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Clinical Radiology
The Royal College of Radiologists

Recommendations for cross-sectional imaging in cancer management, Second edition

Risks of radiation exposure

Faculty of Clinical Radiology

Contents

Risks of radiation exposure **2**
What are the risks? 2
Dose measurement 3
Practical measures to reduce radiation dose 4
Conclusion 5

References **6**

Risks of radiation exposure

Exposure of the general population to ionising radiation from medical examinations is increasing annually as the use of diagnostic imaging, and CT scanning in particular, increases.[1] Newer techniques such as PET-CT and SPECT-CT are also adding to the dose burden.

For clarity, units of radiation dose are recorded in either Sieverts (Sv = 1J/Kg) or Grays (Gy = 1J/Kg). The 'Gray' is the unit used to identify absorbed dose while the term 'Sievert' refers to equivalent dose. They are essentially an identical quantity of energy.

In the UK, the average annual radiation dose from all sources – both natural and manmade – is 2.7 mSv/person/annum. The per caput effective dose from diagnostic medical exposures (0.4 mSv/annum)[2] remains low in comparison with many other countries (European range = 0.4–2 mSv/annum;[3] USA = 2.2 mSv/annum in 2006 having increased by 460% since the early 1980s).[4] Figures from France indicate that CT accounts for 8% of the total number of examinations but 39% of the collective dose.[5] In the UK, CT accounted for about 7% of the number of all medical and dental X-ray examinations in 2008, but 68% of their resultant total collective dose.[2] This latter proportion is similar to that derived for the USA.[4] In the USA, it was estimated that more than 60 million CT examinations were acquired per annum in 2007,[6] leading to a per caput dose from CT of 1.5 mSv/annum,[4] which is somewhat larger than the corresponding figure for the UK of 0.27 mSv/annum.[2]

To put the above figures into perspective, the general population of the UK is exposed to naturally occurring radiation (mostly from radon) every day and while the average dose per caput from this source is 1.3 mSv/annum, this increases in Cornwall to 7.8 mSv.[7]

Radiation effects are classified into 'stochastic' (essentially cancer induction) and tissue reactions (formerly known as deterministic effects) such as skin burns and cataract formation.[8] Rates of cancer induction have been extrapolated from studies of those exposed to the atomic bombs at Hiroshima and Nagasaki and also following environmental exposures such as Chernobyl. The Radiation Effects Research Foundation[9] has recorded 7,851 solid cancers in 44,635 during the period 1958 to 1998. The estimated excess number of solid cancers was 848 (10.7%). Sixty-two per cent of survivors received doses in what is perceived as the low-dose range; that is, 5 to 100 mSv. These are comparable to some medical exposures particularly when one considers that repeat exposures add to the total risk.

Whether this model is directly comparable to exposure to ionising radiation related to medical imaging is questionable as the majority of radiation that a-bomb survivors were exposed to was gamma radiation and neutron doses.

What is important is that both radiologists and referring clinicians are aware of the risks when considering the use of cross-sectional imaging both for diagnostic purposes and perhaps more importantly, for follow-up after treatment. These risks must be balanced against the benefits of diagnostic imaging. A prospective study randomised patients admitted with severe abdominal pain to have a CT scan within 24 hours of admission or to standard care.[10] Seven of 63 patients who did not undergo an early CT scan subsequently died compared with none of the 55 patients who had CT ($p=<0.05$).

We must also remember that patients and the media are increasingly aware of risks from radiation. Their concerns are compounded by widely reported errors in both diagnostic and therapeutic radiation dose delivery.

What are the risks?

The main risk we should concern ourselves with in CT imaging is that of developing cancer.

Current scientific evidence supports the assumption for radiation protection purposes of a 'linear–no-threshold' dose–response relationship between exposure to ionising radiation and the development of cancer in humans.[11] The risk of cancer induction is estimated to reach about

0.5% at an effective dose of 100 mSv.[3] The Food and Drug Administration (FDA) estimates that a CT examination with an effective dose of 10 mSv may be associated with an increased chance of developing fatal cancer for approximately one patient in 2,000.[11] This is equivalent to the dose from an average CT of the abdomen and pelvis and is more relevant to everyday radiology practice. The National Research Council published a report of a seventh committee in a series concerning biological effects of ionising radiation (BEIR VII).[12] The report includes a lifetime risk model predicting that one individual in 1,000 will develop cancer following similar low-dose exposure to that of a-bomb survivors. Furthermore, whole-body PET combined with CT is increasingly used to determine oncology management and may involve doses in the order of 25 mSv, although standard practice in the UK usually involves lower doses of approximately 15 mSv.[13]

For comparison, based on 2008 statistics, there is a similar risk (one in 2,000) of accidental death travelling 40,000 miles in a motor vehicle.[14] On the basis of detailed analyses of radiation risks for X-ray examinations in the UK,[15] total lifetime cancer risks for CT examinations of the trunk are typically classified as being 'low risk' (in the range one in 10,000 to one in 1,000) for patients of average age (30–39 years). These typical risk levels can be compared with the natural baseline lifetime risk of developing cancer in the UK, which is currently about one in three.

The risk of cancer increases proportionally with organ dose, is higher the younger the age at exposure, is different for each organ and females may be more susceptible than males,[15] especially at younger ages. Huda and He estimated cancer risks from the amount of radiation exposure while performing body CT examination.[16] In this study, for CT examinations that included the chest, the risks for females were markedly higher than those for males, whereas in examinations that included the pelvis, risks in males were slightly higher than in females.

For abdominal CT scans, increasing patient age from 20 to 80 years resulted in a reduction in patient risk of nearly a factor of five. In children, young adults and for the fetus during pregnancy the risk is higher as their tissue is biologically more sensitive. Co-efficients of risk per unit of effective dose for X-ray examinations performed on patients in the 0–9 year age group are about two to three times larger than those for the 30–39 year age group, whereas, relative to this latter group, co-efficients for patients aged in their sixties and eighties are typically lower by factors of about one-half and one-tenth respectively.[15]

Radiation-induced genetic effects have not been demonstrated in humans and studies based on 70,000 children of a-bomb survivors indicate that radiation doses of <0.2 Gy are unlikely to double the risk of inheritable disease.[12] Similarly studies of nuclear workers' children have not convincingly linked exposure to heritable diseases. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) estimated the doubling dose at about 1 Sv, far in excess of any doses expected in diagnostic studies.[17] However, the International Commission on Radiological Protection (ICRP) regards radiation doses of >100 mGy as potentially teratogenic and studies in mice do provide evidence of radiation-induced mutations in mammals.[18] On the basis of detailed analyses of radiation risks for X-ray examinations in the UK, the risks of heritable effects for CT examinations of the lower trunk are typically classified as being 'minimal risk' (in the range 1 in a million to 1 in 100,000) or 'very low risk' (in the range 1 in 100,000 to 1 in 10,000) for patients of reproductive potential.[15]

Tissue reactions such as skin erythema, ulceration, fibrosis and cataract formation secondary to radiation have a threshold above which they are likely to occur.[18] Injuries such as hair loss and erythema have been reported during prolonged scanning in relation to CT brain perfusion studies[19] and image-guided interventions (see FDA website). The threshold for development of skin erythema is between 3–5 Gy associated with an exposure time of 150–250 minutes of normal fluoroscopy.[3] The threshold for cataract formation is far less (0.5 Gy) reached with exposure times of 50–100 minutes of normal fluoroscopy (0.02 Gy/min) but only 5–10 minutes of higher dose fluoroscopy (0.2 Gy/min).[3]

Dose measurement

The dose to individual organs and tissues can be determined either with measurements using suitable detectors and phantoms or Monte Carlo

simulations of energy deposition.[20] These dose values are weighted and summed to give the 'effective dose' as defined by the ICRP.[8] Quantities of radiation that can be measured are combined with 'absorbed dose conversion co-efficients' to estimate typical organ or effective doses.[21]

The Computed Tomographic Dose Index (CTDI) is a measure of the absorbed dose (in mGy) to a standard CT dosimetry phantom from a single rotation of the CT scanner gantry (with no movement of the patient couch); it is calculated from the integral of the dose profile and the width of the X-ray beam in the axial direction (along which the patient lies).[21] CTDI is measured using a pencil ionisation chamber inserted into central and peripheral positions within the phantom. Whereas CTDI is essentially a single-slice measurement, it can be corrected for pitch to provide the CTDI which corresponds to the average dose that would accrue in the phantom in the centre of a scanned length of 100 mm. It is not intended to represent any particular absorbed dose to the patient but rather a broad indication of exposure level in CT for the purposes of comparison. The dose-length product (DLP; mGy/cm) is an indication of the total irradiation and is the CTDI multiplied by the irradiated patient length.[22] Both the CTDI and the DLP are indicated on the scan console both before the examination and afterwards in a dose record available both in the patient image set and in the DICOM image information. DLP values can be converted to estimates of effective dose in mSv by multiplying with appropriate conversion factors.

The International Atomic Energy Authority promotes a scientifically based code of practice for dosimetry in diagnostic radiology to standardise the measurement of dose and dose indicators including guidance for both direct and indirect measurement on patients or phantoms.[23]

Practical measures to reduce radiation dose

Patient information leaflets, while not standard practice in UK for diagnostic imaging, may help alleviate patient concerns regarding radiation. One example is the widely used NRPB/HPA leaflet *X-rays – how safe are they?* published in 2001.[24]

There are many measures we as radiologists can take to reduce the radiation dose to which patients are exposed. These include justification and optimisation of examinations, as required by the *Ionising Radiation (Medical Exposure) Regulations 2000* (IRMER 2000), in addition to technical factors related to the exposure itself.[25]

The ICRP considers justification to involve three entities:[8] the method of examination, specifically for evaluating the clinical suspicion and individually for the current patient. Radiologists and clinicians must be aware of the diagnostic potential and biological effects associated with an examination they may perform or request. This information involves educating referrers either during medical school as proposed by the International Radiation Protection Association and the European Union-proposed Council Directive laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation and/or during junior doctor training posts for them to choose the most appropriate diagnostic pathway.

Justification must be evidence-based and with electronic requesting ideally would incorporate integrated decision support. This is especially important in the current environment where less inter-personal discussion takes place before imaging and the sheer volume of requests makes individual vetting desirable but unlikely.

Some newer imaging techniques such as PET-CT provide a higher dose to the patient, may be performed in addition to a 'normal' CT examination, are more expensive and availability is limited. For this reason some centres justify such examinations during a multidisciplinary cancer team discussion with reference to appropriate guidelines.[26]

If integrated decision support is not available, referral guidelines should be introduced to help referrers request the correct type of examination for the clinical circumstances.[27]

Informed referral may result in other modalities being chosen for imaging such as MRI for screening and follow-up of patients with Von Hippel-Lindau disease.

In other cases, a simple ultrasound may characterise a lesion rather than a three-phase CT examination.

Once the examination is justified, optimisation should follow the as low as reasonably practicable (ALARP) principle.[8]

Dose measurement and recording allows comparison with national diagnostic reference levels (DRLs), which are benchmarks set at the 75th percentile of the distributions of typical doses from wide-scale surveys which should not be exceeded in a group of patients of average body size.[28] They are not an absolute threshold but act as a guide to potentially poor performance. National DRLs have been established for individual countries with relatively homogeneous levels of healthcare. These measurements can also be used for audit purposes. In the UK, individual radiology departments should also have local DRLs as reflecting their typical practice.[28]

Quality assurance (QA) programmes are recommended to ensure that a facility will produce consistently high-quality images with minimal exposure.[29]

Clinical audit should be used to confirm the extent to which justification and optimisation have been implemented within a radiology department.

Radiation dose is determined by tube potential and current as well as table speed (not all multi-slice scanners) and gantry rotation time. The kVp and mAs/slice are independent and raising one while keeping the other constant will increase the dose, whereas lowering these parameters will reduce dose but may increase noise. This may be acceptable for some examinations such as CT-KUB to look for calcification but otherwise may result in images of poor diagnostic quality. Automatic tube current modulation is a system in which the tube current is automatically adjusted to the minimum level required to obtain a constant pre-specified image quality according to the size and density of the tissue being scanned.[29] Use of this technology can reduce radiation dose by 20–44% but is only available on certain manufacturers' scanners.[30,31]

Some people advocate the use of in-plane bismuth shields primarily for protection of the female breast; they are also available for eyes and thyroid. There are reports of reduction in radiation dose of 29% to paediatric female breast and 40% to adult female breast.[32,33] However, the use of bismuth shields is controversial for the following reasons. While they attenuate the beam when the gantry is anterior to the patient, they will also attenuate the beam exiting the patient when the gantry is posterior resulting in reduced radiation reaching the detector; that is, a reduction in the number of photons available to produce the image. Bismuth shielding causes streak and beam hardening artefacts which can artifactually increase CT numbers and affect density interpretation. Geleijns *et al* recommend minimising dose in paediatric chest CT by a reduction in the tube current to achieve the required image quality at the lowest possible dose and the use of angular and z-axis tube current modulation, which has been shown to reduce dose to the region of the breast by approximately 50% without altering the accuracy of CT numbers or introducing artefacts.[34] It is also recognised that in-beam shielding could interfere with automatic exposure control and dose modulation systems which are increasingly available on CT scanning machines.[35] The American Association of Physicists in Medicine recommends against the use of bismuth shields.[36]

Conclusion

There are many factors to be considered by clinicians and radiologists with respect to cross-sectional examinations involving ionising radiation. Optimisation is best implemented by a multidisciplinary team of radiologist, radiographer and radiation physics expert. Other methods of restricting radiation exposure of patients, such as education and referral guidelines are much simpler ideas but not necessarily easy to introduce.

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