

Patient exposure trends and problems to be solved in implementing ALARA

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Radiation doses incurred in medical x-ray imaging

Although x-rays and sealed or unsealed radioactive sources are used in medicine for imaging the inside of the body and for treating benign and malignant conditions, this paper will concentrate solely on patient exposures from medical imaging procedures using x-rays. These are by far the most frequent type of medical exposure, being experienced by between $\frac{1}{4}$ and $\frac{1}{2}$ of the population in developed countries each year.

Medical x-ray imaging is a vital tool for the diagnosis of a wide range of injuries and diseases and is increasingly being used to guide minimally invasive therapeutic procedures that offer safer and quicker ways of treating serious medical conditions than conventional surgery. In a multitude of clinical situations diagnostic radiology is of indisputable benefit to patients as the most appropriate diagnostic test and the most reliable means for checking on progress in the treatment of injury or disease. As long as the exposures are clinically justified, the clear benefits to the healthcare of the patient should overwhelmingly outweigh the small radiation risks.

Medical x-rays involve partial body exposures to soft x-ray beams (photon energies between 20 and 120 keV), resulting in very non-uniform dose distributions in the patient's body. About 73% of x-ray imaging procedures in developed countries such as the UK are plain film radiographic examinations of the chest, teeth and limbs [1]. These involve absorbed doses of no more than a few mGy to small volumes of tissue, resulting in effective doses of less than 20 μ Sv (see Table 1).

Table 1. X-ray imaging procedures divided into four dose bands

Effective dose range (mSv)	Typical x-ray procedures	% of total number of procedures	% of total collective dose
< 0.02	Radiography of chest, limbs and teeth	73	1
0.02 – 0.2	Radiography of head, neck and joints	5	1
0.2 – 2.0	Radiography of spine, abdomen and pelvis	16	20
2 – 20	CT, angiography, Contrast studies of GI, biliary & urinary tracts	6	78

A further 21% of x-ray imaging procedures also involve plain film radiography (i.e. require no use of contrast media) but result in effective doses of between 20 μ Sv and 2 mSv. Higher radiation exposures are required for these procedures because the x-ray beam has to penetrate thicker or denser sections of the body, such as for lumbar spine examinations. The higher effective doses are also due to the fact that a larger volume of the body is exposed, which may contain a number of radiosensitive organs, and a number of radiographs taken from different directions may be needed to accurately diagnose the suspected pathology or trauma.

Only about 6% of x-ray imaging procedures result in effective doses greater than 2mSv and very few of these exceed 20 mSv. This relatively small number of high-dose procedures was responsible for 78% of the collective effective dose to the UK population from all medical x-ray imaging in 1998 [1]. They are mostly procedures that involve many radiographs and fluoroscopy or computed tomography (CT) and where contrast media are used to visualise the alimentary, urinary or biliary tract, the central nervous system or the blood vessels (angiography). Fluoroscopy uses image intensifiers to produce instant moving images of internal anatomy while CT uses a rotating x-ray source and bank of solid state detectors on opposite sides of the body to obtain cross-sectional images with much more soft tissue detail than is possible with conventional radiographs. Absorbed doses to the most highly exposed tissues within the body can approach 100 mGy during some of the more complicated diagnostic procedures, particularly if they involve prolonged fluoroscopy or CT.

Recent developments in medical imaging

Medical imaging is in the throws of a digital revolution, in the same way as photography. Conventional film-screen radiography is being replaced by digital radiography using photostimulable phosphors or flat panel detectors. In fluoroscopy, the moving images obtained from image intensifiers have been processed digitally for many years now to enhance diagnostically useful features and more recently the image intensifiers are being replaced by a new breed of ultra-fast flat panel detectors. Digital processing of images after they have been acquired often avoids the need for retakes if the exposure conditions were not correct the first time. But digital systems are not always more sensitive than film-screen systems, the exposure conditions are usually selected automatically and the appearance of the image provides no indication of the dose levels used to obtain it (unlike film-screen systems). Consequently, without good quality control checks in place there is potential for higher patient doses than necessary going undetected.

The advent of multislice helical CT scanners, capable of high-speed imaging with sub-millimetre isotropic spatial resolution, has led to an explosive growth in clinical applications for CT. The whole trunk can now be scanned in a single breath hold (to reduce motion artifacts) and with ecg-gating even the heartbeat can be frozen to provide clear 3-dimensional images of the coronary arteries. Multi-phase studies are becoming increasingly common where, after the injection of small quantities of contrast medium, organs are imaged in both arterial and venous phases to detect abnormalities in the blood supply that are indicative of disease. All these improvements in diagnostic accuracy are achieved at the expense of relatively high patient doses. However the benefits can be correspondingly large, since many of these new applications are bringing real improvements to the care of patients suffering from the major killers like heart disease and cancer.

In interventional radiology fine catheters are passed down arteries to carry out minimally invasive therapeutic procedures that offer safer and quicker ways of treating serious medical conditions than conventional surgery. Fluoroscopy is used to guide these catheters on their often very intricate journeys from the point of insertion to the site of blockage or leakage

where the surgery is to be conducted and to observe the effectiveness of the treatment. In difficult cases it can take up to an hour of continuous fluoroscopy to complete the procedure and occasionally, acute effects such as erythema, epilation and even desquamation and tissue necrosis at the point of entry of the x-ray beam have been reported, implying localised skin doses in excess of a few gray [2].

Practical dose quantities used in medical x-ray imaging

Since it is not possible to measure effective doses directly in patients subjected to x-ray imaging procedures, a number of practical dose quantities have been developed, similar to the operational dose quantities used in occupational dosimetry. The most commonly used quantities are:

- entrance surface dose (ESD) for individual radiographs
- dose-area product (DAP) for complete radiographic/fluoroscopic exams
- computed tomography dose index (CTDI) for individual CT slices
- dose length product (DLP) for complete CT exams

Computational dosimetry techniques have been developed that simulate medical x-ray exposures on computerised phantoms and use Monte Carlo radiation transport codes to calculate the energy deposited in each organ necessary for estimating the effective dose. Large numbers of radiographic, fluoroscopic and CT examinations have been simulated to provide coefficients relating organ and effective doses to the above practical dose quantities that can be easily measured in the x-ray beam outside the patient. If required, the calculated organ dose coefficients can be combined with appropriate dose measurements to estimate the organ and effective doses actually delivered in clinical practice.

However, the practical dose quantities themselves can also be used to monitor trends in patient exposures and to compare the typical patient doses used in different hospitals and countries. Surveys of patient doses in a number of European countries throughout the 1980s and early 1990s indicated that, in practice, doses can vary widely for the same examination between individual patients (due to differences in physique and pathology) and between different operators and hospitals (due to differences in imaging equipment and procedures). Whereas a degree of inter-patient variability is unavoidable, the substantial differences seen in the typical doses used by different x-ray imaging facilities for the same examination, suggests that not all are using the optimum patient protection techniques. It was apparent that a practical system for raising awareness about patient doses and allowing x-ray departments to see how their performance compared with national and international norms would be an extremely useful aid to the optimisation of patient exposures.

Radiation protection principles for medical exposures

Because of the potential direct health benefit to patients from medical exposures, there are no recommendations from national or international radiological protection organisations on unacceptable levels of patient exposure; i.e. there are no prescribed dose limits. However, ICRP recommendations [3], the IAEA Basic Safety Standards [4] and the EC Medical Exposure Directive [5], require all patient exposures to be justified in terms of there being a sufficient potential diagnostic benefit to the individual patient to outweigh the individual detriment that the exposure may cause. Once a medical exposure has been justified, the principle of optimisation applies in the same way as for occupational and public exposures. Consequently, there is a requirement for those carrying out medical exposures to select imaging equipment and techniques to ensure that patient exposures are as low as reasonably achievable (ALARA) consistent with obtaining the required diagnostic information.

The quality of medical images is linked in a number of ways to the radiation dose delivered to the image receptor and patient doses should not be reduced to the extent that the diagnostic quality of the images becomes less than adequate for the particular clinical task. Whereas radiologists subjectively assess the adequacy of their images every time they report on them, they cannot intuitively assess the patient dose. Which is why it is so important to have a system for alerting radiology practitioners when the radiation doses that they are using for a particular examination become unusually high.

Diagnostic reference levels – the first step to implementing ALARA

The concept of diagnostic reference levels (DRLs), as a simple indication of unusually high doses, has evolved from work in the USA, UK and Europe over the past 30 years. The concept became recognised internationally by the ICRP in Publications 60 (1991) [2] and 73 (1996) [6] and by the IAEA, as ‘guidance levels’, in its Basic Safety Standards published in 1994 [4]. In 1997, the requirement for Member States of the European Union to establish and use DRLs for patient dose management was written into the EC Medical Exposure Directive [5]. By 1999, European DRLs (or reference dose values) were available in three sets of European Guidelines on quality criteria for radiographic examinations on adults [7], or children [8] and for computed tomography (CT) examinations (on adults) [9].

Most countries have adopted the approach of setting DRLs at the third quartile values of the distributions of doses observed for a particular x-ray examination on representative samples of patients in national patient dose surveys. In subsequent local surveys, hospitals finding that their mean dose for a particular examination exceeds the national DRL, should investigate the reasons why they are in the top quartile and if they can find no clinical justification for using such high doses, should take corrective action to reduce them. Thus the purpose of the DRL is to provide a trigger to the first step in the optimisation of patient exposures, by simply identifying those practices in most urgent need of investigation and possible corrective action. The DRL is essentially an *investigation level* and attainment of patient doses at or below the DRL is, by itself, not necessarily indicative of optimum performance. Neither is the DRL intended to be used as a ‘*dose constraint*’ that should never be exceeded in any optimised practice, as recommended by ICRP for occupational and public exposures in its latest draft recommendations [10]. The DRL is simply a trigger to instigate further investigation of the imaging equipment and the examination procedures to determine whether the protection has been adequately optimised and the patient exposures are ALARA, consistent with obtaining the required diagnostic information.

On exceeding a DRL, the subsequent investigation will involve a detailed analysis of the quality control checks on the imaging equipment that should already be in place, as well as a review of how the equipment was being used in comparison with national and international guidelines on good practice. The quality control checks should include simple tests of image quality based, for example, on contrast/detail test objects or measurements of image noise and spatial resolution. In the UK, national guidelines on the routine performance testing of diagnostic x-ray imaging systems has been published in IPEM Report 91 [11]. The European Guidelines on quality criteria for radiographic and CT examinations mentioned above [7, 8, 9,] provide examples of good imaging techniques and also specify image quality criteria expressed in terms of the required level of visibility of important anatomical features in images taken for specific types of x-ray examination. The investigation will also consider whether the DRL was exceeded due to inappropriate selection of the sample of patients on whom doses were measured (e.g. they were predominantly larger than average size) or due to an exceptional case mix (e.g. all ‘difficult’ cases being referred to the most experienced radiologist) in which case exceeding the DRL may well be clinically justified.

Thus this complete process of establishing and using DRLs to instigate reviews of local radiology practice and to take corrective action when the unusually high doses cannot be clinically justified, provides the current framework for the implementation of ALARA for diagnostic medical exposures.

Patient exposure trends following the implementation of ALARA through DRLs

National DRLs are usually set by appropriate national authorities in collaboration with the professional medical bodies involved in diagnostic radiology. According to ICRP Publication 73 [6], they should be reviewed at intervals that represent a compromise between the necessary stability and long-term changes in observed dose distributions. National reference doses for common conventional (i.e. not CT) examinations have been reviewed three times over the past 20 years in the UK and it is interesting to observe the trends in patient doses over that period.

Table 2 shows the third quartile values of the mean entrance surface doses (ESD) or mean dose-area product values (DAP) used by each hospital for the types of radiograph or x-ray examination that have appeared in all three UK reviews [12]. There has been a continuing reduction in these values with time, for nearly all types of radiograph. The average reduction between 1995 and 2000 has been about 20% and they have approximately halved in the 15 years since the original survey in the mid-1980s.

This substantial reduction in patient doses has been possible because of increases in the sensitivity of imaging equipment (e.g. the introduction of rare-earth intensifying screens and sodium iodide phosphors in image intensifiers) and the exploitation of dose-saving techniques (e.g. the use of higher tube voltages, additional filtration and tighter beam collimation). However, it is doubtful whether these would have been implemented so quickly and so widely if it were not for the raised awareness of patient doses and how they compare with national and international norms that was brought about by the adoption of DRLs.

Table 2. National reference doses derived from 3 reviews of UK national patient dose data since the mid-1980s

Radiograph or Examination	Rounded third quartile values		
	Mid-1980s Survey	1995 review	2000 review
	ESD per radiograph (mGy)		
Skull AP/PA	5	4	3
Skull LAT	3	2	1.6
Chest PA	0.3	0.2	0.2
Chest LAT	1.5	0.7	1
Thoracic spine AP	7	5	3.5
Thoracic spine LAT	20	16	10
Lumbar spine AP	10	7	6
Lumbar spine LAT	30	20	14
Lumbar spine LSJ	40	35	26
Abdomen AP	10	7	6
Pelvis AP	10	5	4
	DAP per examination (Gy cm ²)		
IVU	40	25	16
Barium meal	25	17	13
Barium enema	60	35	31

Now that film-screen radiography and sodium iodide image intensifiers are being replaced by digital imaging systems, DRLs will play an increasingly important role in ensuring that the benefits of these new imaging modalities are not achieved at the expense of an unacceptable increase in patient doses.

With CT examinations now providing about 50% of the collective effective dose from medical x-ray imaging in most developed countries, it is important to establish national DRLs for the common CT procedures and to keep them up to date with the rapid developments in this technology. National surveys of CT practice were conducted in the UK in 1991 and 2003 [13] and national reference doses have been derived from these surveys in terms of the practical dose quantities CTDI and DLP. Table 3 shows both the reference (3rd quartile) values of DLP and the typical (mean) effective doses for common CT examinations found in these two surveys. Only single-slice CT scanners (SSCT) were available in 1991 and the data for 2003 relate to the multi-slice CT scanners (MSCT) that were being rapidly introduced at that time.

Table 3. National reference doses in terms of DLP and typical effective doses (E) for common CT examination in 1991 and 2003

CT examination	1991 (SSCT)		2003 (MSCT)	
	DLP (mGy cm)	E (mSv)	DLP (mGy cm)	E (mSv)
Head	1050	2	930	1.5
Chest	650	8	580	5.8
Abdomen	780	10	470	5.3
Pelvis	570	10		
Abdo + pelvis			560	7.1
Chest + abdo + pelvis			940	9.9

In the 12 years between these surveys technological developments in CT scanning had resulted in 20-50% reductions in patient doses for scans of the head, chest or abdomen. However, the speed of scanning had increased so much that scans of the whole trunk were becoming routine and patient exposures were creeping back to the same effective dose levels (~10 mSv) as before.

Ultimately it is only the radiologists who are performing the examinations who can decide whether these increasing patient exposures are 'reasonable' in relation to the extra amount of useful diagnostic information that they yield. But they need to be reminded regularly of the need to consider whether the exposures they are giving to patients are ALARA. The establishment and use of DRLs for these new high-dose imaging modalities would be an effective way of doing this. Consequently, how to keep abreast of all the recent developments in medical imaging and their impact on patient exposures is one of the major problems that needs to be solved in implementing ALARA for patient exposures.

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