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Radiation safety and the anaesthetist

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INTRODUCTION

Background ionising radiation exposure in the general population is a combination of environmental and artificial radiation. According to the International Commission for Radiation Safety 'medical procedures make up most of the manufactured dose, by far'.[1] This does not include the therapeutic uses of ionising radiation, but rather radiation used for diagnostic purposes. Given the proximity of healthcare personnel to medical procedures utilising radiation on a day-to-day basis, limiting and measuring occupational radiation exposure is a necessary safety measure that should be present in all healthcare systems and hospitals. The anaesthetist is frequently involved in such medical procedures, whether in operating theatres or in remote procedure rooms, and previous research has identified poor baseline knowledge and practice of radiation protection in anaesthetists. This article will outline the basic science of radiation effects on the body (radiobiology) and identify the potential risks of occupational radiation exposure for anaesthetists. We will then set out the current best practices to reduce exposure to the lowest possible occupational risk.

BASIC SCIENCES OF RADIOBIOLOGY

Ionising radiation

Radiation is energy travelling through space in the form of subatomic particles or electromagnetic waves. Ionising radiation, the type than can cause tissue damage, can be defined as radiation with the ability to displace electrons from atoms. Ionising radiation can be divided into photons of the electromagnetic spectrum (gamma rays, X-rays) and subatomic particles (alpha and beta particles).[2] Table 1 summarises the types of ionising radiation and its relevance to the general population.

Table 1. Types of ionising radiation

Type	Composition	Penetration	Radiation weighting factor
Alpha particles	Helium nucleus (two neutrons & two protons)	Very low (will not penetrate skin)	20
Beta particles	Electron or positron	Low (may penetrate skin, absorbed by clothing)	1
X-rays	Photon	Penetrates body	1
Gamma rays	Photo	Penetrates body	1

Ionisation of a molecule may lead to the breakage of chemical bonds and production of highly reactive free radicals. It is by these processes that the adverse effects of ionising radiation occur. The biological effectiveness (or destructive ability of ionising radiation against living tissue) of different types of ionising radiation is measured by the dimensionless factor Wr (radiation weighting factor). X-rays have a Wr of 1, while alpha particles have a Wr of 20.

Stochastic versus deterministic effects

The adverse effects of radiation fall into two categories:

- Stochastic effects are those where the probability of an event is dose-related, with no lower threshold. Stochastic effects in humans include cancer induction.
- Deterministic effects (tissue reactions) are those where the severity of an event is dose-related, with a lower threshold below which an event will not occur.[3] Deterministic effects include cataract formation, hair loss, radiation burns, radiation pneumonitis, sterility, and death.

While this classification of radiation effects has recently been challenged,[4] for the purposes of the article we will focus mostly on the stochastic effects of radiation, namely the risk of cancer induction. Cancer induction is the major concern in occupational radiation exposure outside of radiation accidents and disasters.

Cancer induction

It is important to understand that as a stochastic effect, there is no safe dose below which cancer induction will not occur. This linear no-threshold model suggests that any exposure to ionising radiation will increase the risk, but not the severity, of cancer induction. Ionising radiation causes DNA damage directly, via an interaction between ionising particles and DNA, and indirectly, by production of reactive oxygen species. Double-stranded DNA damage from radiation often results in cellular apoptosis, however lesser damage may lead to altered function and potentially malignant proliferation.

While there are no radiation-specific cancers, some cancers are more commonly associated with radiation exposure than others.[5] The Law of Bergoiné and Tribondeau states that the radiosensitivity of biological tissue is directly proportional to the mitotic activity and inversely proportional to the degree of differentiation of its cells.[6] This is why haematopoietic, reproductive, gastrointestinal, and foetal cells are among the most radiosensitive cells, and associated malignancies are seen more commonly in radiation exposure. Radiation has been implicated in all steps of carcinogenesis: from initiation, promotion, and progression of a tumour. As a result, radiotherapy itself can increase the risk of developing further malignancy. For example, retinoblastoma patients have a higher risk of developing osteosarcoma of the orbit following radiotherapy. Given that the same tumour suppressor gene has been implicated in both cancers, radiation provides the 'second hit' required to induce cancer transformation in the bone.[7]

BACKGROUND AND OCCUPATIONAL EXPOSURE

Dosing scalars, for the purposes of quantifying background and radiation exposure, are traditionally described in units of Gray (Gy) and Sieverts (Sv) although these are very large amounts of radiation so mSv and mGy are often used. Commonly utilised units, and their means of calculation, are presented in Table 2.

Table 2. Dosing scalars for ionising radiation

Dosing	Unit	Calculation
Absorbed dose	Gray (Gy)	joule/kg deposited
Equivalent dose	Seivert (Sv)	absorbed dose (Gy) x radiation weighting factor (Wr)
Effective dose	Seivert (Sv)	equivalent Dose (Sv) x Σ Wt (tissue weighting factor)

The *absorbed dose* is the amount of energy deposited. This is the unit radiation oncologists use to prescribe treatment in cancer.

The *equivalent dose* takes into account the type of ionising radiation being deposited, and its relative biological effectiveness (see radiation weighting factor above).

The effective dose further corrects the dose by the various body tissues that have been irradiated. The organs and tissue in the body have different sensitivities to ionising radiation, and therefore the effects of partial irradiation on the body can be calculated using the effective dose. The sum of all tissue weighting factors will add up to one, and therefore if the entire body has been irradiated, the effective dose will equal the equivalent dose.[8] Organs such as the gonads and bone marrow will have a much higher tissue weighting factor than bone and skin.

Total annual background radiation exposure in the population is variable, differing from region to region. A report by the UK Centre for Radiation, Chemical and Environmental Hazards Radiation Protection Division concluded that the average background radiation exposure in the UK population was 2.7 mSv per year. Of this, 16 per cent was artificial radiation exposure, mostly medical radiation.[9] The United Nations Scientific Committee on the Effects of Atomic Radiation report in 2008 found an approximate yearly exposure of 3 mSv, of which 0.6 mSv was due to artificial exposure, mostly medical radiation.[10] Therefore, by far the greatest source of artificial ionising radiation worldwide is related to diagnostic medical procedures.

Occupational radiation dosing limits are set out by the International Commission for Radiation Protection (ICRP). Outside of rescue operations and catastrophic incidents, occupational radiation dose is limited to 20 mSv/year effective dose, averaged over five years (to a total 100 mSv), with no single year exceeding 50 mSv effective dose.[11] The ICRP recommends that all pregnant women should have exposure levels similar to that of the general population and limit the dose to the fetus to 1 mSv for the remainder of the pregnancy. To put this in context, the effective dose of a chest X-ray (antero-posterior and lateral views) is 0.1 mSv, and for a CT abdomen-pelvis, 8 to 14 mSv.[12]

HOW MUCH RADIATION IS THE ANAESTHETIST EXPOSED TO?

To answer the question of how much radiation an anaesthetist is exposed to, it is important to consider individual differences in workplace practice. The environments of potential exposure include:

- operating theatres - X-rays, fluoroscopy via C-Arm
- interventional radiology suite
- diagnostic radiology
- endoscopy - endoscopic retrograde cholangiopancreatography (ERCP)
- cardiac catheterisation suite
- nuclear medicine suite - brachytherapy, external beam radiotherapy
- emergency departments

The specific areas of increased risk have been highlighted as endoscopy (ERCP), cardiac catheterisation suite, interventional radiology suite, vascular and neurointerventional fluoroscopy.[13]

In the past two decades, there has been an increase in interest in radiation safety for the anaesthetist, with several studies published measuring longitudinal exposure in anaesthetists. Individual exposure is quite easy to measure with the aid of a personal radiation monitor (dosimeter). These monitors should be used in all medical facilities where medical ionising radiation is present, and provided to all staff who are at risk of regular exposure. They should be worn on the outside of lead aprons as they are intended to measure the radiation staff are exposed to, not that which they receive. The Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) code on radiation protection stipulates that a dosimeter 'is provided to each occupationally exposed person who is likely to be exposed to ionising radiation in excess of 1mSv in any one year'.[14] One millisievert is defined as the average accumulated background radiation dose to an individual for 1 year, exclusive of radon, in the United States, or the dose produced by exposure to 1 milligray (mGy) of radiation. Pragmatic examples of clinical exposures (for a patient) are summarised in Table 3.

Table 3. Common clinical radiation dose exposures

Radiological technique	Estimated average radiation exposure (mSv)
Chest x-ray (PA film)	0.02
Lumbar spine	1.5
I.V. urogram	3
Upper G.I. exam	6
Barium enema	8
CT head	2
CT chest	7
CT abdomen	8
Coronary artery calcification CT	3
Coronary CT angiogram	16
Cross-country airplane flight	0.04

Extracted from: Average effective dose in millisieverts (mSv) from McCollough CH, et al[37]

The challenge, therefore, is to identify which anaesthetists are likely to be exposed to this level of radiation. Unsurprisingly, given the utility and simplicity of the dosimeter, there have been a number of studies measuring anaesthetists' longitudinal exposure to radiation in their workplace using these dosimeters. A review of the literature shows that some anaesthetists may well cross this annual threshold of 1 mSv. Although, 1mSv is the threshold for recommending the utilisation of a dosimeter. Occupational exposure limits are set as less than 20 mSv per year, averaged over 5 years, with no single year being greater than 50 mSv.

A 2006 paper from Charles Gairdner Hospital followed 29 fulltime anaesthetists over a period of one month.[15] The casemix could be described as typical of a large adult tertiary referral centre, where 'IR exposure could occur'. A dosimeter was placed behind a lead apron, and a second on the exposed collar to enable estimates of whole-body exposure. Of the 29 anaesthetists, seven exceeded the threshold for radiation detection. These numbers were extrapolated to obtain estimated annual exposure, of which the highest effective dose was 2.14 mSv/year, although most were much lower.

A similar trainee-led project from the United States in 2017 followed 41 anaesthesiology trainees over periods of three months wearing thermoluminescent dosimeters to measure shallow, deep and eye exposure.[16] Mean shallow dose (exposure at tissue depth of 0.007cm) was 0.214 mSv over three months. The highest deep dose recorded (exposure at a tissue depth of 1 cm, estimating internal organ exposure) was 0.52 mSv. Extrapolating this dose over a year would yield a maximal exposure of 2.08 mSv.

These numbers are reassuring as they fall well below the 50 mSv maximum and 20 mSv averaged yearly dose limits set by the ICRP. To put this into perspective, the Centers for Disease Control and Prevention states that 'commercial airline crew have the largest annual effective dose of radiation (3.07 mSv) of all US radiation exposed workers',[17] with exposure ranging from 0.2 to 5 mSv per year. The UK National Radiological Protection Board Survey estimated average annual air crew doses of 4.6 mSv per year, higher than nuclear workers (3.6 mSv).[18]

There are particular areas of the hospital where ionising radiation exposure is potentially higher. A report from Yonsei University College of Medicine, Korea, tracked the exposure to ionising radiation of three senior anaesthesiology trainees over three months through a combined 363 procedures in the ERCP room.[19] Dosimeters were worn on the neck and wrist. Over three months the highest deep dose measured at the neck was 0.59 mSv and 1.27 mSv at the wrist. Of note, the anaesthetist who had the highest exposure at the wrist also performed the greatest amount of jaw thrusts. Mayr et al in 2019 placed a lead-lined cap on the head of an anaesthetist who assisted in 32 transcatheter aortic valve implantation procedures in the space of 15 days. Dosimeters were placed on the inside and outside of the cap. The maximum dose recorded on the outside of the cap over this period was 0.55 mSv.[20]

Finally, it is often thought that the proceduralists, with their close proximity to the patient and therefore the X-ray beam would naturally be at risk of highest exposure. In a comparison of exposure between the proceduralist and anaesthetists in a neurointerventional suite, dosimeters were placed on the foreheads of staff over the course of 31 diagnostic and interventional procedures.[21] The anaesthetist was found to have a three-fold greater exposure than the radiologist/proceduralist. The authors proposed that this surprising finding was likely

due to theatre design, especially C-arm spatial configuration favouring protection of the proceduralist and not the anaesthetist. Another publication showed that the location receiving the highest dose of radiation in an endovascular suite during thoracoabdominal aortic aneurysm repairs was the anaesthetic machine, higher than the proceduralist, scrub nurse or radiographer.[22] This was attributed to there being no protective equipment around the anaesthetic machine.

Cataracts and occupational radiation exposure: stochastic or deterministic?

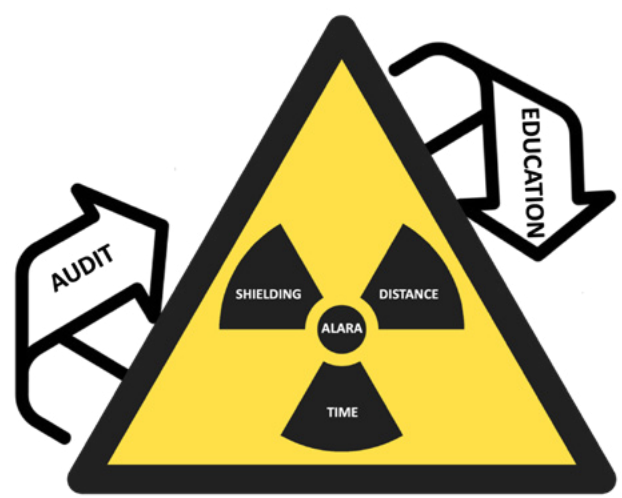
Those regularly anaesthetising for interventional radiology procedures or in the cardiac catheter laboratory may have noticed fellow radiologists and cardiologists wearing an extra piece of equipment over their eyes in addition to the standard lead apron and thyroid shield. Radiation protection eyewear or lead glasses are increasingly being recommended for radiation-exposed workers, and the evidence suggests that eye exposure to ionising radiation in anaesthetists is increasing.[23] Veno et al, in 2010, found the incidence of posterior lens opacities in interventional cardiologists to be significantly higher than in age-matched controls (38% versus 12%).[24] A subsequent systematic review in 2020 included 21 eligible studies, the vast majority of which involved radiologists, radiology technicians and interventional cardiologists, and found an increased incidence of cataracts, especially posterior subcapsular cataracts.[25] Ionising radiation exposure is strongly associated with posterior lens opacities, as shown from data investigating cataracts and atomic bomb survivors and nuclear accident clean-up workers.[26] In 2012 the ICRP reviewed and reduced the acceptable occupational equivalent dose to the lens from 150 mSv to 20 mSv,[27] with the proviso that this would continue to be reviewed. While the risk of cataracts has historically been seen as deterministic, this has been challenged in the literature, and it may indeed follow a non-linear model with no apparent threshold below which radiation-induced cataracts will not occur.[28]

Overall, the results from the literature are reassuring. Most anaesthetists are unlikely to reach yearly occupational safety limits outside of accidents and disasters. Anaesthetists are, however, radiation-exposed workers, potentially to a greater degree than many other healthcare colleagues and this may indeed be underrecognised.

PRINCIPLES OF RADIATION PROTECTION

The ALARA principle – as low as reasonably achievable – is the guiding principle of radiation safety. The principle is to utilise the smallest dose possible to produce the desired effect (e.g. adequate imaging) and reduce exposure to unwanted radiation. This principle can further be broken down into the 'big three' of radiation safety: time, distance, protection. We would like to add 'regular education' and 'audit' to these principles. This is graphically represented in Figure 1.

Figure 1. Radiation safety principles: As low as reasonably achievable (ALARA)



Time

Minimising exposure to radiation, either through reducing the total time the radiation source is active (e.g. screening time), or reducing the time spent near the active source (e.g. leaving the room during screening).

Distance

The amount of radiation exposure from a source is inversely proportional to the square of the distance. Known as the inverse square law, this implies that doubling the distance from the radiation source will effectively reduce exposure four-fold. X-ray exposure in the operating theatre (such as from a C-arm) is a combination of scatter (from the patient, equipment, floor) and direct beam exposure. Distancing oneself from the source and the beam is therefore very important.

In practice then, how far is safe enough? A systematic review looking at radiation doses received at certain distances from a C-arm found that the dose received decreased significantly with increasing distance, and that at distances of 1.5 metres or greater, either no dose or insignificant doses were recorded. This article even went so far as to question the need for lead protection for anaesthetists who are routinely at 1.5 metres or more away from a fluoroscopy unit.[29] Looking at one particular study analysed in the review, investigators placed dosimeters in certain locations of a fluoroscopy room, labelled by distance and with surrogate names of clinicians and their probable location in the room. The fluoroscopy unit was then turned on continuously for ten minutes. The surgeon's dosimeter was placed at 30 cm, and the anaesthetist's at 1.5 metres. While the surgeon recorded a total dose exposure of 0.2 mSv/min of fluoroscopy time, the anaesthetist's dosimeter did not register any positive readings.[30]

It is a recommendation of the ARPANSA that if staff are required to be present in the room during active use of X-ray/CT, they should try to stand at least two metres away from the X-ray tube, and also outside the primary beam. The operator should also, at the very least, be wearing a lead apron.[31]

Shielding

Standing a certain distance from the patient may not be achievable or practical in certain conditions, and certainly not something that can be assured in the practice of general anaesthesia. The third foundation of radiation safety is the use of protective equipment. Structural shielding in the form of mobile lead shields and lead drapes offer protection but may not protect from scatter. Personal protective equipment includes lead aprons, thyroid shields, leaded glasses, and gloves. Lead-free and lead-composite garments are also used. It is recommended that lead aprons have a minimum of 0.25 mm lead thickness.[32] There is a recommendation that staff with higher levels of exposure should consider thicker lead gowns, of the order of 0.50 mm. The garments should regularly be inspected for cracks or defects and should be stored on hangers with minimal folds.

Education and audit

Despite 50 to 70 per cent of orthopaedic surgeons or anaesthesia trainees indicating a concern regarding the potential adverse effects of radiation in surveys of radiation safety, only one-fifth wore adequate personal protective equipment, indicating a discrepancy between concerns and practice.[33]

In our own department, we audited the dosimeter use of 108 anaesthesia trainees and consultants. From 72 respondents, 85% were regularly assigned to lists involving potential radiation exposure but only eight (11%) staff members were in possession of a personal radiation monitor, two of whom declared to have checked their radiation exposure results. Eighty-eight per cent of respondents without dosimeters declared being interested in obtaining one for future use. We are currently in the process of obtaining dosimeters and hope to measure the yearly exposure to assess the risk. Suggested audit questions for anaesthesia departments are given in Table 4.

A before-and-after study of a single education session on radiation safety given to anaesthetists and surgeons identified that, while knowledge improved (e.g. 'what is an effective dose'), good radiation safety practice did not (e.g. the use of protective equipment).[34] Although there may have been a response bias to this study, it suggested that repeated education may be needed to improve department wide practice.

Table 4. Suggested questionnaire for auditing purposes

Questions	Potential responses (*Italics* = correct where applicable)
Knowledge	
What knowledge level do you think you have about radiation safety?	Excellent, good, adequate, inadequate, minimal
What are the annual occupational dose limits for radiation-exposed workers?	10, 20, 50, 100 mSv per year
What is the ALARA principle?	Free text
If you double your distance from a radiation source, how will your dose change?	same, 75% less, 50% less, *25% less*
What is the maximum occupational dose limit allowed in a given year for a radiation-exposed worker?	10, *20*, 50, 75 mSv
Is there a dose limit below which cancer induction will not occur with ionising radiation?	TRUE or *FALSE*
Where should the dosimeter be worn?	Under radiation PPE to estimate the dose received, *Outside of PPE to measure the radiation exposed to.*
A staff member becomes pregnant. Their annual occupational dose limit as a radiation exposed worker is now	20 mSv for the rest of the pregnancy. *They are not to be considered a radiation-exposed worker during their pregnancy*
Good radiation safety knowledge has been shown to translate into good radiation safety practice.	TRUE / *FALSE*
Practice	
How often are you exposed to ionising radiation at work?	Daily, weekly, monthly, rarely/never
Are you concerned about your radiation exposure at work?	Y or N
What concerns you the most regarding radiation exposure?	Cancer induction, cataracts, effects during pregnancy
Which radiation protective equipment do you wear at work?	Lead apron, thyroid shield, glasses, cap
Have you been provided with a personal radiation monitor?	Y or N
If yes, do you wear it regularly?	Y or N
If yes, where do you wear it?	In a position that it is under a lead PPE, In a position that is outside of lead PPE
If yes, do you check your radiation exposure results?	Y or N
If no, would you like to have a dosimeter provided to you?	Y or N

In addition to ALARA, other important principles include adequate signage (e.g. visible warning signs), regular monitoring of personnel and area exposure, and appointment of a radiation safety officer. The function of a radiation safety officer will depend on their employer, but essentially the role is to protect employees and members of the public from unnecessary exposure to radiation and ensure that employers fulfill their obligations under the Radiation Control Act (1990).[35] These would include ensuring radiation doses to employees and members of the public are as low as reasonably achievable, ensuring the safety and quality control of existing and new procedures where radiation or radioactive material is involved, ensuring regular training of all radiation-exposed workers, and reviewing and reporting incidents and accidents. Qualifications of the radiation safety officer should be appropriate to their workplace – a large teaching hospital's radiation safety officer would likely be assumed by a medical physicist or similar.

Radiation and pregnancy

It is important to stress that occupational safety limits in place for radiation exposed workers do not apply to pregnant members of the workforce. This is because, unlike radiation-exposed workers who have acceptable exposure limits, pregnant staff members' exposure to radiation should be minimised and ideally avoided. While very high doses of radiation (>500 mGy) have very significant deleterious effects on the foetus, such as death, miscarriage, growth retardation, severe intellectual disability, and other malformations, it is unclear if lower doses of absorbed radiation (<10 mGy) increase the risk of childhood leukaemia and cancer.[36] Therefore, once the member of staff has declared their pregnancy, the staff member should not receive a dose greater than 1 mSv for the remainder of the pregnancy. Not surprisingly, the highest risk period for stochastic and deterministic effects of radiation occurs in the first trimester during organogenesis, emphasising the need for routine good radiation safety practice.

CONCLUSION

Anaesthetists support patients through both diagnostic and interventional procedures which require utilisation of radiation, and as such can be classified as radiation-exposed workers. While the overall risks posed to anaesthetists remain low, the exposure of anaesthetists to ionising radiation may be underappreciated compared to other specialties. Infrastructure and safety measures should be built into every healthcare setting and regularly audited and appraised to ensure stringent measures are in place to monitor patients' and workers' exposure. It is important to emphasise that the stochastic effects of radiation, namely cancer induction, have no threshold below which an increase in risk will not occur. Utilising the principles of time, distance and shielding is effective in reducing overall exposure. Ongoing education is likely needed for these principles to be reliably put into practice.

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