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ORIGINAL ARTICLE

Female gonadal shielding with automatic exposure control increases radiation risks

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Abstract
Background Gonadal shielding remains common, but current estimates of gonadal radiation risk are lower than estimated risks to colon and stomach. A female gonadal shield may attenuate active automatic exposure control (AEC) sensors, resulting in increased dose to colon and stomach as well as to ovaries outside the shielded area.
Objective We assess changes in dose–area product (DAP) and absorbed organ dose when female gonadal shielding is used with AEC for pelvis radiography.
Materials and methods We imaged adult and 5-year-old equivalent dosimetry phantoms using pelvis radiograph technique with AEC in the presence and absence of a female gonadal shield. We recorded DAP and mAs and measured organ absorbed dose at six internal sites using film dosimetry.
Results Female gonadal shielding with AEC increased DAP 63% for the 5-year-old phantom and 147% for the adult phantom. Absorbed organ dose at unshielded locations of colon, stomach and ovaries increased 21–51% in the 5-year-old phantom and 17–100% in the adult phantom. Absorbed organ dose sampled under the shield decreased 67% in the 5-year-old phantom and 16% in the adult phantom.
Conclusion Female gonadal shielding combined with AEC during pelvic radiography increases absorbed dose to organs with greater radiation sensitivity and to unshielded ovaries. Difficulty in proper use of gonadal shields has been well described, and use of female gonadal shielding may be inadvisable given the risks of increasing radiation.

Keywords Automatic exposure control · Gonadal shield · Gonads · Ovaries · Radiation dose · Radiography · Shielding

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Introduction

Lead or lead-equivalent gonadal shielding during radiographic exams began in the 1950s out of concerns about reproductive risks of gonadal irradiation [1–6]. Since then, estimates of gonadal radiation risk have dropped considerably. The International Commission on Radiological Protection (ICRP) publishes weighting factors (w_t) meant to estimate the stochastic risk to organs exposed to radiation. In 1977, ICRP Publication 26 first estimated w_t for gonads at 0.25, meaning the gonads were assumed to bear 25% of the biological risk during a whole-body radiation event [6]. The next edition, ICRP Publication 60, reduced that estimate to 20% (w_t=0.20) [7]. Most recently, ICRP Publication 103 further reduced estimates of gonadal risk to a w_t of 0.08 [8]. At the same time, ICRP Publication 103 increased estimates of risk to colon and stomach. These organs were not assigned

individual w_t in the first ICRP estimates, but they are now estimated to have w_t of 0.12 each, a combined risk three times higher than that of gonads. This changing balance of radiation susceptibility suggests that gonadal shielding persists today out of misplaced and outdated concerns about radiation risk.

In addition to the likelihood that gonadal shields do not significantly reduce radiation risk, there is a possibility that female gonadal shields are being used in a way that increases radiation risk. A majority of radiography today is performed using automatic exposure control (AEC) to ensure against overexposure and underexposure. AEC sensors adjacent to the image receptor adjust the radiation output by monitoring air kerma at the receptor and terminating the beam when a predetermined air kerma threshold has been reached [9]. A radiopaque object placed between the beam source and the AEC sensors attenuates the beam, causing the AEC to increase tube output to reach its air kerma threshold [10–14]. For a pelvis radiograph, a properly positioned female gonadal shield directly covers active AEC sensors, increasing radiation to the unshielded anatomy. Guidelines state that a female gonadal shield should not be used in conjunction with AEC [15, 16], but use of AEC is so ubiquitous and gonadal shielding so error-prone [17–29] that it is likely the two techniques are at times combined. If female gonadal shielding is used during pelvic radiography with AEC, it is expected that absorbed organ dose to the more radiation-sensitive colon and stomach, as well as to unshielded ovaries, is higher than if no shield is used.

We investigated quantitative changes in radiation when a female gonadal shield was used in conjunction with AEC. Using 5-year-old and adult equivalent dosimetry phantoms, we measured changes in absorbed organ dose at six sites within the abdomen in the presence and absence of female gonadal shielding. We also measured change in dose–area product (DAP) and tube current-exposure time product (milliampere·seconds [mAs]) to assess the effect of gonadal shielding on clinically available dose parameters. Our experiments are not meant to represent the range of dose changes that occur clinically, which vary widely by body habitus and institutional techniques. Instead, we offer proof of principle in two examples showing the magnitude of change that can occur if gonadal shielding is used in conjunction with AEC under controlled conditions.

Materials and methods

This research used only dosimetry phantoms and was exempt from institutional review board review.

We studied the dose effects of female gonadal shields placed over active AEC sensors using a 5-year-old pediatric dosimetry phantom to model a small child and an adult dosimetry phantom to model an adult or older adolescent (Computerized Imaging Reference Systems [CIRS], Norfolk, VA; 5-year-old trunk phantom 705-TR modeled on a 110-cm, 19-kg child; adult pelvis phantom 701-P, modeled on a 173-cm, 73-kg man). We exposed the phantoms to clinical parameters for an anteroposterior (AP) pelvis radiograph (Table 1) using digital direct radiography (Luminos Agile; Siemens, Erlangen, Germany). We exposed the phantoms with and without a 0.5-mm lead-equivalent gonadal shield (Bar-ray, Littlestown, PA), using a 10-cm triangular shield for the pediatric phantom and a 16-cm triangular shield for the adult phantom. We positioned each shield with the inferior margin just above the expected location of the pubic symphysis. After placing the gonadal shield, we projected a light field demonstrating the location of AEC sensors onto each phantom (Fig. 1). We then performed the AP pelvis radiograph, noting the mAs and the DAP for each condition in each phantom. Our routine departmental quality assurance testing shows that accuracy of DAP reported by the radiography machine is within 10% of measured DAP at the kilovoltage peak (kVp) range in our protocol.

To sample absorbed dose at locations where ovaries, colon or stomach may be positioned, we used film dosimetry strips (Gafchromic; Ashland, Covington, KY), chosen for their flexible positioning and sensitivity in the diagnostic 20- to 200-kVp range. We first calibrated the film with a solid state radiation detector as described in Appendix 1. We used the calibration curve to determine absorbed dose in film strips embedded within the phantoms based on the mean green value of the exposed film. We implanted three film strips at each of six sites in each of the two phantoms (Fig. 2). We marked each site with a radiopaque BB at the caudal aspect of the site (Fig. 2). We selected dosimetry sites from the available plug

Table 1 Radiography technique

Parameter	5-year-old phantom	Adult phantom
AEC (central sensors)	Yes	Yes
AEC air kerma threshold (μGy)	1.79[a]	2.50
Grid	No	Yes[b]
kVp	63	81
SID (cm)	102	102
Collimation (cm)[c]	26×23	34×40

AEC automatic exposure control, *kVp* kilovoltage peak, *SID* source-to-image distance

[a] Our AEC setting for smaller patients is lower than is typical due to dose limit testing performed as part of an earlier dose reduction project

[b] Anti-scatter aluminum grid with 13:1 grid ratio, 115-cm focal distance, 92 lines/cm, and size 460x460 mm was used (P/N 10757617; JPI Healthcare, Seoul, South Korea)

[c] Collimation was placed 2 cm above superior iliac crests, 2 cm below pubic symphysis, and covering the phantom laterally. Anatomy was estimated on phantom externally and confirmed by visualization on each slice

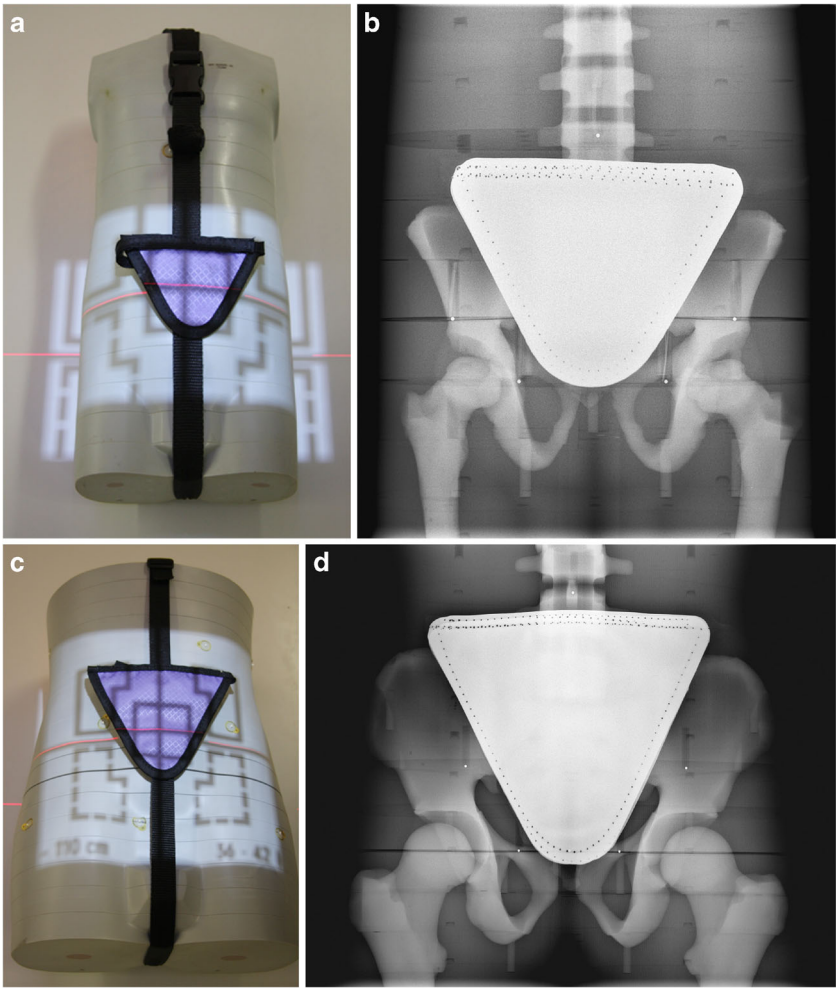

Fig. 1 The 5-year-old (**a, b**) and adult (**c, d**) dosimetry phantoms are shown with automatic exposure control (AEC) field overlays (**a, c**) and the resulting pelvis radiographs (**b, d**). The central AEC sensors, located within the square outlined in black in the center of the field, are the active AEC sensors for pelvis radiographs. The shield nearly completely covers the AEC sensors in the 5-year-old and completely covers them in the adult. Note that use of the peripheral sensors is not an option in the 5-year-old phantom because the body does not fully cover these sensors, which would result in underexposure. In the adult phantom, peripheral AEC sensors are covered by the body, but are also partially covered by the gonadal shield. BB's on the exposed radiographic images mark the inferior aspect of the dosimetry chambers

locations in the phantoms to best represent potential locations of the ovaries, colon and low-lying stomach. We selected analogous sites in the pediatric and adult phantoms, within the limits of the available plug locations. We first performed AP pelvis radiographs with gonadal shielding, then collected the film strips and replaced them with new ones. With the new film strips in place, we aligned the phantom with location markers on the table and repeated the pelvis radiographs without the gonadal shield. The sensitivity of film dosimeters is in the range of 1.0–200 mGy for the kVp in our exams, so we performed serial exposures to reach this range. For the 5-year-old phantom, the exposure was equivalent to 759 shielded exams or 1,201 unshielded exams (2,880 mAs in 9 exposures). For the adult phantom, the exposure was equivalent to 759 unshielded exams or 248 shielded exams (3,600 mAs in 10 exposures). For each of the three film strips in each of the six phantom locations, we sampled mean green values from pixels in 20 locations along the film strip, yielding a total of 60 dose measurements per location. We divided these cumulative doses by the number of clinical exams to determine the sampled site-specific absorbed dose per clinical exam.

We performed statistical analysis separately for the pediatric and adult phantoms. In both phantoms, we expressed change in mAs, DAP, and sampled absorbed organ dose with shielding as a percentage change from the unshielded condition. After graphically confirming a normal distribution of data, we summarized the absorbed organ dose at the dosimetry sites by mean and standard deviation. We evaluated the effect of shielding on the absorbed dose using a linear mixed-effects model, a method commonly used for analyzing correlated data such as repeated measures or clustered data. We modeled shielding as a fixed effect with adjustment for the site effect of different film dosimeter locations. We also took into account potential dose correlation arising from the green values being sampled at multiple sites of each film strip by including a strip-specific random effect. We used a compound symmetry covariance structure to model the within-strip correlation, which assumes the same correlation between any two locations on one strip. We defined significance threshold as $P<0.05$. We performed the statistical analysis using SPSS version 23 (IBM, Armonk, NY).

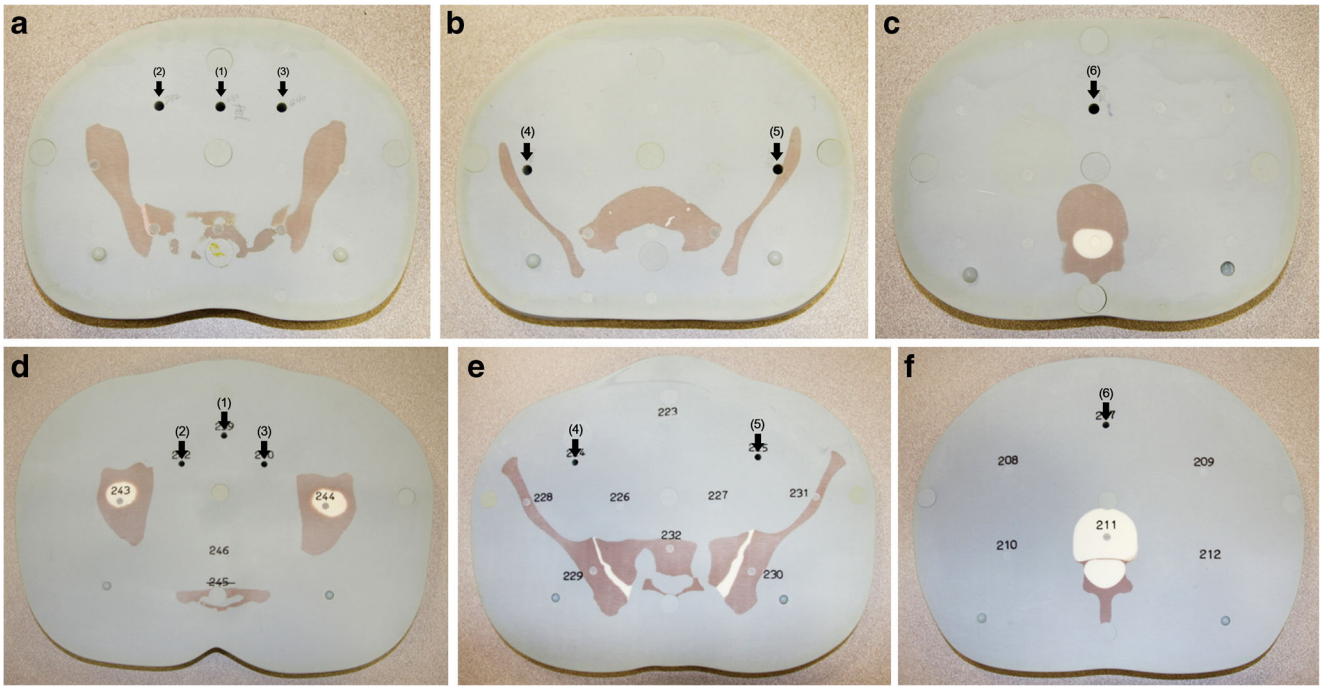

Fig. 2 Film dosimeters were placed in six plug locations in 5-year-old (**a–c**) and adult (**d–f**) equivalent dosimetry phantoms. Location 1 represents shielded ovary or colon. Locations 2 and 3 represent unshielded right and left low pelvic positions of ovary or colon. Locations 4 and 5 represent unshielded right and left high pelvic positions of ovary or colon. Location 6 represents unshielded low abdominal colon or stomach. We made efforts to select the most analogous sites in the 5-year-old and adult phantoms among the available dosimetry chambers

Results

For both phantoms, the cumulative dose was within our calibration curve, ranging 15–76 mGy for the pediatric phantom and 64–190 mGy for the adult. DAP and mAs increased with placement of the female gonadal shield in both phantoms (Table 2). Allowing for variation between DAP and mAs because of the variability in reported DAP, use of a gonadal shield increased these clinical dose parameters by approximately 60% in the 5-year-old phantom and by 147% in the adult phantom.

Absorbed dose at each of the unshielded dosimetry sites also increased when a shield was placed ($P<0.005$; Table 3). Dose decreased under the shielded area in both phantoms ($P<0.001$; Table 3). For the 5-year-old phantom, absorbed dose outside the shielded area increased 21–51% at pelvic sites where colon and unshielded ovaries might be located (Fig. 3). Absorbed dose at the lower abdominal site where colon or stomach may be located increased 44%. At the same time, absorbed dose at the shielded site where a midline ovary might be located decreased 67% in the 5-year-old phantom. For the adult phantom, absorbed dose outside the shielded area increased 17–90% at pelvic sites where colon and unshielded ovaries may be located (Fig. 3). Absorbed dose at the lower abdominal site where colon or stomach may be located increased 100% in the adult phantom. Under the shield, the absorbed dose at the midline pelvic site where an ovary might be located decreased just 16% in the adult phantom.

Table 2 Pelvis radiograph dose

Dose measure	5-year-old phantom			Adult phantom		
	Unshielded	Shielded	Percentage change[a]	Unshielded	Shielded	Percentage change
Tube output (mAs)	2.4	3.8	+58%	14.6	36.0	+147%
DAP (mGy·cm^2)	0.48	0.78	+63%	10.7	26.4	+147%

DAP dose–area product, *mAs* milliamperes

[a] The small difference in percentage change in mAs and dose–area product (DAP) is attributable to the 10% margin of error in DAP measurement

Table 3 Absorbed dose at dosimetry sites

Dosimetry site	Organs represented	5-year-old phantom dose (mGy)			Adult phantom dose (mGy)		
		Unshielded mean (SD)	Shielded mean (SD)	*P*-value	Unshielded mean (SD)	Shielded mean (SD)	*P*-value*
Medial pelvis	Ovary, colon	0.061 (0.001)	0.020 (0.001)	<0.001	0.76 (0.04)	0.63 (0.01)	<0.001
Right low pelvis	Ovary, colon	0.053 (0.002)	0.068 (0.006)	<0.001	0.57 (0.02)	0.66 (0.05)	<0.005
Left low pelvis	Ovary, colon	0.062 (0.002)	0.075 (0.005)	<0.001	0.55 (0.06)	0.80 (0.07)	<0.001
Right high pelvis	Ovary, colon	0.024 (0.001)	0.032 (0.002)	<0.001	0.77 (0.07)	1.34 (0.06)	<0.001
Left high pelvis	Ovary, colon	0.027 (0.002)	0.040 (0.001)	<0.001	0.72 (0.03)	1.36 (0.05)	<0.001
Medial abdomen	Stomach, colon	0.064 (0.002)	0.092 (0.003)	<0.001	0.67 (0.05)	1.33 (0.05)	<0.001

SD standard deviation

*We defined significance threshold as $P<0.05$

Discussion

Our results show increases in both clinical exam dose parameters and absorbed dose to unshielded sites when a female gonadal shield is used in conjunction with AEC. DAP, an indicator of dose in clinical exams, increased by 63% in the 5-year-old phantom and by 147% in the adult phantom in the presence of a gonadal shield (Table 2). While DAP might be inaccurate for measuring patient dose in clinical exams, the change in DAP under our controlled conditions is reliable and is proportional to the increase in effective dose that occurs if a gonadal shield is used with AEC for otherwise identical exam settings. Increases in sampled absorbed organ doses measured by film dosimeters were not as large as the increase in DAP due to beam attenuation at sites within the phantom. Our measurement of dose reduction under the shield is likely greater than would be expected for a typical location of the ovaries. The shielded sample site was anterior and midline, subject to complete coverage by the shield and minimal to no scatter. The typical location of ovaries is more lateral and posterior [24], which would have less dose reduction because of incomplete shield coverage and greater scatter. The difference between reduction in the shielded absorbed dose site of 16% in the adult phantom and 67% in the 5-year-old phantom is likely a result of the higher kV needed in the adult phantom to accommodate a larger body size, resulting in more scatter. In

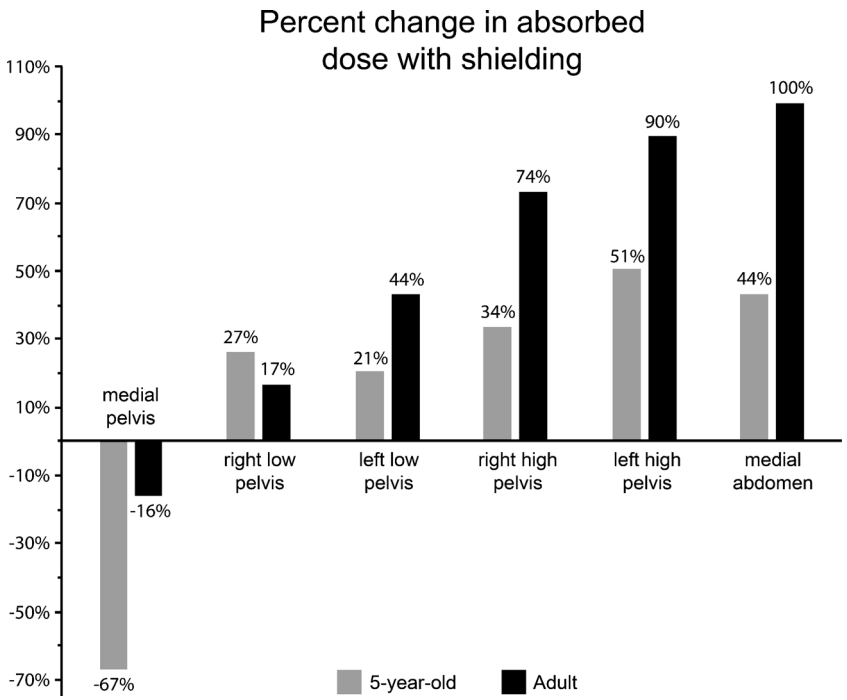

Fig. 3 Graph shows percentage change in sampled absorbed organ dose with placement of a female gonadal shield for individual dosimetry sites. The medial pelvis site represents shielded ovary or colon. The right and left low pelvis sites represent unshielded inferior positions of ovary or colon. The right and left high pelvis sites represent unshielded positions of colon or superiorly positioned ovary. The medial abdomen site represents unshielded position of colon or low-lying stomach. All changes in absorbed organ dose with gonadal shielding compared with no shielding were $P<0.005$ (Table 3). No error bars are displayed because the graph shows percentage change, not measured absorbed dose values

addition, the 0.5-mm lead-equivalent shield is less effective at higher kV, and attenuates fewer photons at 81 kV than it does at 63 kV. This difference in dose reduction in larger body habitus has clinical significance. Many of our adolescent hip radiographs are in overweight children with concern for slipped capital femoral epiphysis, so they would benefit less from gonadal shielding because of the higher kV needed for their exams. The balance of dose reduction with gonadal shielding would seem to be more favorable in a younger, smaller child. However, ovaries in younger children are more likely to be located outside the shielded area [24], so gonadal shielding in a small child would be more likely to paradoxically increase absorbed dose to the ovaries themselves.

In the United States, 46 of 50 states have legal statutes requiring use of gonadal shields [30]. In most, a clause for physician discretion is included. However, physicians have little guidance for forming institutional policies. The American College of Radiology and Society for Pediatric Radiology practice guidelines state, "Gonad shielding should be used when appropriate as per department protocol" [31]. The ICRP recognizes that "In abdominal or pelvic examinations for girls, gonad protection may not be possible" [32], but stops short of making practice recommendations. Technologist guidelines state that shields should not be placed in a position that could interfere with the ability of the radiography software to identify the exposure field [15]. To comply with gonadal shielding laws, technologists would be required to turn off the AEC for female pelvis radiographs before performing a shielded exam. No other examinations require a technologist to manually disengage the AEC, and this exception to the normal workflow introduces yet another opportunity for systematic error into the already error-prone practice of gonadal shielding [29].

AEC sensors are not present throughout the field of view but are configured in central or peripheral arrangements based on the body part being examined and the imaging protocol in use (Fig. 1). These fields do not change with collimation or patient size. Using peripheral AEC fields while shielding the central pelvis could potentially avoid shield–AEC interaction but would likely result in frequent underexposure if the patient's body did not fully cover the AEC [16]. As demonstrated in Fig. 1, the peripheral AEC fields are not covered in the 5-year-old phantom. The position of the AEC sensors in relation to a shield and the patient's body depends on collimation and centering of the field of view, so it is possible to still attenuate a peripheral AEC with a gonadal shield if the patient is not centered in the field of view. Eliminating AEC from pelvis protocols could be considered, and this would allow gonadal shield use with manual technique. However, AEC is very effective at optimizing dose, and it is likely that more repeat studies would occur because of poor image quality if AEC were not used. For manual radiography protocols, there is a tendency toward "dose creep," with technologists and radiologists preferring studies with higher dose and better image quality [33]. Given the low risk to the gonads during diagnostic radiography, there is little to be gained by developing protocols to allow gonadal shielding at the expense of image quality and likely increases in overall dose.

Although our study is the first to examine the adverse dose effects of gonadal shielding from interaction with the AEC, other authors have described an array of other problems. Gonadal shielding has been found to obscure clinically important structures, prompting repeat imaging in up to 28% of exams in one study [27]. The need to repeat exams is difficult to quantify because suboptimal images might be discarded and therefore omitted from quality assurance reviews, leading to underestimation of the number of malpositioned gonadal shields requiring repeat exams. Correct positioning and consistent use of gonadal shields has been documented to occur just 8–22% of the time in females and 25–46% of the time in males [19–21, 26]. The frequency of true ovarian shielding is likely lower because the position of the ovaries changes with age and bladder volume. In as many as 35.2% of girls, ovaries are located outside the pelvic rim [24, 25]. It is possible to improve gonadal shielding through practice quality-improvement efforts [21]. Although families often request or even insist on shielding, inconsistent use of gonadal shields might also be concerning to families, who might see this variation in practice as a sign of poor-quality medical care. Some practices have eliminated gonadal shielding based on low estimates of benefit compared with the persistent problems of poor consistency in use, inadequate positioning, and the risk of obscuring important findings [27].

While our study provides quantification for the dose increases that can occur when a gonadal shield is used in conjunction with AEC, we do not attempt to describe the range of dose increases that could occur in patients. Our study used only two phantoms, of two different sizes, and used only one size, thickness and position of the shield for each phantom. For each phantom, we tested only one condition for collimation, filtration, grid use, source-to-image distance and detector air kerma. We measured absorbed organ dose just at six sampled sites, which do not represent the absorbed dose to the entire organ. For patients, the amount of colon or stomach in the field of view varies by collimation and individual anatomy. The absorbed organ doses in this study were measured following a single series of exposures for each condition, rather than multiple independent exposures. This technique complements the use of film dosimetry strips and was accounted for in the use of the linear mixed-effects model for statistical analysis of repeated measures. Our preliminary work on phantom dosimetry with gonadal shielding confirms similar direction but different magnitude for changes in absorbed dose with shielding [34]. Differences between our preliminary results and our current results primarily arise from use of different dosimetry sites and preclude combining earlier data with our current

work. In this paper, we attempted to model the dose effects of gonadal shielding for two body sizes and radiography techniques by measuring comparable dosimetry sites in two different-size phantoms. We describe percentage change in DAP and absorbed dose with shielding to estimate the dose differences that could occur in a patient if a shield is inadvertently placed over an active AEC compared with using no shield. Assessing percentage change minimizes the role of technical factors and institutional settings such as AEC air kerma threshold, which were the same for both shielded and unshielded conditions in our study but might differ among institutions. Our 1.79-μGy AEC air kerma threshold is lower than the standard setting because of earlier efforts to reduce dose for small children, who bear relatively higher risks with radiation exposure. By medical physics standards, the AEC threshold should be lower for large patients than for small patients, allowing the possibility to further lower dose in our larger patients by adjusting the AEC threshold lower for these exams.

At our institution, we are reconsidering our gonadal shielding policies, which currently call for shielding one view of a 2-view orthopedic pelvis exam. Our orthopedic service orders nearly 2,000 2-view pelvis exams annually, so any change would affect a large number of patients and the providers who rely on our exams. While female gonadal shielding increases dose when used in combination with AEC, it remains to be seen how often this problem occurs in clinical practice. In addition, any change in policy would require a comprehensive assessment of shielding for both boys and girls. While a female shield might easily cover the AEC sensors, a male shield would not be expected to obscure the sensors. However, male shields might be malpositioned in a way that overlaps the AEC sensors, or the exam might be poorly collimated with AEC sensors underlying a male gonadal shield. It would be preferable to have a single policy on gonadal shielding, rather than a gender-specific policy that calls for shielding in boys but not girls, and more research remains to be done in this area.

The concern over gonadal irradiation is deeply ingrained in the public imagination. In addition to the many popular stories about the mutant powers of radiation, there is likely a lasting imprint of early concerns over gonadal risk. People might also confuse the stochastic risks at very low levels of radiation, such as in diagnostic imaging, with the well-publicized deterministic effects at high levels of radiation that can result in infertility for radiation oncology patients. Medical professionals in radiology need to continue educating colleagues, patients and families on evolving best practices in medical radiation use. Lead-equivalent shielding of tissues adjacent to the field of view remains appropriate for reducing exposure to unnecessary scatter radiation [16, 31]. However, current understanding of radiation biology and the clinical risk-to-benefit ratio of gonadal shielding argue against placing radiopaque shields within the field of view.

Conclusion

Female gonadal shields used in combination with AEC are likely to increase overall radiation risk by increasing absorbed dose to the more radiation-sensitive colon and stomach as well as to ovaries positioned outside the shielded area. The dose savings under the shield likely diminish as patient size increases. With the lower w_t now assigned to gonads, there is no compelling reason to continue using gonadal shields.

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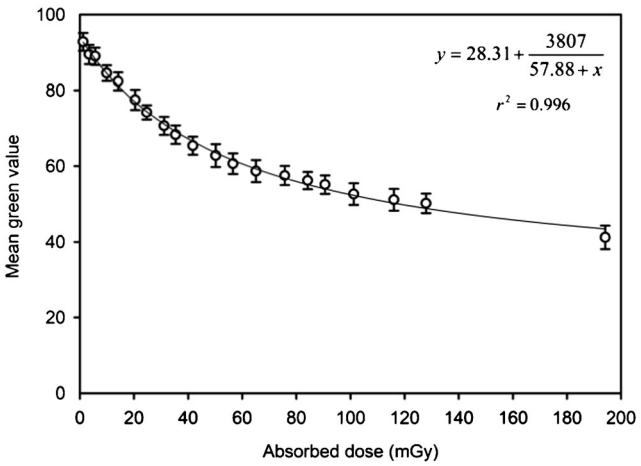
Compliance with ethical standards

Conflicts of interest None

Appendix 1 Calibration curve



This calibration curve was used to determine absorbed dose from film dosimeters implanted in the phantoms. To make the curve, we exposed film samples (Gafchromic, Ashland) together with a solid state radiation detector (Black Piranha with an external T20 dose probe; RTI Group AB, Sweden) to multiple known amounts of radiation between 2.17 and 124.4 mGy. The solid state detector is calibrated on a 2-year cycle by the manufacturer's accredited calibration laboratory (ISO/IEC 17025). During calibration the detector is compared to a reference ion chamber, which is traceable through PTB (Germany) to national or international measurement standards. The standard uncertainty of measurement is in compliance with EAL Publication EA-4/02 and is ±1.4% at standard

reference condition. The uncertainty increases to ±2.7% when the T20 probe is used with a calibrated Piranha for radiation dose measurements. We measured film green values from these exposures and fit the calibration green values to a three-parameter hyperbolic decay curve as above, where y = film darkening, or mean green value, and x= absorbed dose in mGy. The film was scanned using a commercially available flatbed optical scanner (Mustek Systems Inc., Taiwan). The resultant images were evaluated with ImageJ 1.48v software (National Institutes of Health, Bethesda, MD), and the curve fit for the data was analyzed using Sigma Plot 13 (Systat Software Inc., San Jose, CA). The coefficient of determination R^2=0.996, indicated that the exponential decay function fit the calibration data well. We calculated absorbed dose in our experiments by locating the mean green values of our exposed films along this calibration curve.

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