Lead-rubber shielding effect on radiation dose to the gonads from a bilateral hand X-ray examination

Welborn, D, and Lockwood, P.

Introduction

The dose received from diagnostic X-ray examinations has no deterministic effects but poses the risk of stochastic effects.[1] Therefore, with the assumption that all ionising radiation carries the risk of causing malignant harm, there is always a need to follow the As Low As Reasonably Practicable (ALARP) principle,[2,3] especially when concerning radiosensitive organs such as the gonads.

Due to the risks involved with ionising radiation, there have been several studies exploring methods of dose reduction. For example, research by Debes et al.[4] and Zetterberg and Espeland[5] have investigated the use of collimation to reduce dose, and Hayre et al.[6] who investigated the use of lead (Pb) shielding inferolateral to the light beam diaphragm to limit radiation exposure. Due to the high density and atomic number (Z=82) of Pb, it grants high photoelectric absorption to ionising radiation from a diagnostic X-ray beam[7] and is commonly used in both research and clinical practice alongside other radiation protection methods, such as collimation and distance, to limit the radiation dose the patient receives. Application of Pb shielding is also deemed good practice by the International Atomic Energy Agency (IAEA)[8] to protect radiosensitive organs.

Within the United Kingdom (UK), over ten million people have arthritis.[9] Joints within the hands are one of the most commonly affected areas and can be diagnosed at any age.[10] Bilateral hand X-rays are frequently undertaken to diagnose and monitor rheumatological disorders, predominantly in rheumatoid arthritis.[11]

Bilateral hand X-rays are performed with the patient facing towards the examination table, X-ray detector and primary X-ray beam. Both hands are placed upon the detector pronated into a dorsi-palmer (DP) position side by side. This is often accompanied by a ball-catcher (Nørgaard) projection where both hands are supinated with the dorsal aspect placed upon the detector with a 45-degree medial rotation.[11] As patients are positioned facing the primary beam, it creates a risk of receiving a radiation dose to the gonads due to scattering secondary radiation.[12]

Hayre et al.[6], Hayre, Bungay, and Jeffery[13] exploring radiation dose from an elbow X-ray examination and Mekiš, Zontar and Skrk[14] investigating lumbar spine X-ray examinations have all conducted experiments into the use of Pb shielding to assist dose reduction and radiation protection. The work of Hayre et al.[6]; Hayre, Bungay, and Jeffery[13] and Mekiš, Zontar and Skrk[14] have demonstrated that the use of Pb shielding resulted in a reduction of dose from scattered secondary radiation towards the shielded radiosensitive organs. Confirmation of this finding can be seen in the work of Singhal et al.[15] and Stranden et al.[16] who determined using Pb shielding covering male gonads during radiographic examinations, where the gonads are not located within the primary beam, results in a reduction of dose to the gonads. Clancy et al.[17] surmised that it is in the best interest of patients during a lumbar spine X-ray examination to have their gonads covered by Pb shielding. However, Clancy et al.[17] did not measure the dose received to the female gonads during their experiment. Warlow, Walker-Birch and Cosson[18] reasoned that Pb shielding for female gonads during anterior-posterior (AP) pelvic X-ray examinations is not practical due to varied positions of ovaries and the risk of covering the desired anatomy. However, Warlow, Walker-Birch and Cosson[18] rationalised that Pb shielding for male gonads during AP pelvis X-ray examinations remains practical.

Warlow, Walker-Birch and Cosson[18] discussed the impracticality of female gonadal protection due to the gonads being located within the primary beam of AP pelvis X-ray examinations. However, for this experiment, the ovaries will be located outside of the primary beam. Within the literature for Pb protection towards gonads, there appears to be a bias towards testes compared to ovaries. Therefore, this experiment design will consider the dose received by both the testes and ovaries. With various literature revolving around the use of Pb shielding during radiographic examinations[6,13-18], there has not as yet been any exploration of bilateral hand X-ray examinations.

It has been acknowledged by Hayre et al.[19] that some radiographers do not utilise the use of Pb shielding during their practice, and recent guidance from the British Institute of Radiology (BIR)[20] and the American Association of Physicists in Medicine (AAPM)[21] recommends the cessation of patient Lead-rubber (Pb) shielding placed within the Field of View (FOV) that may influence image exposure or quality. Furthermore, the BIR[20] assert shielding organs greater than 5cm from the primary X-ray beam will have a negligible effect to the received radiation dose.

This, alongside a paucity of literature concerning gonadal dose during bilateral hand X-rays, is the rationale for this research. The aim is to investigate the scattered secondary radiation dose to the gonads during a bilateral hand X-ray using a phantom, with and without Pb shielding outside the FOV at a greater distance than 5cm from the primary beam. The null hypothesis (H_0) is that there would be no statistically significant dose reduction to the gonads during a bilateral hand X-ray between the two observations. The alternate hypothesis (H_1) is that there would be a statistically significant dose reduction to the gonads during bilateral hand X-ray between the two observations.

Method

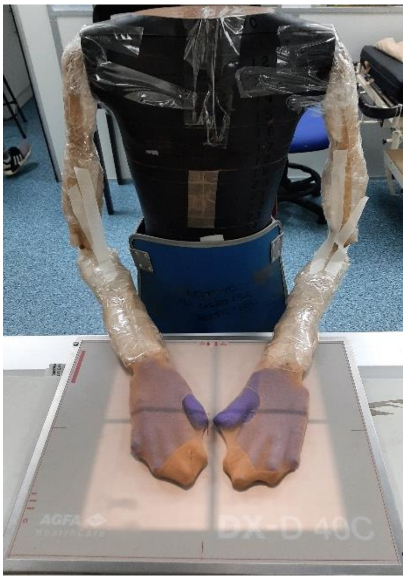
The experiment was carried out within a controlled X-ray laboratory setting with a standard X-ray tube (Siemens X-ray tube Opti 150/30/50HC-100, Germany), and Digital Radiography (DR) equipment (AGFA NX3.0 Muscia Acquisition Workstation, AGFA DX-D 40C cassette 43x35cm, Belgium). The radiation was measured with Ion radiation dose chambers (Fluke Biomedical LLC

150cc Ion chamber and TNT 12000 DoseMate, USA), a Dose Area Product (DAP) with a reader (KermaX plus DDP, Iba Dosimetry, Germany), and Thermoluminescent Dosimeters (TLD's) Lithium Fluoride (LiF) detector chips (Landauer ⅛" x ⅛" x 0.15" TLD-100H, England). The research followed the local rules set out by the Radiation Protection Supervisor, adhering to the Ionising Radiations Regulations.[3] An ethical application and risk assessment was submitted and approved by (*anonymised for peer review*) University Faculty Ethics Panel (S18/RPR/DW).

An anthropomorphic phantom (RANDO Phantom, Alderson Research Laboratories Inc., USA) with human tissue equivalence was used to represent the 'patient' due to containing similar tissue densities and comparative radiosensitive organs to that of a human adult.[22] There were various considerations into the material used to construct the upper limb phantoms, including human bone, porcine bone and artificial bone substitute. Human bone was rejected as a suitable material due to restrictions from the Human Tissue Act.[23] Although porcine bone has similar bone morphology, anatomy and bone mineral density to human bone,[24,25] this material was rejected due to the inability to procure a similar anatomy size and shape to replicate the upper limbs. Therefore, an artificial bone substitute was used, which was created from materials containing similar mineral components to natural bone. The bone substitute was made using the methods from Tins and Kuiper[26] using multi-purpose powder filler (Bartoline Ltd, UK) mixed with polystyrene pellets simulating spongey bone with fatty marrow spaces. The 'spongey bone' was covered in a layer of air-drying modelling clay (DAS, Daler-Rowney, UK), with a thickness of 2-3mm to simulate cortical bone. The multi-purpose filler consisted of calcium magnesium carbonate, calcium sulphate hemihydrate and organic acids, acting as setting time modifiers. The mineral components were similar to natural bone and had a similar attenuation to natural bone.[26] The humeral, ulna and radial bones were created separately, but the phalanx and metacarpal bones for each finger were assembled together, and the carpal bones for each wrist were formed together. To represent the soft tissue for the upper limb phantoms, saline bags filled with water were used due to having a similar density to human muscle and fatty soft tissues.[6] The limbs were held together with thin fabric to maintain an anatomical shape (figure 1).

Figure 1. Phantom upper limbs assembled.

There were six exposures carried out in total, three without the use of Pb shielding (Wardray, UK) shown in figure 2, and three exposures with the use of Pb (rubber) shielding shown in figure 3.

Figures 2 and 3. Phantom positioned without (left) and with (right) Pb (rubber) shielding at the waist.

Exposure factors of 60kVp and 2.5mAs hand X-ray examination pre-sets were used, reflecting local clinical practice of bilateral hand X-rays exams. The source to image distance (SID) was at 100cm. The phantom was placed into a position mimicking a patient attending a bilateral hand X-ray examination, with their hands in the DP position (figure 4). The image centering point, tube collimation and phantom positioning followed recommended best practice radiographic positioning techniques for hand X-rays. The phantom was positioned 'seated facing the table' (Whitely et al.[27] p.59), legs 'not under the table to avoid direct exposure by the primary beam' (Whitely et al.[27] p15), but 'seated at the end of the table with lead shielding' (Lampignano and Kendrick,[28] p.25). These independent variables (IV) remained constant throughout the experiment.

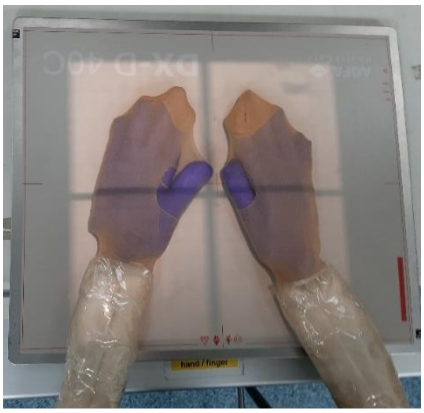


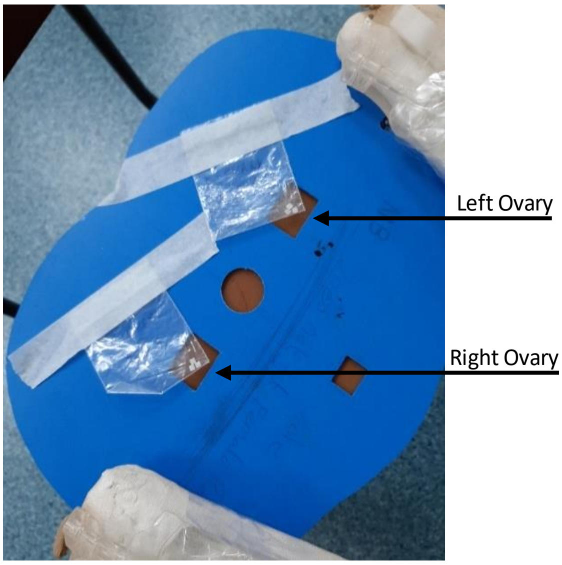
Figure 4. Bilateral hand DP positioning of the phantom upper limbs.

Quality assurance (QA) was carried out on the X-ray tube before the experiment using an ion chamber (DoseMate, Fluke Biomedical LLC, USA), DAP reader (KermaX plus DDP, lba Dosimetry, Germany) and exposure factors of 60kVp and 2.5mAs, to ensure consistency of the tube (Siemens Healthcare GmbH, Belgium). The Pb shielding (Wardray, UK) was screened radiographically to ensure integrity of the apron and confirm no defects (cracks, changes in lead equivalence, or deterioration of the vinyl) were present.

During the QA, all the TLDs were first annealed prior to any irradiations using the TLD oven (Carbolite TLD/3, England) for thermal treatment of 30 minutes to warm up to 243 degrees Celsius (^{o}C), then 10 minutes at 243^{o}C before 20 minutes forced cooling down to 100^{o}C, then cooled to room temperature. The TLD's (Landauer, England) were calibrated with an initial exposure (the TLD's store the energy received from ionising radiation), and the light counts read in the TLD reader (Harshaw 5500 TLD Reader, Thermo Scientific, USA) using software (Win REMS v.8.1.0.0, Saint-Gobain Crystals & Detectors, USA). The TLDs were then organised into groups of three based on a sensitivity factor to avoid variations owing to individual sensitivity of each TLD, improving the reproducibility of the batch and reducing the relative standard deviations to a few percent. TLD batch uniformity/homogeneity (amount of variation from the mean reading of the group) was determined by the total light emission during the heating process and reading of the glow curve of several glow peaks at different temperatures to record different thermal stability. This follows international requirements established by the International Electrotechnical Commission.[29] During reading of the TLDs (lithium fluoride chips) by the reader under nitrogen atmosphere (Harshaw 5500 TLD Reader TLD, Thermo Scientific, USA) the TLD emits light to the intensity of which is proportional to the energy deposited during irradiation.[30] As such, it provides an accurate level of measurement due to its high sensitivity to detect the luminescent emission in respect to the energy of low dose radiation.[30]

The background dose was calculated (Win REMS v.8.1.0.0, Saint-Gobain Crystals & Detectors, USA) using the three most sensitive TLD's placed within the X-ray control room away from and shielded to the primary beam. The remaining TLD's were divided with vacuum tweezers (Dymax 30, Charles Austen Pumps, England) into groups of three and placed at the site of each gonad (figures 5, 6 and 7) within the phantom (female representation) and outside the phantom (male representation). It is recognised that the position of the ovaries varies significantly, with age and with body habitus,[18] and the phantom position of female gonads is based on an average, to demonstrate the concept.

Once exposed, the TLD's were placed with vacuum tweezers (Dymax 30, Charles Austen Pumps) within the TLD reader (Harshaw 5500 TLD Reader TLD, Thermo Scientific) and heated, causing them to emit light. This light was then read by a photomultiplier measuring the intensity of the light counts. The intensity of the light is proportional to the energy deposited during irradiation the TLD was exposed to.[31,21] The radiation dose was then calculated from the TLD light counts (Win REMS v.8.1.0.0, Saint-Gobain Crystals & Detectors), with the background dose subtracted to increase the precision of the radiation dose values further. Finally, a mean dose was calculated from each group of three TLD's. Three exposures with and without Pb shielding were undertaken to calculate the mean dose values to each gonad to counter anomaly from any electrical fluctuation variance from the generator, further enhancing the precision of dose values.



Figures 5 and 6. Demonstrating the location of the TLD placement into the left and right ovary positions of the anatomical holder (blue plate) of the phantoms pelvis.

Figure 7. Demonstrating the location of the TLD placement positioning over the testes of the phantom.

Statistical analysis will calculate the mean doses of the exposures to the testes, left and right ovary and a paired two-sample *t*-test will determine any dose limitation between the use of with and without Pb shielding. The *t*-test approach was selected to test the null hypothesis (H_0) from the sample and calculate a *p*-value. The *t*-test *p*-value significance is determined if there is a 5% ($p \leq 0.05$) or less finding, which would signify a difference between the samples to reject the null hypothesis (H_0) and consider any statistical significance within the experimental results.[33,34]

Results

The mean doses recorded in microgray units (µGy) for each exposure and the overall mean with and without Pb shielding are displayed in Table 1. In addition, the standard deviation (SD) for each mean dose calculation allows a measure of the accuracy of the spread of the data around the mean, which is useful when comparing sets of data with similar mean scores. The overall limitation of dose with Pb shielding is displayed within Table 2, demonstrating a reduction of dose to all the gonads, notably to the testes with a reduction of 56.6%. Additionally, the left ovary and right ovaries recorded a 29.2% and 32.4% reduction, respectively.

	Without Pb covering gonads				
Gonad	**Exposure 1 (µGy)**	**Exposure 2 (µGy)**	**Exposure 3 (µGy)**	**Mean (µGy)**	**SD**
Testes	5.2	4.4	6.0	5.2	0.8
Left Ovary	40.1	39.8	42.1	40.6	1.2
Right Ovary	39.8	36.2	39.4	39.5	1.9
	With Pb covering gonads				
Gonad	**Exposure 4 (µGy)**	**Exposure 5 (µGy)**	**Exposure 6 (µGy)**	**Mean (µGy)**	**SD**
Testes	2.3	2.5	2.0	2.3	0.2
Left Ovary	28.3	27.3	30.7	28.8	1.7
Right Ovary	26.2	26.0	27.8	26.6	1.0

Table 1. Dose (µGy) to gonads - with and without the use of lead-rubber (Pb).

Gonad	**Without Pb Mean dose (µGy)**	**With Pb Mean dose (µGy)**	**Dose Difference (µGy)**	**Dose Reduction (%)**
Testes	5.3	2.3	3.0	56.6%
Left Ovary	40.6	28.8	11.9	29.2%
Right Ovary	39.5	26.6	12.8	32.4%

Table 2. Dose (µGy) reduction to gonads when lead-rubber (Pb) applied.

The data determines that Pb shielding covering the gonads during a bilateral hand X-ray will limit the ionising radiation dose received by the gonads. The results of the paired two-sample *t*-test of the mean doses displayed in Table 3 demonstrate the number of observations (*n*), the overall mean with and without Pb, the SD, degrees of freedom (df) and the value of *t* alongside the *p*-value.

	n	**Mean dose (µGy)**	**SD**	**df**	***t*-score**	***p*-value**
Without Pb protection	9	28.2	1.3	8	5.8	0.0039
With Pb protection	9	19.3	1.0	8		

Table 3. Paired two sample t-test for mean scores.

With a *p*-value of *p*=0.0039 the results are statistically significant, predicting the limitation of the dose being achieved when Pb shielding is placed over the gonads during a bilateral hand X-ray. This result allows the rejection of the null hypothesis (H_0) and acceptance of the alternate hypothesis (H_1) of a difference (reduction) in dose values.

Discussion

Although the radiation doses used within X-ray imaging are extremely low, and follow ALARP practices, research by Pijipe et al[35] and Nguyen et al[36] highlight the risk of radiation induced genetic damage at low doses and the epidemiological evidence of cancer (stochastic risk) from radiation by Ozasa et al[37] suggest there is importance in exploring the use of Pb shielding outside the FOV imaging.

Based on the results, when Pb shielding is placed over the gonads, there were significant reductions to the testes (56.6%), left ovary (29.2%) and right ovary (32.4%). Using exposure factors commonly used for a diagnostic bilateral hand X-ray within the experiment further demonstrates the evidence of Pb shielding for radiation protection in clinical settings. Regarding the percentage of dose limitation to each of the gonads, the testes received the highest reduction. Possibly due to the distance furthest away from the ovaries in comparison to the primary beam. Additionally, the left ovary received more dose than the right ovary during both observations (with and without the use of Pb shielding), as well as a lower percentage of dose limitation (table 2). Potentially, this may be due to TLD sensitivity and/or human error by the phantom being positioned with the left side marginally closer to the primary beam. Consideration is further warranted to account for the source of organ dose recorded, and acknowledgement that the Pb shielding may have contributed to this. The AAPM[21] state the main source of radiation dose to internal organs outside the imaging FOV is internal body scatter, and that surface shielding would not reduce this residual dose recorded. Acknowledging this the BIR[20] state internal scatter is however difficult to quantify, and difficult to shield. That said there is additionally the possibility that a small and superficial proportion of the organ dose received is from extra-focal back scatter [38,39] from objects under and around the patient (chair, table, etc) which might also have contributed to the organ dose recorded.

Similar to this experiment, Singhal et al.[15] and Stranden et al.[16] concluded a reduction of dose to the testes when Pb is used, when the testes are not located within the primary beam. Thus, the results from this experiment corroborate their findings and further demonstrates a reduction in dose to the ovaries under the same conditions. Additionally, Hayre, Bungay and Jeffery[13] demonstrate similar decreased doses of male and female gonads during a left lateral elbow X-ray. Although, Hayre, Bungay and Jeffery[13] utilised a full Pb apron as opposed to just a Pb sheet. Regardless, there was still a statistically significant reduction in dose to male and female gonads (tables 2 and 3).

The international body of consensus around keeping X-ray doses ALARP and the endorsement of Pb shielding currently includes the IAEA,[8] the Image Gently Campaign,[40] and the European ALARA network,[41] and this experiment further confirms these recommendations. Although, recently representatives from various UK radiological professional bodies BIR, The Society and College of Radiographers, The Royal College of Radiologists, Institute of Physics and Engineering in Medicine, Society for Radiological Protection and Public Health England reviewed[20,42] the evidence-base for patient contact shielding. Their conclusion was to recommend that for the majority of imaging procedures, Pb shielding is not recommended within general radiography.[20,42] However, the BIR[20] guidance focuses on shielding placed within the FOV which may cut off anatomy or effect the Automatic Exposure Control (AEC), thus further increasing the radiation dose should not be used. Therefore, the BIR[20]recommend other positioning should be used where possible, and as such, organs outside the primary beam by more than 5cm have a 'negligible risk' from the radiation dose received. Regarding the gonads, the BIR[20] do not currently recommend Pb shielding except for the male gonads if they are less than 5cm from the primary beam. However, the results from this experiment demonstrated a statistically significant dose reduction towards the gonads at a distance greater than 5cm from the primary beam.

The IR(ME)R[2] legislation ensures the safety of all individuals where ionising radiation is used from any medical imaging examination and is enforced by the Care Quality Commission.[43] The ALARP principle within IR(ME)R[2] applies to any radiographic examination ensuring that patients receive as little dose as possible. Conceivably this is down to the referrers, operators and practitioners; if the radiograph is justified, the dose to anatomy outside the area of interest needs to be limited.

Additionally, within the Health and Care Professions Council Standards of Proficiency for Radiographers[44] section 2.5-2.6 and 4, states radiographers must be up to date with all current legislation pertaining to their role and practice as autonomous professionals. With this in mind, it is at the discretion of the radiographer to use their judgement on how they interpret the ALARP principle and the evidence within their profession and practice on Pb shielding. Feasibly this can be done by radiographers applying Pb shielding to the pelvic area during hand x-rays, as evidenced by the results of this experiment (tables 2 and 3) limiting dose to the gonads.

Limitations

Due to the practicalities of radiographic positioning of the anthropomorphic phantom for long periods of testing, the positioned adopted followed the example shown in Clark's Positioning in Radiography[27] 'seated facing the table' (Whitely et al.[27] p.59), and Bontrager's Handbook of Radiographic Positioning and Techniques[28] 'seated at the end of the table with lead shielding' (Lampignano and Kendrick,[28] p.25). In this position both male/female gonads would be equidistant to the image receptor. But we acknowledge the position of the patient in clinical practice during bilateral hand radiography may also adopt a more flexible position of having the pelvis orientated to the side of the table, therefore both hands would be at 90 degrees to the pelvis with the chest facing the image receptor and the torso/abdomen twisting somewhere in between as displayed in Clark's Positioning in Radiography[27] for a single hand examination (Whitely et al.[27] p.58). In the twisted torso position one of the gonads would be further away from the other and the x-ray tube and thus this would potentially influence the absorbed dose.

Additionally, it is recognised that the use of different radiographic manufacturer equipment and exposure factors may provide a variance in results. This study covered only one radiographic projection of bilateral hand, in clinical practice, two projections (DP and ball-catcher) would be performed for arthritic assessment, further increasing radiation exposure and dose.

Conclusion

The study demonstrated dose limitation from scattered secondary radiation to the gonads when Pb shielding was used during a bilateral hand X-ray positioned facing the table/image receptor at distances greater than 5cm from the primary X-ray beam on anatomy outside the FOV. The difference evident in the radiation dose reduction measured were significant (p=0.0039) to the testes (56.6%), left ovary (29.2%) and right ovary (32.4%), when assessed within the experiment.

References

1. Farr RF, Allisy-Roberts PJ, Physics for medical imaging. 1997. Saunders Company.
2. Ionising Radiation (Medical Exposure) Regulations (IR(ME)R) 2017 (SI 2017/1322). London HMSO 2017. http://www.legislation.gov.uk/uksi/2017/1322/made
3. Ionising Radiations Regulations (IRR) 2017 (SI 2017/1075). London HMSO 2017. http://www.legislation.gov.uk/uksi/2017/1075/contents
4. Debess J, Johnsen K, Sørensen KV, Thomsen H. Digital chest radiography: collimation and dose reduction. European Congress of Radiology 2015. https://doi.org/10.1594/ecr2015/C-1939
5. Zetterberg LG, Espeland A. Lumbar spine radiography—poor collimation practices after implementation of digital technology. The British Journal of Radiology 2011;84(1002):566-9. https://doi.org/10.1259/bjr/74571469
6. Hayre C, Bungay H, Jeffery C, Cobb C, Atutornu J. Can placing lead-rubber inferolateral to the light beam diaphragm limit ionising radiation to multiple radiosensitive organs?. Radiography 2018;24(1):15-21. https://doi.org/10.1016/j.radi.2017.09.002
7. Seeram E, Brennan PC. Radiation protection in diagnostic X-ray imaging. Jones & Bartlett Publishers; 2017.
8. International Atomic Energy Agency. Good practices in radiography. 2021. https://www.iaea.org/resources/rpop/health-professionals/radiology/radiography/good-practices
9. National Health Service. Overview: Arthritis. 2018. https://www.nhs.uk/conditions/arthritis/#:~:text=In%20the%20UK%2C%20more%20than,of%20all%20ages%2C%20including%20children
10. Koarada S. (ed.) Rheumatoid Arthritis: A Systemic Approach. Volume 3; Bentham Science Publishers. 2018.
11. Whitley AS, Sloane C, Hoadley G, Moore AD, Alsop W. Clark's Positioning in Radiography. 12th edn. 2005. London: Arnold.
12. Bushberg JT, Boone JM. The essential physics of medical imaging.3rd edn. Lippincott Williams & Wilkins; 2011.
13. Hayre CM, Bungay H, Jeffery C. How effective are lead-rubber aprons in protecting radiosensitive organs from secondary ionizing radiation?. Radiography 2020;26(4):e264-9. https://doi.org/10.1016/j.radi.2020.03.013
14. Mekiš N, Zontar D, Skrk D. The effect of breast shielding during lumbar spine radiography. Radiology and Oncology 2013;47(1):26-31. https://doi.org/10.2478/raon-2013-0004

15. Singhal MK, Kapoor A, Singh D, Bagri PK, Narayan S, Nirban RK, Kumar HS. Scattered radiation to gonads: role of testicular shielding for para-aortic and homolateral illiac nodal radiotherapy. Journal of the Egyptian National Cancer Institute 2014;26(2):99-101. https://doi.org/10.1016/j.jnci.2014.03.002
16. Stranden E, Andersen DA, Bergwitz-Larsen E, Eriksen JA, Hydal JB. Main factors influencing the use of scrotum shields during X-ray examinations in major hospitals in Norway and Denmark. European Journal of Radiography 2009;1(1):7-11. https://doi.org/10.1016/j.ejradi.2008.12.002
17. Clancy CL, O'Reilly G, Brennan PC, McEntee MF. The effect of patient shield position on gonad dose during lumbar spine radiography. Radiography 2010;16(2):131-5. https://doi.org/10.1016/j.radi.2009.10.004
18. Warlow T, Walker-Birch P, Cosson P. Gonad shielding in paediatric pelvic radiography: Effectiveness and practice. Radiography 2014;20(3):178-82 https://doi.org/10.1016/j.radi.2014.01.002
19. Hayre CM, Blackman S, Carlton K, Eyden A. Attitudes and perceptions of radiographers applying lead (Pb) protection in general radiography: an ethnographic study. Radiography 2018;24(1):e13-8. https://doi.org/10.1016/j.radi.2017.07.010
20. The British Institute of Radiology. Guidance on using shielding on patients for diagnostic radiology applications. 2020. The British Institute of Radiology https://www.bir.org.uk/media/416143/final_patient_shielding_guidance.r1.pdf
21. American Association of Physicists in Medicine. AAPM position statement on the use of patient gonadal and fetal shielding. Policy Statement PP-32A 2019. American Association of Physicists in Medicine. https://www.aapm.org/org/policies/details.asp?id=468
22. Wu J, Shih CT, Ho CH, Liu YL, Chang YJ, Chao MM, Hsu JT. Radiation dose evaluation of dental cone beam computed tomography using an anthropomorphic adult head phantom. Radiation Physics and Chemistry 2014;104:287-91. https://doi.org/10.1016/j.radphyschem.2013.11.024
23. Human Tissue Act. c. 30. London HMSO 2004. https://www.legislation.gov.uk/ukpga/2004/30/contents
24. Aerssens J, Boonen S, Lowet G, Dequeker J. Interspecies differences in bone composition, density, and quality: potential implications for in vivo bone research. Endocrinology 1998;139(2):663-70. https://doi.org/10.1210/endo.139.2.5751

25. El-Rashidy AA, Roether JA, Harhaus L, Kneser U, Boccaccini AR. Regenerating bone with bioactive glass scaffolds: A review of in vivo studies in bone defect models. Acta Biomaterialia 2017;62: pp.1-28. https://doi.org/10.1016/j.actbio.2017.08.030
26. Tins B, Kuiper JH. Building an orthopaedic CT phantom for under £50. The British Journal of Radiology 2019;92(1094):20180279. https://doi.org/10.1259/bjr.20180279
27. Whitley, A. et al. 2015. Clark's Positioning in Radiography 13th edition, Taylor & Francis Group, p15, p59.
28. Lampignano, J. and Kendrick, L.E., 2020. Bontrager's Handbook of Radiographic Positioning and Techniques. Elsevier Health Sciences, p.25.
29. International Electrochemical Commission. Thermoluminescence dosimetry systems for personal and environmental monitoring. International Standard 1991 IEC Geneva.
30. Fernández SDS, Garcia-Salcedo R, Sanchez-Guzman D, Ramírez-Rodríguez G, et al. Thermoluminescent dosimeters for low dose X-ray measurements. Applied Radiation and Isotopes 2016, 107:340-345.
31. Bilski P, Gieszczyk W, Obryk B, Hodyr K. Comparison of commercial thermoluminescent readers regarding high-dose high-temperature measurements. Radiation Measurements 2014;65:8-13. https://doi.org/10.1016/j.radmeas.2014.04.020
32. Sherer MA, Visconti PJ, Ritenour ER, Kelli Haynes MS. Radiation protection in medical radiography. 8th edn. Elsevier Health Sciences; 2018
33. Langdridge D, Hagger-Johnson G. Introduction to Research Methods and Data Analysis in Psychology. 3rd edn. 2013. Harlow: Pearson Education Limited. p236-240.
34. Wood SN. Core Statistics. 2015. Cambridge: Cambridge University Press (Institute of Mathematical Statistics Textbooks 6). P33. https://doi.org/10.1017/CBO9781107741973
35. Pijpe A, Andrieu N, Easton DF, Kesminiene A, et al. Exposure to diagnostic radiation and risk of breast cancer among carriers of BRCA1/2 mutations: retrospective cohort study (GENE-RAD-RISK). BMJ 2012, 345, e5660:1-15.
36. Nguyen PK, Lee WH, Li YF, Hong WX, et al. Assessment of the radiation effects of cardiac CT angiography using protein and genetic biomarkers. Cardiovascular Imaging 2015, 8(8), pp.873-884.
37. Ozasa K, Shimizu Y, Suyama A, Kasagi F, et al. Studies of the mortality of atomic bomb survivors, Report 14, 1950–2003: an overview of cancer and noncancer diseases. Radiation Research 2012, 177(3):229-243.
38. Matyagin YP, Collins PJ. Effectiveness of abdominal shields in chest radiography: a Monte Carlo evaluation. British Journal of Radiology 2016; 89(1066):20160465.

39. Culp M, Barbara J. Shield placement: Effect on exposure. Radiol. Technol 2014; 85(4):369–376.
40. The Alliance for Radiation Safety in Pediatric Imaging. Implementation Manual Image Gently® Digital Radiography Safety Checklist. 2011. https://www.imagegently.org/Portals/6/Procedures/Attachment%20C.FINAL%20Implementation%20Manual.pdf
41. European ALARA Network. Optimization of Radiation Protection. ALARA: A Practical Guidebook 2019. https://www.eu-alara.net/index.php/activities/documents-related-to-alara/330-optimization-of-radiological-protection-alara-a-practical-guidebook.html
42. The Radiological Protection Centre. Summary of "Guidance on using shielding for diagnostic radiology applications" by the British Institute of Radiology 5/3/2020. http://www.sghrpc.co.uk/Information%20Leaflets/Summary%20of%20BIR%20Shielding%20Guidance%20(Mar%202020).pdf
43. Care Quality Commission. Ionising Radiation (Medical Exposre) Regulations (IR(ME)R). London HMSO 2020. https://www.cqc.org.uk/guidance-providers/ionising-radiation/ionising-radiation-medical-exposure-regulations-irmer
44. Health & Care Professions Council. The standards of proficiency for radiographers. 2013. https://www.hcpc-uk.org/standards/standards-of-proficiency/radiographers/