm^{-2} (min-max: 0.55–3.36 µSv/Gy·cm^{-2}), respectively. Similarly, KAP-normalized H_p(0.07) for DIS and TLDs were 1.04 ± 0.83 µSv/Gy·cm^{-2} (min-max: 0.26–2.54 µSv/Gy·cm^{-2}) and 2.27 ± 1.71 µSv/Gy·cm^{-2} (min-max: 0.79–5.77 µSv/Gy·cm^{-2}), respectively. The mean KAP-normalized H_p(3) was 0.57 ± 0.27 µSv/Gy·cm^{-2} (min-max: 0.30–1.07 µSv/Gy·cm^{-2}). Furthermore, the conversion factor from H_p(10) to H_p(3) was 0.49 ± 0.23 (min-max: 0.22–2.13) for DIS and 0.34 ± 0.13 (min-max: 0.13–1.01) for TLD-100. The conversion factor from H_p (0.07) to H_p(3) was 0.48 ± 0.22 (min-max: 0.22–1.19) for DIS and 0.24 ± 0.11 (min-max: 0.08–0.73) for TLD-100.

▶ **Table 3** summarizes the estimated H_p(10), H_p(0.07), and H_p(3) of an operator per procedure. The mobile c-arm typically produced higher doses than the floor-mounted system. Personal eye lens dose equivalent H_p(3) per procedure, measured on the left temple and outside the leaded eyewear of each surgeon, ranged from 0.0 to 12.5 µSv in non-PSC ERCPs, from 0.2 to 7.9 µSv in PSC ERCPs, and from 0.0 to 3.5 µSv in other procedures. On average, PSC ERCPs resulted in higher eye lens doses than other procedures (P<0.001). In non-PSC ERCPs, deep-dose equivalent H_p(10) per procedure ranged from 0.0 to 32.4 µSv and from 0.0 to 48.7 µSv with DIS and TLD-100 dosimeters, respectively. In PSC ERCPs, H_p(10) per procedure ranged from 0.0 to 26.9 µSv with DIS and from 0.4 to 40.5 µSv with TLD-100. Similarly, H_p(10) per other gastrointestinal endoscopy procedure varied from 0.0 to 6.7 µSv and from 0.0 to 9.2 µSv with DIS and TLD-100, respectively. Personal shallow-dose equivalent H_p(0.07) of operator per non-PSC ERCP and PSC ERCP ranged from 0.0 to 36.7 µSv and from 0.0 to 26.9 µSv with DIS, respectively, and from 0.0 to 83.6 µSv and from 0.8 to 69.5 µSv with TLD-100, respectively. The operator H_p(0.07) per other gastrointestinal procedure ranged from 0.0 to 5.5 µSv with DIS and from 0.0 to 11.4 µSv with TLD-100. According to TLD-100 results, PSC ERCPs yielded on average higher H_p(10) and H_p(0.07) to operator than non-PSC ERCPs or other procedures (P<0.001). However, no such differences in operator H_p(10) and H_p(0.07) were observed with DIS. Occupational dose results achieved with DIS and TLD-100 correlated well (correlation coefficient was at lowest 0.82 [95 % confidence interval 0.79–0.84, P<0.001] and at highest 0.97 [95 % confidence interval 0.97–0.98, P<0.001]). However, TLDs showed systematically higher doses than DIS dosimeters.

▶ **Fig. 1a–c** shows the estimated operator-specific personal dose equivalents from ERCPs according to procedural complexity level. Considering all ERCPs, the ASGE complexity grading significantly affected operator doses (P<0.001 to P=0.002). Significant differences were also observed between the interventionists (P<0.001).

The estimated assisting staff doses are shown in ▶ **Table 4**. Assisting physician and nurse doses were systematically lower than doses measured for an operator (▶ **Table 3**). Dose differences observed in TLD readings were significant between opera-

▶ **Table 2** Dose indices and fluoroscopy times of the procedures provided as median (IQR) for different procedure types, systems, and in ERCP procedures also according to procedural complexity level.

Procedure and system	Fluoroscopy time (s)	KAP_{study} (Gy·cm²)	$KAP_{exposure}$ (Gy·cm²)	$K_{a,r,study}$ (mGy)	$K_{a,r,exposure}$ (mGy)	Number of single images
ERCP w/o PSC: Artis Zee MP (n = 276)	47 (22–92)	0.6 (0.3–1.4)	0.0 (0.0–0.2)	2.5 (1.0–5.8)	0.1 (0.0–0.9)	1.0 (0.0–1.0)
▪ Complexity level 1 (n = 10)	19 (10–46)	0.3 (0.1–1.5)	0.1 (0.0–0.6)	0.9 (0.4–6.5)	0.5 (0.0–2.2)	1.0 (0.0–2.0)
▪ Complexity level 2 (n = 120)	36 (21–62)	0.6 (0.3–0.9)	0.0 (0.0–0.2)	2.0 (1.0–3.8)	0.0 (0.0–0.8)	0.0 (0.0–1.0)
▪ Complexity level 3 (n = 106)	58 (32–145)	0.8 (0.3–2.0)	0.1 (0.0–0.3)	3.3 (1.2–7.2)	0.3 (0.0–1.1)	1.0 (0.0–1.0)
▪ Complexity level 4 (n = 40)	36 (19–136)	0.5 (0.2–1.2)	0.0 (0.0–0.2)	1.8 (0.8–8.1)	0.0 (0.0–0.7)	0.0 (0.0–1.0)
▪ P-value (complexity levels)	0.001	0.060	0.281	0.050	0.330	0.378
ERCP w/o PSC: Cios Alpha (n = 148)	48 (27–114)	2.0 (0.8–4.1)	0.0 (0.0–0.0)	7.0 (3.0–15.5)	0.0 (0.0–0.1)	0.0 (0.0–1.0)
▪ Complexity level 1 (n = 4)	25 (19–30)	1.0 (0.8–1.3)	0.0 (0.0–0.0)	3.6 (2.7–4.1)	0.0 (0.0–0.1)	0.5 (0.0–1.0)
▪ Complexity level 2 (n = 67)	32 (19–65)	1.2 (0.5–2.4)	0.0 (0.0–0.0)	4.0 (2.2–8.3)	0.0 (0.0–0.0)	0.0 (0.0–0.5)
▪ Complexity level 3 (n = 70)	103 (48–214)	3.5 (1.6–7.8)	0.0 (0.0–0.0)	12.9 (5.2–28.2)	0.0 (0.0–0.1)	0.0 (0.0–1.0)
▪ Complexity level 4 (n = 7)	27 (16–39)	1.2 (0.6–3.1)	0.0 (0.0–0.0)	2.9 (1.6–7.3)	0.0 (0.0–0.0)	0.0 (0.0–0.0)
▪ P-value (complexity levels)	<0.001	<0.001	0.609	<0.001	0.708	0.696
▪ P-value (ERCP w/o PSC: systems)	0.092	<0.001	<0.001	<0.001	<0.001	<0.001
ERCP PSC: Artis Zee MP (n = 135)	82 (35–143)	1.3 (0.8–2.2)	0.6 (0.4–0.9)	8.3 (5.1–12.7)	3.7 (2.6–4.6)	5.0 (5.0–7.0)
▪ Complexity level 1 (n = 93)	61 (26–98)	1.2 (0.8–1.8)	0.7 (0.5–0.8)	6.8 (4.8–11.5)	3.7 (2.7–4.6)	5.0 (5.0–7.0)
▪ Complexity level 2 (n = 35)	134 (96–202)	2.1 (1.2–4.2)	0.6 (0.4–0.9)	11.0 (7.8–20.3)	3.6 (2.5–4.7)	5.0 (3.0–5.5)
▪ Complexity level 3 (n = 7)	116 (57–301)	1.4 (0.9–3.4)	0.5 (0.3–0.6)	9.4 (5.2–15.5)	2.9 (1.5–3.7)	4.0 (3.0–5.5)
▪ Complexity level 4 (n = 0)	–	–	–	–	–	–
▪ P-value (complexity levels)	<0.001	<0.001	0.385	0.001	0.359	<0.001
▪ P-value (ERCP: PSC wrt w/o PSC)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
ERCP PSC: Cios Alpha (n = 1)	113 (113–113)	2.4 (2.4–2.4)	0.0 (0.0–0.0)	5.6 (5.6–5.6)	0.0 (0.0–0.0)	0.0 (0.0–0.0)
▪ Complexity level 1 (n = 0)	–	–	–	–	–	–
▪ Complexity level 2 (n = 1)	113 (113–113)	2.4 (2.4–2.4)	0.0 (0.0–0.0)	5.6 (5.6–5.6)	0.0 (0.0–0.0)	0.0 (0.0–0.0)
▪ Complexity level 3 (n = 0)	–	–	–	–	–	–
▪ Complexity level 4 (n = 0)	–	–	–	–	–	–
▪ *P* value (complexity levels)	N/A	N/A	N/A	N/A	N/A	N/A
▪ *P* value (ERCP PSC: systems)	0.735	0.426	0.029	0.563	0.029	0.029
▪ *P* value (ERCP: PSC wrt w/o PSC)	0.523	0.859	0.738	0.913	0.738	0.738
Other GE procedure: Artis Zee MP (n = 26)	37 (11–72)	0.6 (0.2–1.7)	0.0 (0.0–0.1)	1.4 (0.9–4.4)	0.0 (0.0–0.5)	0.0 (0.0–0.8)
Other GE procedure: Cios Alpha (n = 18)	63 (12–95)	1.7 (0.4–4.1)	0.0 (0.0–0.0)	4.0 (1.0–9.6)	0.0 (0.0–0.0)	0.0 (0.0–0.0)
▪ *P* value (other GE procedure: systems)	0.214	0.053	0.018	0.129	0.018	0.018
▪ *P* value (procedure types: ERCP w/o PSC wrt ERCP PSC wrt other)	<0.001	0.001	<0.001	<0.001	<0.001	<0.001

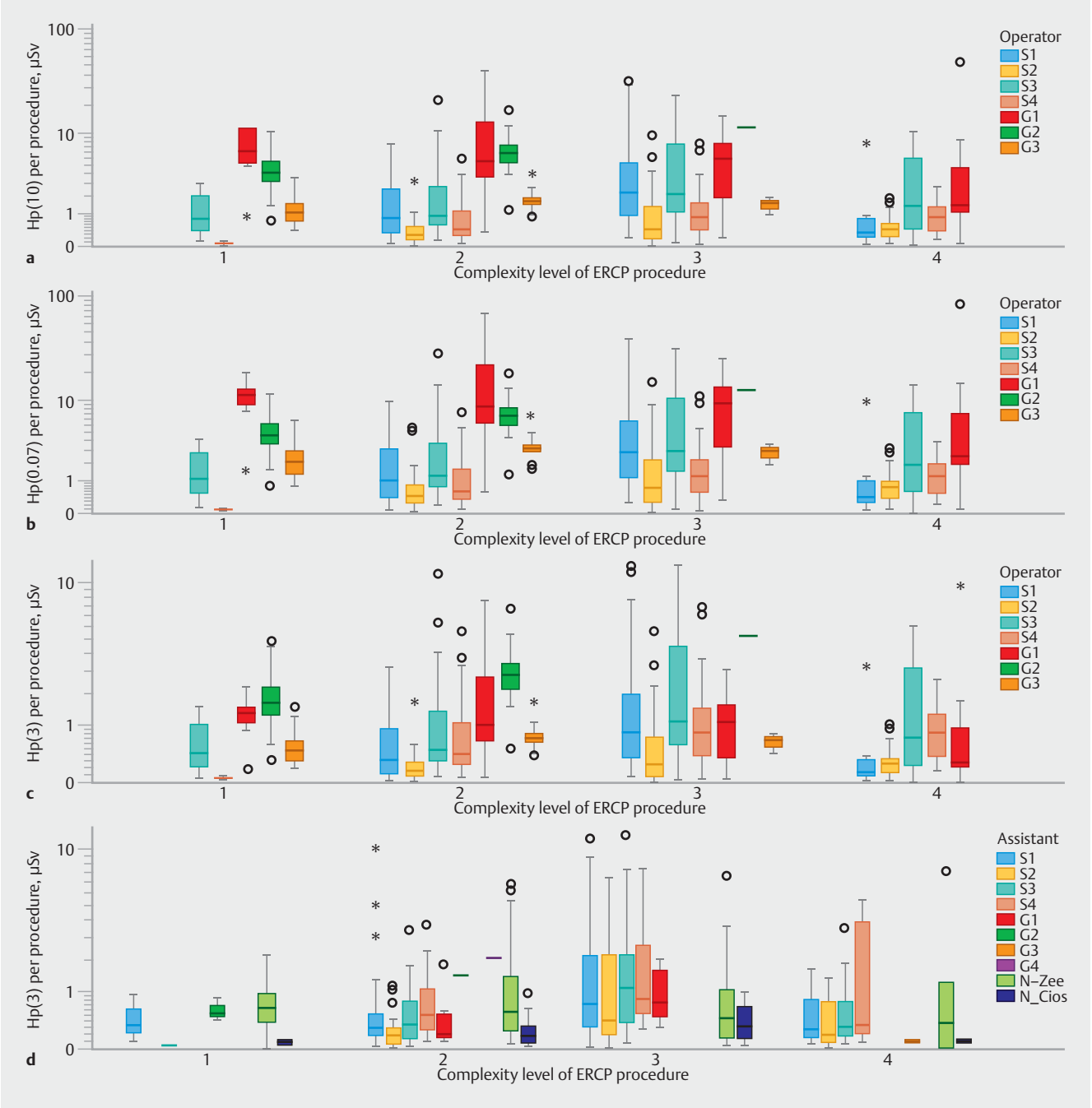
ERCP, endoscopic retrograde cholangiopancreatography; GE, gastrointestinal endoscopy; KAP_{study}, kerma-area product for the entire examination including contributions from fluoroscopy and exposures/single digital radiographic images; $KAP_{exposure}$, kerma-area product resulting from the exposures/single images; $K_{a,r,study}$, air-kerma at reference point for the entire examination; $K_{a,r,exposure}$, air-kerma at reference point resulting from the exposures/single images; PSC, primary sclerosing cholangitis

▶ **Table 3** Calculated personal dose equivalents $H_p(10)$, $H_p(0.07)$, and $H_p(3)$ resulting from a single procedure to the operator.

Procedure and system	DIS		TLD-100		EYE-D TLD
	$H_p(10)$, µSv	$H_p(0.07)$, µSv	$H_p(10)$, µSv	$H_p(0.07)$, µSv	$H_p(3)$, µSv
ERCP w/o PSC: Artis Zee MP (n = 276)	0.3 (0.1–0.9)	0.4 (0.1–0.9)	0.5 (0.2–1.4)	0.8 (0.3–2.1)	0.3 (0.1–0.7)
▪ Complexity level 1 (n = 10)	0.2 (0.0–1.5)	0.2 (0.1–1.8)	0.2 (0.1–1.9)	0.3 (0.1–2.5)	0.2 (0.1–1.0)
▪ Complexity level 2 (n = 120)	0.3 (0.1–0.8)	0.3 (0.1–0.8)	0.5 (0.3–1.2)	0.7 (0.3–1.6)	0.2 (0.1–0.5)
▪ Complexity level 3 (n = 106)	0.5 (0.2–1.1)	0.5 (0.2–1.1)	0.7 (0.3–1.7)	0.9 (0.4–2.4)	0.4 (0.1–0.9)
▪ Complexity level 4 (n = 40)	0.3 (0.1–0.8)	0.3 (0.1–0.9)	0.4 (0.2–1.3)	0.7 (0.3–2.0)	0.2 (0.1–0.5)
▪ *P* value (complexity levels)	0.383	0.520	0.305	0.281	0.185
ERCP w/o PSC: Cios Alpha (n = 148)	1.2 (0.5–3.2)	1.2 (0.5–2.7)	1.7 (0.8–4.5)	2.4 (1.1–5.8)	1.0 (0.4–2.0)
▪ Complexity level 1 (n = 4)	0.8 (0.7–1.1)	1.0 (0.8–1.4)	1.0 (0.8–1.4)	1.4 (1.1–1.9)	0.6 (0.4–0.7)
▪ Complexity level 2 (n = 67)	0.6 (0.3–1.8)	0.7 (0.3–1.7)	1.1 (0.5–2.6)	1.5 (0.7–3.6)	0.6 (0.3–1.3)
▪ Complexity level 3 (n = 70)	2.3 (1.0–6.8)	1.8 (0.9–5.6)	3.3 (1.4–8.7)	4.3 (1.9–11.7)	1.4 (0.7–4.1)
▪ Complexity level 4 (n = 7)	1.1 (0.6–1.2)	1.1 (0.5–1.3)	1.4 (0.8–1.7)	1.8 (1.0–2.8)	0.7 (0.3–0.9)
▪ *P* value (complexity levels)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
▪ *P* value (ERCP w/o PSC: systems)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
ERCP PSC: Artis Zee MP (n = 135)	1.5 (0.0–3.0)	1.5 (0.0–3.1)	3.1 (1.4–5.5)	3.7 (2.3–7.1)	1.0 (0.6–1.9)
▪ Complexity level 1 (n = 93)	0.9 (0.0–2.3)	0.9 (0.0–2.3)	2.1 (1.1–4.5)	3.3 (1.9–5.2)	0.9 (0.5–1.6)
▪ Complexity level 2 (n = 35)	3.2 (0.6–7.7)	3.2 (0.6–8.1)	5.5 (3.0–12.5)	7.3 (4.3–18.1)	1.5 (0.7–3.0)
▪ Complexity level 3 (n = 7)	1.0 (0.0–5.7)	1.1 (0.0–6.0)	1.8 (1.5–9.9)	3.4 (2.7–13.4)	0.8 (0.5–2.3)
▪ Complexity level 4 (n = 0)	–	–	–	–	–
▪ *P* value (complexity levels)	< 0.001	< 0.001	< 0.001	< 0.001	0.015
▪ *P* value (ERCP: PSC wrt w/o PSC)	0.158	0.326	< 0.001	< 0.001	< 0.001
ERCP PSC: Cios Alpha (n = 1)	3.1 (3.1–3.1)	3.0 (3.0–3.0)	6.0 (6.0–6.0)	6.7 (6.7–6.7)	2.5 (2.5–2.5)
▪ Complexity level 1 (n = 0)	–	–	–	–	–
▪ Complexity level 2 (n = 1)	3.1 (3.1–3.1)	3.0 (3.0–3.0)	6.0 (6.0–6.0)	6.7 (6.7–6.7)	2.5 (2.5–2.5)
▪ Complexity level 3 (n = 0)	–	–	–	–	–
▪ Complexity level 4 (n = 0)	–	–	–	–	–
▪ *P* value (complexity levels)	N/A	N/A	N/A	N/A	N/A
▪ *P* value (ERCP PSC: systems)	0.485	0.529	0.471	0.544	0.309
▪ *P* value (ERCP: PSC wrt w/o PSC)	0.550	0.483	0.416	0.443	0.456
Other GE procedure: Artis Zee MP (n = 26)	0.3 (0.1–0.6)	0.4 (0.1–0.8)	0.7 (0.2–1.2)	0.9 (0.3–1.6)	0.3 (0.1–0.8)
Other GE procedure: Cios Alpha (n = 18)	0.8 (0.3–3.0)	0.9 (0.4–3.7)	1.3 (0.4–3.9)	1.9 (0.6–5.2)	0.7 (0.2–2.3)
▪ *P* value (other GE procedure: systems)	0.032	0.030	0.038	0.050	0.056
▪ *P* value (procedure types: ERCP w/o PSC wrt ERCP PSC wrt other)	0.547	0.748	< 0.001	< 0.001	< 0.001

ERCP, endoscopic retrograde cholangiopancreatography; GE, gastrointestinal endoscopy; $H_p(10)$, personal deep-dose equivalent; $H_p(0.07)$, personal shallow-dose equivalent; $H_p(3)$, personal eye lens dose equivalent; PSC, primary sclerosing cholangitis; TLD, thermoluminescent dosimeter.
$H_p(10)$ and $H_p(0.07)$ were measured with DIS and TLD-100 dosimeters positioned on the protective apron at chest level of each surgeon, while $H_p(3)$ was measured with EYE-D TLD dosimeter attached on the left temple and outside the leaded eyewear of each endoscopist. Results are given as median (IQR).

tors and assisting staff members for $H_p(10)$ ($P = 0.016$), $H_p(0.07)$ ($P = 0.005$), and $H_p(3)$ ($P = 0.002$). The estimated $H_p(3)$ per procedure to an assisting staff member ranged from 0.0 to 12.2 µSv in non-PSC ERCPs, from 0.1 to 6.3 µSv in PSC ERCPs,



▶ **Fig. 1** Occupational radiation doses in a single ERCP intervention according to complexity level of procedure. Operator-specific personal dose equivalents **a** $H_p(10)$, **b** $H_p(0.07)$, and **c** $H_p(3)$ and **d** assistant-specific eye lens dose equivalent $H_p(3)$ per ERCP procedure. The $H_p(10)$ and $H_p(0.07)$ shown represent doses estimated from TLD-100 measurements. Logarithmic scale is used on the y-axis.

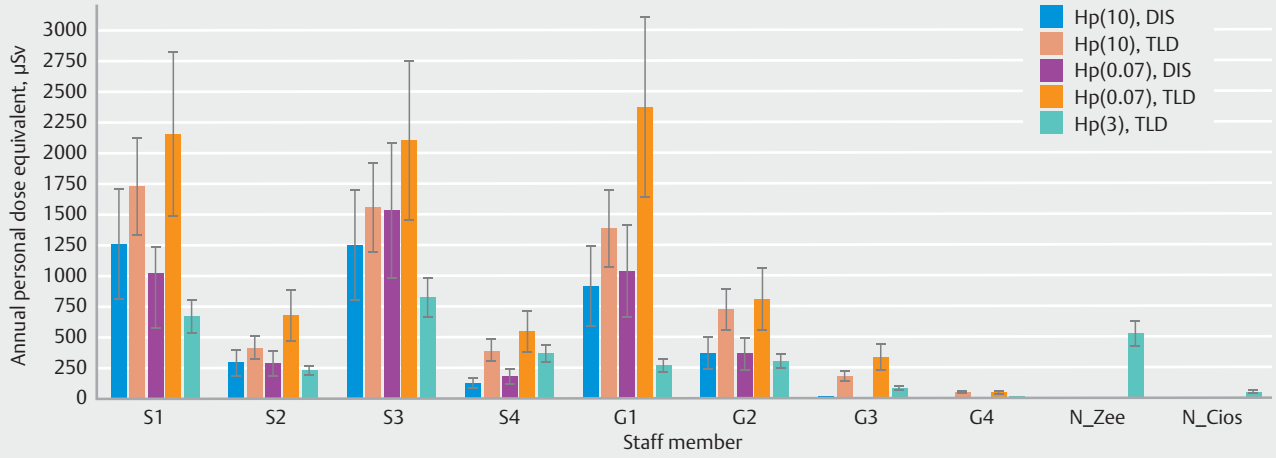
and from 0.0 to 1.8 µSv in other gastrointestinal endoscopy procedures. Significant differences in assisting staff eye lens doses were seen between the procedure types ($P<0.001$). $H_p(10)$ per non-PSC ERCP ranged from 0.0 to 22.0 µSv with DIS and from 0.0 to 30.3 µSv with TLD-100. $H_p(0.07)$ per non-PSC ERCP ranged from 0.0 to 22.8 µSv with DIS and from 0.0 to 37.7 µSv with TLD-100. Considering all ERCPs, ASGE complexity level of the procedure (▶ **Fig. 1d**) significantly affected the assisting staff doses ($P<0.001$).

▶ **Fig. 2** shows the extrapolated annual personal dose equivalents for the exposed endoscopy unit workers. For each staff member and personal dose equivalent value, the annual dose estimation was achieved by multiplying the accumulated dosimeter reading by 365 days divided by 140 days (total measurement period of this study). The highest estimated annual $H_p(10)$ for an interventionist was approximately 1.7 mSv, annual $H_p(0.07)$ was 2.4 mSv, and annual $H_p(3)$ was 0.8 mSv. The highest estimated annual $H_p(3)$ for nurse group dosimeter was ap-

▶ **Table 4** Calculated personal dose equivalents $H_p(10)$, $H_p(0.07)$, and $H_p(3)$ resulting from a single procedure to assisting staff member.

Procedure and system	DIS		TLD-100		EYE-D TLD
	$H_p(10)$, µSv	$H_p(0.07)$, µSv	$H_p(10)$, µSv	$H_p(0.07)$, µSv	$H_p(3)$, µSv
ERCP w/o PSC: Artis Zee MP (n = 276)	0.4 (0.2–1.0)	0.4 (0.2–1.1)	0.6 (0.3–1.5)	0.9 (0.4–2.1)	0.3 (0.1–0.7)
▪ Complexity level 1 (n = 10)	0.2 (0.1–0.4)	0.1 (0.1–0.3)	0.2 (0.2–0.6)	0.3 (0.2–0.7)	0.1 (0.0–0.8)
▪ Complexity level 2 (n = 120)	0.3 (0.2–0.8)	0.3 (0.2–0.7)	0.5 (0.2–1.2)	0.8 (0.3–1.5)	0.3 (0.1–0.5)
▪ Complexity level 3 (n = 106)	0.6 (0.3–1.6)	0.6 (0.3–1.8)	0.8 (0.4–2.4)	1.1 (0.5–3.3)	0.4 (0.2–1.0)
▪ Complexity level 4 (n = 40)	0.3 (0.1–1.0)	0.3 (0.1–0.9)	0.4 (0.2–1.4)	0.6 (0.3–1.7)	0.2 (0.1–0.7)
▪ *P* value (complexity levels)	0.043	0.020	0.052	0.036	0.075
ERCP w/o PSC: Cios Alpha (n = 148)	1.5 (0.5–2.8)	1.3 (0.5–3.2)	2.0 (0.8–4.5)	2.7 (1.0–6.4)	0.5 (0.2–1.3)
▪ Complexity level 1 (n = 4)	1.8 (1.8–1.8)	1.3 (1.3–1.3)	2.5 (2.5–2.5)	3.1 (3.1–3.1)	0.1 (0.1–0.3)
▪ Complexity level 2 (n = 67)	0.6 (0.5–1.3)	0.7 (0.4–1.3)	1.1 (0.6–1.7)	1.4 (0.8–2.3)	0.3 (0.1–0.6)
▪ Complexity level 3 (n = 70)	2.7 (0.9–5.2)	2.7 (0.9–4.9)	3.9 (1.7–7.5)	5.6 (2.3–11.6)	0.8 (0.3–2.5)
▪ Complexity level 4 (n = 7)	1.7 (0.5–2.8)	2.2 (0.3–2.5)	3.5 (0.6–4.2)	4.7 (0.8–5.3)	0.2 (0.1–1.7)
▪ *P* value (complexity levels)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
▪ *P* value (ERCP w/o PSC: systems)	< 0.001	< 0.001	< 0.001	< 0.001	0.005
ERCP PSC: Artis Zee MP (n = 135)	0.7 (0.6–1.1)	0.8 (0.6–1.1)	1.3 (1.0–2.1)	1.4 (1.1–2.3)	0.7 (0.5–1.1)
▪ Complexity level 1 (n = 93)	0.6 (0.6–0.9)	0.6 (0.6–0.8)	1.3 (1.1–1.7)	1.4 (1.3–1.9)	0.6 (0.4–0.9)
▪ Complexity level 2 (n = 35)	1.7 (1.7–1.7)	1.7 (1.7–1.7)	3.4 (3.4–3.4)	3.8 (3.8–3.8)	1.2 (0.6–2.2)
▪ Complexity level 3 (n = 7)	0.7 (0.7–0.7)	0.8 (0.8–0.8)	0.8 (0.8–0.8)	1.1 (1.1–1.1)	0.7 (0.5–1.8)
▪ Complexity level 4 (n = 0)	–	–	–	–	–
▪ *P* value (complexity levels)	0.344	0.344	0.202	0.202	< 0.001
▪ *P* value (ERCP: PSC wrt w/o PSC)	0.139	0.135	0.069	0.130	< 0.001
ERCP PSC: Cios Alpha (n = 1)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	20.0 (20.0–20.0)	20.0 (20.0–20.0)	2.0 (2.0–2.0)
▪ Complexity level 1 (n = 0)	–	–	–	–	–
▪ Complexity level 2 (n = 1)	0.0 (0.0–0.0)	0.0 (0.0–0.0)	20.0 (20.0–20.0)	20.0 (20.0–20.0)	2.0 (2.0–2.0)
▪ Complexity level 3 (n = 0)	–	–	–	–	–
▪ Complexity level 4 (n = 0)	–	–	–	–	–
▪ *P* value (complexity levels)	N/A	N/A	N/A	N/A	N/A
▪ *P* value (ERCP PSC: systems)	0.333	0.333	0.333	0.333	0.221
▪ *P* value (ERCP: PSC wrt w/o PSC)	0.024	0.024	0.119	0.143	0.349
Other GE procedure: Artis Zee MP (n = 26)	0.3 (0.1–1.1)	0.4 (0.1–1.3)	0.8 (0.1–1.7)	1.1 (0.2–2.3)	0.3 (0.1–1.0)
Other GE procedure: Cios Alpha (n = 18)	1.2 (0.8–1.7)	1.5 (1.0–2.1)	1.8 (1.4–2.2)	2.5 (2.0–3.0)	0.2 (0.0–0.4)
▪ *P* value (other GE procedure: systems)	0.308	0.308	0.231	0.231	0.262
▪ *P* value (procedure types: ERCP w/o PSC wrt ERCP PSC wrt other)	0.415	0.698	0.153	0.243	< 0.001

ERCP, endoscopic retrograde cholangiopancreatography; GE, gastrointestinal endoscopy; $H_p(10)$, personal deep-dose equivalent; $H_p(0.07)$, personal shallow-dose equivalent; $H_p(3)$, personal eye lens dose equivalent; PSC, primary sclerosing cholangitis; TLD, thermoluminescent dosimeter.
$H_p(10)$ and $H_p(0.07)$ were measured with DIS and TLD-100 dosimeters positioned on the protective apron at chest level of each assisting surgeon or gastroenterologist, while $H_p(3)$ was measured with EYE-D TLD attached on the left temple and outside the leaded eyewear of each assisting staff member. Results are given as median (IQR).



▶ **Fig. 2** Estimated annual personal dose equivalents $H_p(10)$, $H_p(0.07)$, and $H_p(3)$ for endoscopy staff (operators and assistants) based on measurements from various dosimeters. Surgeons are indicated as S1-S4, gastroenterologists as G1-G4, and group dosimeters for nurses as N_Zee and N_Cios. The error bars represent expanded uncertainties with coverage factor k = 2, corresponding to approximately 95 % confidence level.

proximately 0.5 mSv in the floor-mounted fluoroscopy system examination room. TLDs measured systematically higher doses than DIS dosimeters.

Discussion

In this study, we estimated personal dose equivalents $H_p(10)$, $H_p(0.07)$, and $H_p(3)$ resulting from gastrointestinal endoscopy procedures to operators and assisting staff. We also produced conversion coefficients from KAP to personal eye lens dose equivalent $H_p(3)$ and from personal deep-dose $H_p(10)$ and shallow-dose equivalent $H_p(0.07)$ to $H_p(3)$.

PSC ERCPs were observed to yield higher dose indices and fluoroscopy times compared to non-PSC ERCPs and other gastrointestinal x-ray interventions. Compared to previous publications, this study showed remarkably lower KAP and personal dose equivalent values per ERCP procedure. For example, the European ORAMED study [20] reported a median eye lens dose of 18 µSv and an average of 102 µSv for surgeons during ERCP. More recently, O'Connor et al. [14] reported surgeon eye lens doses to vary from 10 to 100 µSv per procedure, depending on the endoscopy site, equipment, and x-ray tube position during the procedure. For nurses, they reported eye lens doses from < 10 to 30 µSv. The current study estimated median operator eye lens dose (measured on the left temple and outside the leaded eyewear) per ERCP to be 0.6 µSv (0.4 and 1.0 µSv for non-PSC and PSC ERCPs, respectively) with a maximum dose of 12.5 µSv per procedure. For nurses and assisting physicians, the median $H_p(3)$ per procedure was estimated to be 0.4 µSv (0.3 and 0.7 µSv for non-PSC and PSC ERCPs, respectively) with a maximum dose of 12.2 µSv per procedure. The median KAP per ERCP in this study was 1.0 Gy·cm^2 (0.8 and 1.3 Gy·cm^2 in non-PSC and PSC ERCP, respectively) and third quartile 2.3 Gy·cm^2. O'Connor et al. [14] reported remarkably higher KAP, with mean KAP per procedure being 5.4 to 14.5 Gy·cm^2 and third quartiles 7.9 to 19.6 Gy·cm^2, depending on the endoscopy site and image intensifier fluoroscopy system used. Both systems used in this study were flat-panel devices, which together with regular staff training and special focus on radiation protection and dose-optimization practices explain the lower observed doses to patients and staff. In this study, the floor-mounted fluoroscopy system had significantly lower KAP and personal dose equivalents per procedure than the movable c-arm. This was expected, as the floor-mounted system contained a greater amount of additional copper filtration than the movable c-arm. Additionally, the floor-mounted system had adjustable tube-detector distance. In contrast, this was fixed on the mobile c-arm, which also affected optimal positioning of the x-ray tube and detector.

Saukko et al. [21] reported median KAP to be 1.83 Gy·cm^2 (IQR: 1.20–2.90 Gy·cm^2) in their ERCP study. They also observed that procedural complexity level affects KAP and fluoroscopy time; complexity level 3 yielded significantly higher doses than level-1 and level-2 procedures. In the current study, ERCP procedural complexity level in terms of ASGE grading system was also shown to affect dose indices, fluoroscopy times, and occupational doses. On average, ERCPs belonging to complexity level 3 produced the highest dose indices and fluoroscopy times. ERCPs performed to diagnose and follow up PSC, which were often graded as complexity level 1, involved more single image acquisitions than other procedures. This together with the longer fluoroscopy times caused higher KAP.

All personal dose equivalents varied significantly between operators. This observation together with KAP differences may be signs of operator-specific differences in dose optimization and radiation protection practices. For example, variation in positioning the ceiling-suspended lead glass shield during the procedure may have occurred and affected the occupational

exposure. This may also explain why some operators received significantly higher $H_p(10)$ and $H_p(0.07)$ values per procedure than others, while no such large differences in $H_p(3)$ were seen. In general, when the ceiling-mounted lead glass shield is not positioned low enough and as close as possible to the patient body during fluoroscopy, more scattered radiation may be exposed to the stomach and chest area of an operator, although the head of an operator would already be sufficiently protected. Radiation protection practices are not only important for the operating interventionist but also for the assisting staff. As ceiling-mounted shields are specifically designed to protect the operator from scattered radiation, assistants should be positioned as far from the scattering patient as practically possible and preferably behind the operator. Based on the measured occupational doses, there was probably also some variation in positioning of assisting staff members.

Remarkable differences in operator-specific KAP-normalized personal dose equivalents were observed in this study. The mean conversion coefficient from KAP to $H_p(10)$ was $0.86 \pm 0.76\,\mu Sv/Gy{\cdot}cm^{-2}$ with DIS and $1.55 \pm 1.05\,\mu Sv/Gy{\cdot}cm^{-2}$ with TLDs. Particularly high standard deviations of the determined conversion coefficients support the anticipated differences in working practices. Moreover, the mean KAP-normalized $H_p(3)$ was $0.57 \pm 0.27\,\mu Sv/Gy{\cdot}cm^{-2}$, reflecting more equal protection of cranial tissues. The KAP-normalized $H_p(3)$ values were smaller than those reported by O'Connor et al. [14], who reported $0.98–1.43\,\mu Sv/Gy{\cdot}cm^{-2}$ and $14.5–21.2\,\mu Sv/Gy{\cdot}cm^{-2}$ in sites using under couch and over couch x-ray tube geometry during the procedure, respectively. Their study highlights the necessity of using under couch irradiation instead of over couch geometry, which results in a significant amount of scattered radiation to the upper body of the operator and assisting staff.

Although this study revealed statistically significant differences in occupational doses between operators, systems, ERCP procedure types (i. e., PSC or non-PSC ERCP), and ASGE procedural complexity levels, the absolute dose differences remained particularly small, mostly because the doses were generally very low. For example, the greatest difference in interventionists' median $H_p(3)$ was $< 1.5\,\mu Sv$, which is equivalent to less than 1 day of background radiation. Thus, although statistically significant, the dose differences remained mostly insignificant in terms of excess radiation risk. For the sake of comparison, the excess relative cataract risk has been estimated to be 1.31 per Gy for a linear no-threshold model by the EURALOC study [10]. Another comparison can be made to the nominal threshold dose of 0.5 Gy for the deterministic model of cataract formation described by the International Commission on Radiological Protection (ICRP) [22].

Use of ionizing radiation should be optimized to reduce radiation doses to patients and staff. Protective aprons, thyroid collars, leaded eyewear, ceiling-mounted lead glasses, table-mounted shields, and mobile shielding screens should be used consistently to protect the staff. By following good practices of using ionizing radiation, estimated occupational doses remained clearly below the given dose limits for radiation workers [5]. For example, the greatest annual $H_p(10)$ and $H_p(3)$ for the interventionist were estimated to be 1.7 mSv and 1.3 mSv, respectively. These doses are not only clearly below the maximum allowed levels but are considerably lower than the respective annual limits for category B workers [5]. Further, dose equivalents were measured outside the protective aprons, and to estimate effective doses from the measured $H_p(10)$ values, the reported values should be divided by a factor of 30–120 [23]. Similarly, the eye lens doses were measured by positioning TLDs outside the leaded eyewear. As protective glasses typically lower the eye lens dose by 50–80 %, a conversion factor of 0.5 may be used to estimate $H_p(3)$ under the glasses to account for the effect of protective glasses [17, 20, 24, 25]. Regarding these essential dose aspects, the occupational exposure in gastrointestinal endoscopy procedures may be kept very low when proper optimization practices are followed. However, some of the previous studies focused on operator ocular doses have anticipated that the given annual dose limit for the eye lenses may be exceeded in surgeons who frequently perform ERCP procedures [15–17]. Based on the measured personal dose equivalents of this study, monitoring interventionists' eye lens doses with a specific dosimeter is not required in dose-optimized gastrointestinal endoscopy procedures. The $H_p(3)$ may be estimated with sufficiently good agreement from the $H_p(10)$ and $H_p(0.07)$ to ensure compliance to the eye lens equivalent dose limits, especially considering that the conversion factors from $H_p(10)$ and $H_p(0.07)$ to $H_p(3)$ were < 1, thus providing conservative estimates of the eye lens dose.

This study has certain limitations. First and foremost, operator and assisting staff doses were estimated using the same dosimeters. Therefore, the exact contributions of each role on personal dose equivalent cannot be determined. However, measurements performed for educational purposes with an anthropomorphic phantom and dosimeters resulted in similar dose behavior between operator and assisting staff members. Second, only five 4-week data collection periods with a limited number of patients for each operator were gathered. Ideally, the dosimeters should have been read after each procedure. However, this was not feasible practically. Third, the $H_p(10)$ and $H_p(0.07)$ results from TLDs differed remarkably from DIS results. This may have been due to the longer periods between preparing and reading the TLDs. The TLDs arrived at the hospital from the dosimetry service approximately 1 week before a new measurement period began and they were read 1 to 2 weeks after each measurement period due to shipping and other delays in the process. Although the background correction was performed for the TLDs at the dosimetry service, there may have been some remaining uncertainties. Furthermore, both dosimeters had particularly high expanded uncertainty (e. g., 36 % and 23 % for $H_p(10)$ with DIS and TLD-100, respectively). Fourth, ERCP complexity level was evaluated and recorded after each procedure by the staff. There may have been some ambiguous differences in the grading used between operators. Fifth, procedural classification into three groups may not be ideal as, for example, PSC ERCPs and other gastrointestinal procedures may vary widely. Some previous publications also recommend evaluating diagnostic and therapeutic ERCPs separately. In our hospital, most diagnostic ERCPs, excluding PSCs, have been replaced with other diagnostic methods (e. g.

magnetic resonance imaging). The classification to PSC or non-PSC ERCPs was done to further categorize procedures in a way that is relevant in terms of radiation exposure. More single image acquisitions were performed in PSC ERCPs than in other ERCPs, producing higher radiation exposures. Finally, a limited number of staff members participated in the study and only two fluoroscopy systems were used. The radiation protection practices used in other centers may vary remarkably from what has been reported here, and therefore the resultant patient and occupational doses may not be interchangeable with other endoscopy departments and fluoroscopy systems.

Conclusions

In conclusion, by following good working practices and focusing on dose optimization in gastrointestinal x-ray interventions, including ERCPs, personal dose equivalents $H_p(10)$, $H_p(0.07)$, and $H_p(3)$ for an operator and assisting staff member per procedure remain low and annual dose limits are unlikely to be exceeded. The eye lens dose equivalent $H_p(3)$ may be estimated with sufficiently good agreement from the $H_p(10)$ and $H_p(0.07)$ measurements to ensure compliance to dose limits in gastrointestinal procedures. However, relatively high variation in patient dose and occupational exposure may be seen due to operator-specific and fluoroscopy system-related reasons.

Competing interests

The authors declare that they have no conflict of interest.

Funding

State Subsidy for University Hospitals in Finland

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