National Protocol for Patient Dose Measurements in Diagnostic Radiology

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Dosimetry Working Party of the
Institute of Physical Sciences in Medicine

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Foreword

The Dosimetry Working Party was set up by the Diagnostic Radiology Topic Group of the Institute of Physical Sciences in Medicine (IPSM) in 1990 to supervise and report on IPSM participation in a number of national and international projects concerned with radiation dosimetry in diagnostic radiology. One of these projects, following the recommendations of a joint report by the Royal College of Radiologists and the National Radiological Protection Board on patient dose reduction, was to draw up national protocols for the routine measurement of patient doses as part of quality assurance programmes in radiology departments. This document has been published by NRPB to fulfil this objective.

Members of the Dosimetry Working Party who participated in the preparation of this document were:

M R Holubinka	IPSM, Portsmouth
A P Jones	IPSM, Manchester
D J Rawlings	IPSM, Newcastle-upon-Tyne
P J Roberts	IPSM, Southampton
J Robertson	IPSM, Glasgow
B F Wall	IPSM/NRPB, Chilton

and the following representatives from the College of Radiographers were co-opted to advise on the preparation of this document:

S Evans	CoR, Ipswich
T Reynolds	CoR, Coventry

It is intended that one copy of this protocol be distributed to the senior superintendent radiographer at each radiology department in the UK, to medical physicists with an active interest in radiation protection in diagnostic radiology and to the clinical directors of radiology departments.

Such persons who have not received a copy directly can obtain one from:

College of Radiographers
14 Upper Wimpole Street, London W1M 8BN

Institute of Physical Sciences in Medicine
4 Campleshon Road, York YO2 1PE

Synopsis

The potential for reducing the radiation dose to the population from medical X-ray examinations is well established and indeed the requirement to deliver the lowest possible dose consistent with the clinical purpose of the examination is formalised in UK legislation. Presently, however, there are very few diagnostic X-ray facilities where specific information is available on the doses that they deliver to their patients.

This protocol sets out nationally agreed methods for monitoring patient doses from routine X-ray examinations that can be easily carried out by radiographers with advice and assistance from medical physicists. It provides guideline reference doses, that are in line with current national and European practice, against which individual X-ray facilities can compare their performance. These measurements and comparisons will greatly improve confidence in identifying those areas where effort can be most efficiently directed towards complying with the legal requirements for minimising patient dose. They will improve the quality of information available to health service managers and clinical directors of radiology departments for assessing both diagnostic procedures and priorities for expenditure on new imaging equipment.

Radiation Protection Advisers are encouraged in this protocol to participate in a system for the national collation of patient dose data so that the impact of patient protection measures on diagnostic radiology in the UK can be assessed centrally and guideline reference doses periodically revised. Finally, since it is well recognised that there are some circumstances in which over-zealous reductions in patient dose can have deleterious effects on image quality, simple methods for monitoring image quality are outlined.

The recommended methods of patient dose measurement are suitable for use in most types of conventional radiographic or fluoroscopic X-ray examination, although a preferred selection of types of radiograph and examination is given. The methods are not suitable for mammography or computed tomography for which appropriate dosimetry techniques are described elsewhere.

Contents

1 Need for patient dose measurements

X-rays are used so extensively in medicine for the diagnosis of injuries and disease that they represent by far the largest man-made source of public exposure to ionising radiation. In the UK about 90% of the radiation dose to the population from all sources except natural background radiation is due to medical X-rays, as illustrated in Figure 1. This amounted to a collective UK population dose of some 20,000 man Sv from diagnostic radiology in 1990, outweighing the contribution from routine discharges from the nuclear power industry, for example, by a factor approaching 1000.

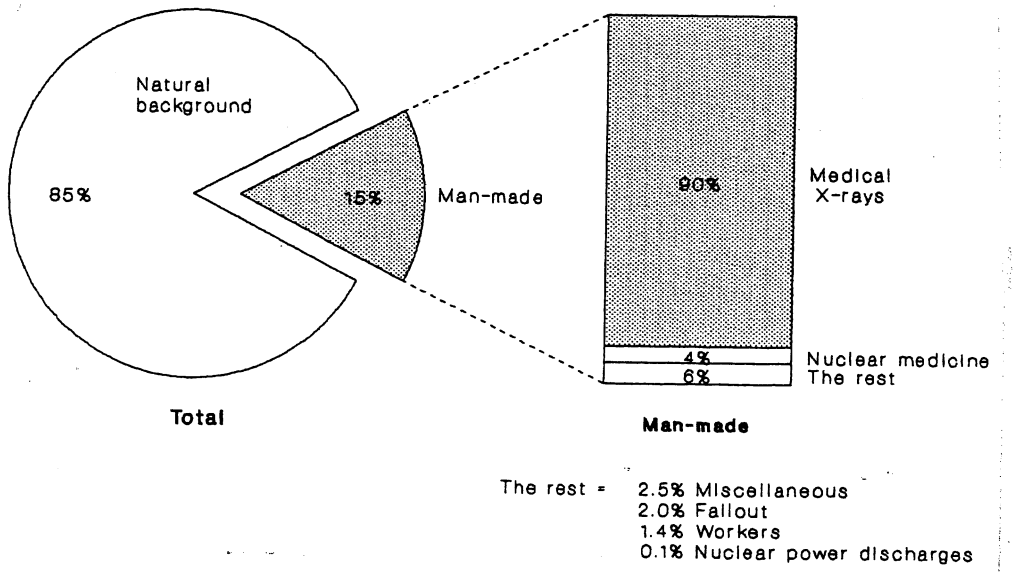

FIGURE 1 Contributions of different sources to the collective effective dose for the UK population in 1990

There is considerable evidence that substantial reductions in these medical exposures are possible without detriment to patient care. A recent review by the Royal College of Radiologists and the National Radiological Protection Board[1] highlighted the large potential for patient dose reduction in diagnostic radiology. It drew on evidence from national surveys of patient doses that have shown very wide variations for the same types of X-ray examination carried out on different patients and in different hospitals[2]. For example, Figure 2 shows distributions in the entrance surface dose that were measured on patients in a random sample of 20 English hospitals for 4 different types of routine radiograph.

The white histograms show the wide distributions in dose observed for all patients in the survey, with the maximum value about 5 times the mean value and up to 50 times the minimum. The shaded and black histograms show doses for the 'best' and 'worst' hospitals, respectively, and clearly illustrate that some hospitals are able to exercise much tighter control over patient doses than others. Evidence for such wide variability in current medical practice led RCR and NRPB to recommend that *regular patient dose monitoring should be an essential component of quality assurance (QA) programmes in diagnostic radiology.*

The Government White Paper 'Working for Patients'[3] places great emphasis on medical audit, which it defines as 'the systematic, critical analysis of the quality of medical care, including procedures used for diagnosis and treatment, the use of resources and the resulting outcome

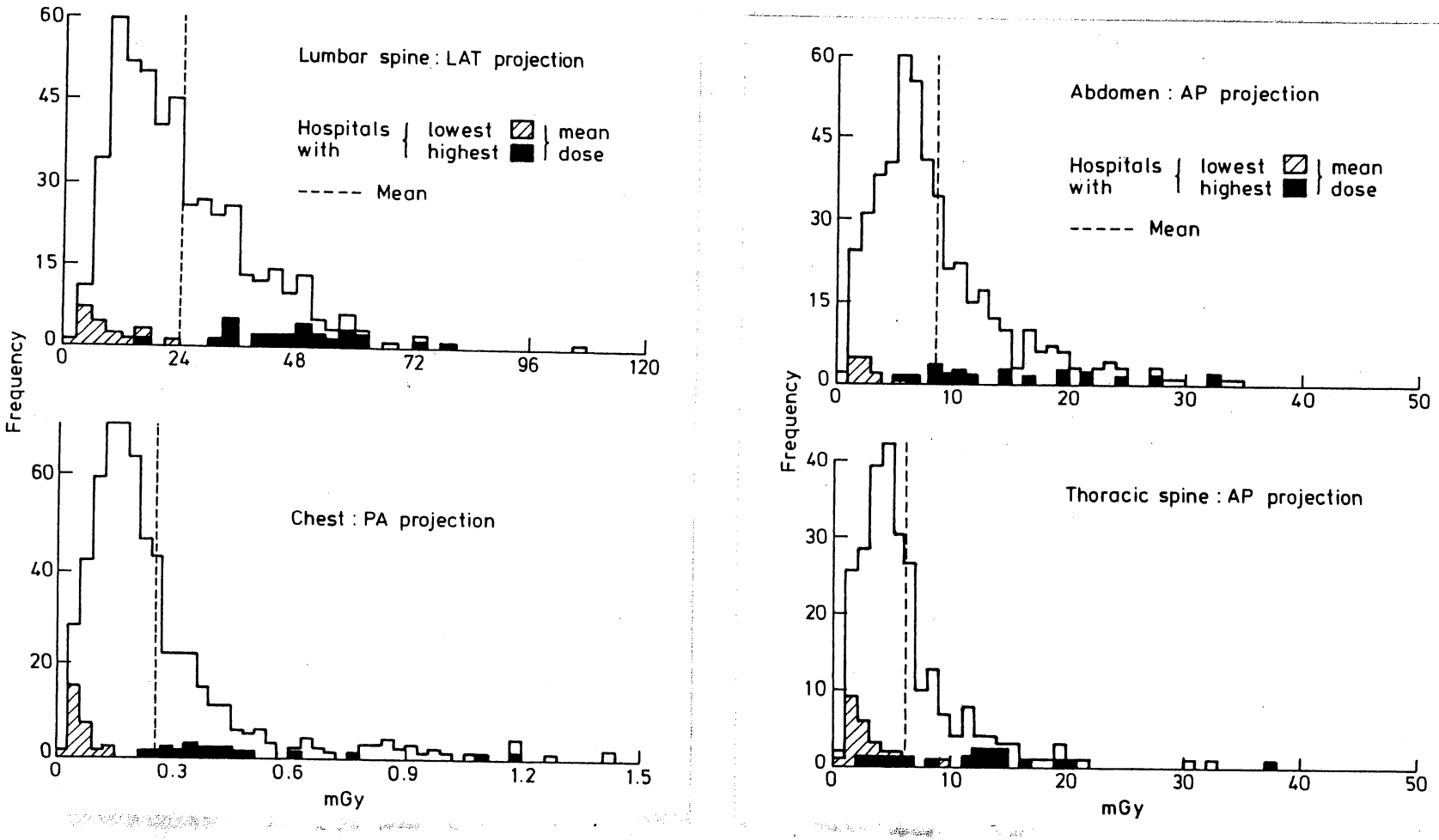

FIGURE 2 Histograms of the entrance surface dose per radiograph measured at a random sample of 20 English hospitals in the mid-1980s

and quality of life for the patient'. Whereas audit is usually the retrospective study of performance, it is closely linked to quality assurance which is mainly prospective, since what is decided after audit becomes quality assurance. A first essential step in auditing the quality of diagnostic radiology services is to obtain data on patient doses. Without regular patient dose monitoring, radiology staff have no access to reliable data.

For some years there have been UK statutory requirements embodied in the Ionising Radiation (Protection of Persons Undergoing Medical Examination or Treatment) Regulations 1988 calling for:

(a) patient doses to be in accordance with accepted diagnostic practice,

(b) patient doses to be as low as reasonably practicable in order to achieve the required diagnostic purpose,

(c) professionals directing and conducting medical exposures to be familiar with typical doses, methods of measurement and means of dose reduction.

These regulations have led to an increased awareness amongst professionals in diagnostic radiology of the need for reductions in unnecessary patient dose. The practical implementation of this concern has been further encouraged by Department of Health Circulars requiring health authorities and clinicians to formulate a 'strategy for dose reduction'[4,5] and Health Service Guidelines to consider the minimisation of patient dose when selecting equipment for purchase[6].

Service quality and patient radiation dose are high profile parameters by which today's X-ray service is judged. Health service managers should consider the small staff time and resource overhead involved as necessary demonstration of the health service commitment to service quality and patient safety. The employer's general liability to facilitate best professional practice is implicit in the relevant regulations, and administrative support for the dose measurement, comparison and collation procedures described in this protocol will go a long way towards discharging it. Radiologists, particularly those in the position of clinical director of departments of radiology, also have legal and professional responsibilities to ensure that these assessments are made. Medical physicists, often in the role of Radiation Protection Adviser (RPA), play an important role in advising both hospital management and staff in radiology departments on the need to obtain reliable information on doses delivered to patients and to make recommendations on procedures for obtaining such information.

Radiographers physically perform the majority of X-ray examinations in a radiology department while at the same time being responsible for the safety and comfort of patients in their charge. They are naturally concerned about the radiation protection of patients and it is recognised that they are in a good position to monitor the doses delivered to patients by the routine procedures adopted in a department. Direct involvement of radiographers in the measurement process would improve their awareness of patient doses and the effectiveness of patient protection measures. Furthermore, it helps them to improve the quality of the service they offer and to reassure the increasing numbers of patients who question the safety of medical X-rays.

Radiologists clinically direct all X-ray examinations in departments of radiology and physically perform many of the high dose examinations, particularly those involving fluoroscopy. The close involvement and support of radiologists in patient dose monitoring is essential and the Royal College of Radiologists has given formal support to this protocol. RCR endorses the

importance of periodically providing radiology department staff with a clear indication of the doses that they are delivering to patients and how they compare with national norms.

This protocol therefore sets out nationally agreed methods for monitoring patient doses from routine X-ray examinations that can be easily carried out by radiology department staff with advice and assistance from medical physicists. The protocol has been drawn up by the Dosimetry Working Party of the IPSM Diagnostic Radiology Topic Group with co-opted members from the College of Radiographers. Guideline reference doses are provided that are in line with current national and European practice, against which individual X-ray facilities can compare their performance. RPAs are encouraged to participate in a system for the national collation of patient dose data so that the impact of patient protection measures on diagnostic radiology in the UK can be assessed centrally and guideline reference doses periodically revised. Finally, since it is well recognised that there are some circumstances in which over-zealous reductions in patient dose can have deleterious effects on image quality, simple methods for monitoring image quality are outlined.

The recommended methods of patient dose measurement are suitable for use in most types of conventional radiographic or fluoroscopic X-ray examination, although a preferred selection of types of radiograph and examination is given. The methods are not particularly suitable for mammography or computed tomography for which appropriate dosimetry techniques are described in IPSM Report 59[7] and NRPB-R249[8], respectively. These reports are available from IPSM and HMSO, respectively.

2 Impact on other recommendations and regulations

In an ideal world patient dose monitoring would be carried out continuously on every patient attending a particular X-ray facility. If this were possible it would not only provide a complete and continuous assessment of patient protection but would also enable compliance, in probably the simplest way, with paragraph 2.12 of the Guidance Notes for the Protection of Persons Against Ionising Radiations Arising from Medical and Dental Use[9] which recommends that 'After the examination has been carried out, arrangements should be made to ensure that details relevant to the estimation of the radiation dose are inserted in the patient's records'.

The method recommended later in this protocol for monitoring patient doses from complete X-ray examinations, using a dose–area product meter, would allow continuous dose monitoring for every patient at the expense of only minimal extra effort or resources, once the dosemeter had been installed. A note of the dose–area product meter reading at the completion of the examination in the patient's records would go a long way towards meeting this recommendation.

Such continuous dose monitoring would also provide immediate indication of accidental overexposures that might otherwise go unnoticed. As well as hastening corrective action, this would considerably aid the detailed investigation and patient dose assessment that is required by Regulation 33(2) of the Ionising Radiations Regulations 1985 when such overexposures are the result of equipment defects and lead to patient exposures much greater than intended.

The simplification of compliance with these recommendations and regulations afforded by the regular use of dose–area product meters provides an additional incentive for their adoption. The main justification, however, lies in the importance of periodically providing radiology department staff with a clear indication of the doses they are delivering to their patients and how they compare with national norms.

3 Quantities to be measured

The recommended dose quantities have been selected to meet the following objectives:

(a) to be capable of unambiguous definition so that everyone can clearly understand exactly what is to be measured,

(b) to be capable of simple, direct measurement with readily available dosemeters of sufficient precision and accuracy – valid comparisons can then be made with previous measurements at the same facility, with measurements in other facilities and with national norms,

(c) to provide a measurement of the typical dose received by patients examined in a particular facility from either:

  (i) a particular type of radiograph,

  (ii) a particular type of complete examination.

Comparison of measurements of type (i) with national norms provides a measure of the relative sensitivity of the radiographic imaging system as operated in the particular facility. Comparison of measurements of type (ii) with national norms provides a measure of the degree of patient protection afforded by both the imaging equipment and the examination procedures that are adopted in a particular facility.

To meet these objectives the following two dose quantities are recommended:

(a) entrance surface dose for individual radiographs.

(b) dose–area product for complete examinations.

Other dose quantities exist which may be more closely related to the radiation risk to the patient, eg organ dose, effective dose or the total energy imparted to the patient. They cannot, however, be measured directly and the various assumptions and uncertainties involved in their estimation can lead to ambiguity in their expression. Standardised methods for deriving such quantities from the directly measurable quantities recommended in this protocol have been developed by NRPB[10,11] and are being extended. These will increase the utility of the two above recommended quantities, which still, however, remain more practicable for the periodic checking of patient doses in radiology departments.

3.1 Entrance surface dose

For the purposes of this protocol entrance surface dose is defined as the absorbed dose to air at the point of intersection of the X-ray beam axis with the entrance surface of the patient, including backscattered radiation. The entrance surface dose is to be expressed in mGy.

The reasons for specifying absorbed dose to air rather than absorbed dose to muscle, as has been previously suggested[12], are explained in Appendix A.

The amount of radiation scattered back from the patient into a dosemeter placed on the skin can be substantial and typical backscatter factors for diagnostic X-ray fields are tabulated in Appendix B. It is essential that this backscattered radiation be completely included in the measurement of entrance surface dose and this is best achieved by using a dosemeter of small volume attached directly to the patient's skin.

Appropriate dosemeters are described in Section 4.

3.2 Dose–area product

For the purposes of this protocol dose–area product is defined as the absorbed dose to air (or the air kerma) averaged over the area of the X-ray beam in a plane perpendicular to the beam axis, multiplied by the area of the beam in the same plane. The dose–area product is to be expressed in Gy cm^2. If dose–area products for complete X-ray examinations are expressed in mGy cm^2, their numerical values will frequently exceed 10,000 for complex examinations and become rather cumbersome. Hence Gy cm^2 is the preferred unit.

In this quantity, radiation backscattered from the patient is excluded. Dose–area product can be measured at any point between the diaphragm housing of the X-ray tube and the patient since it is invariant with distance from the tube focus, as long as the point of measurement is not close enough to the patient to receive significant backscattered radiation.

Large area, parallel-plate ionisation chambers are available which can be mounted on the diaphragm housing to intercept the entire cross-section of the X-ray beam and essentially integrate the absorbed dose over the whole beam area and for any number of exposures. If reset to zero at the beginning of each examination they can provide a single measurement of the total amount of radiation used in even the most complex examinations involving radiography and fluoroscopy.

Appropriate dosemeters are discussed in Section 4.

4 Choice of dosemeter

4.1 Entrance surface dose per radiograph

Two types of dosemeter are commonly used for estimating entrance surface doses to patients during X-ray examinations, namely thermoluminescent dosemeters (TLDs) and ionisation chambers.

TLDs have the advantage of being physically small, enabling them to be stuck directly and unobtrusively to the patient's skin with very little interference in patient mobility or comfort. They will fully measure the radiation backscattered from the patient, an essential component of the entrance surface dose, and they are unlikely to obscure useful diagnostic information.

Ionisation chambers, being more bulky and requiring connecting cables, are usually difficult to attach in sufficiently close contact to the patient's skin to ensure complete measurement of the backscattered radiation, severely restrict patient mobility and cast interfering shadows on radiographs. They are consequently not recommended for *direct* measurement of entrance surface dose on the skin of the patient. They can, however, be used to make measurements of the absorbed dose to air, in free air, on the axis of the X-ray beam without a patient or phantom present, *in suitable circumstances*. Such measurements can then be corrected using appropriate backscatter factors (see Appendix B) and the inverse square law to estimate the entrance surface dose. Circumstances in which such free-in-air measurements may prove to be difficult to perform in practice are discussed more fully in Section 5 which deals with the selection of an appropriate sample of measurements.

TLDs are consequently the recommended dosemeter for direct measurements of entrance surface dose. They are available in a variety of physical forms and in different materials. The characteristics of commonly available TLD phosphors are discussed elsewhere[12]. For the measurements described in this protocol, individual chips or pellets of lithium fluoride or lithium borate are probably the most suitable form of TLD.

It is essential that all TLD systems used to carry out the measurements recommended in this protocol be calibrated in the same manner and be capable of performing within recommended levels of accuracy and precision. Suitable calibration methods and acceptable tolerances on precision and accuracy are specified in Appendix C.

Appropriate TLD patient dosimetry services are available from a number of medical physics departments and from the Medical Dosimetry Group at NRPB.

4.2 Dose–area product per examination

The dose–area product is most conveniently measured with specially designed dose–area product meters. As mentioned in Section 3.2, they consist of flat, large area parallel-plate ionisation chambers connected to suitable electrometers, the response of which in terms of the charge collected is proportional both to the area of the chamber that is exposed to the primary X-ray beam and to the dose. When the chamber is set up perpendicular to and centred on the X-ray beam axis in a position where the beam area will never exceed the area of the chamber, its response will be proportional to the product of the beam area and the dose, which is the same for all planes normal to the beam axis. It can consequently be mounted well away from the patient and close to the tube focus where the area of the X-ray beam is relatively small and the dose rates are high. It is normally mounted on the diaphragm housing where it does not interfere with the examination and is unlikely to receive significant radiation backscattered from the patient. For measurement of this quantity, radiation backscattered from the patient is to be avoided.

The ionisation chambers are usually transparent so that when fitted to an overcouch X-ray tube, the light beam diaphragm device can still be used. However, due thought will be required concerning the provision of a suitable mounting system, particularly where it is the practice to install cones, field delineators and external beam filters. In these circumstances dose–area product measurements might have only limited usefulness. Test radiographs should be taken for those procedures employing large film sizes or short focus film distances, or both, to ensure that the edges of either the ionisation chamber or its mounting system do not interfere with the radiograph.

It is essential that all dose–area product meters used to carry out the measurements recommended in this protocol be calibrated in a similar manner and be capable of performing within recommended levels of accuracy and precision. Suitable calibration methods and acceptable tolerances on precision and accuracy are specified in Appendix C. Advice and assistance in the calibration of dose–area product meters should be available from medical physics departments.

Appropriate dose–area product meters are available in the UK from a number of suppliers, including (in alphabetical order) Gammex-RMI, NE Technology Ltd and Radiatron Components Ltd, or they can be installed directly by the manufacturer of the X-ray imaging equipment. In December 1991 the Department of Health announced a substantial capital allocation for the purchase, among other equipment, of dose–area product meters throughout the National Health Service. This was an important first step in the provision of such equipment but it will be some time before the needs of all X-ray departments for dose–area product meters are fully met.

5 Selection of measurement sample

The objective of the measurements is to obtain an indication of the typical dose that is being delivered to an average adult patient by the procedures and equipment used in a particular facility for the types of radiograph or examination under study. To meet this objective

measurements should preferably be made on a representative sample of patients rather than on phantoms or in free air.

There are the following difficulties with phantom or free air measurements.

(a) Suitable phantoms would have to provide the attenuation (if automatic exposure control (AEC) is used) and backscatter appropriate to a standard patient for all radiation qualities to which they are likely to be exposed. As a consequence they cannot be single, homogeneous blocks or sheets of readily available materials but need to be of a more complicated construction such as the 'LucAl' phantoms developed in the USA for use in chest and lumbar spine radiography[13,14]. Different standard phantoms would be required for the different types of radiograph to be measured. For nationally comparable measurements, phantoms of the same standard design would have to be used in all facilities. Such phantoms are neither cheap nor readily available in the UK; furthermore, they are too bulky and heavy to be easily circulated by post.

(b) Free air measurements cannot be made if AEC devices are in use. When manual selection of exposure factors is made there is often disparity between the selection of the appropriate exposure factors for a standard patient by different radiographers, even if the standard patient is specified in detail. A single free air measurement may consequently not be typical of practice on that particular installation. Notwithstanding these problems, it is recognised that free air measurements of X-ray tube output are regularly made as part of existing quality assurance programmes. *In appropriate circumstances* it might be possible for such measurements to be corrected to provide sufficiently accurate estimates of typical entrance surface doses for the purposes of this protocol.

Direct dose measurements during the course of real examinations on real patients provide the best indication of actual clinical practice. Patients will, however, vary in physique and hence in the thickness and density of the part of the body being examined, which may influence the doses required for nominally the same radiograph or examination. For the dose measurements to be indicative of routine practice in a particular facility and to be comparable with those from another facility and with national norms, careful selection of the measurement sample is required.

5.1 Number and choice of patients

The average value of the doses measured on a representative sample of at least ten patients per type of radiograph or examination should provide a good indication of typical clinical practice.

Adult patients only should be included in the sample for the assessment of general diagnostic radiology procedures. Both sexes may be included as long as extremes in physique are avoided. The doses required to obtain satisfactory images can be expected to vary according to the thickness and density of the body part being examined, both of which are reasonably well correlated with the weight of the patient. Selecting patients so that *the mean weight of the sample lies within 5 kg of 70 kg* has been shown to be sufficient for the average value of the doses to be a good indication of the typical dose to an average patient[15]. It would be prudent, at least for frequent examinations, to exclude patients from the sample if their individual weights were much outside 10 kg from 70 kg, and in all cases to exclude patients whose weights were outside 20 kg from 70 kg.

Doses delivered during paediatric radiology depend critically on the size, and hence age, of the patient. At present there are no well-established reference doses for paediatric examinations:

they need to be specified for patients of well-defined size or age ranges. The methods of dose measurement recommended in this protocol can, however, be used equally well in paediatric radiology, as long as the dosemeters are sufficiently sensitive to measure the low doses involved. There is an urgent need to monitor and control doses to neonates and young children who are probably at greater risk from the effects of ionising radiation than adult patients. Radiographers and medical physicists working with paediatric patients are encouraged to measure their doses using the methods described in this protocol and to send the results to the national collation centre described in Section 8. When sufficient data have been collected it should be possible to establish appropriate reference doses for paediatric patients.

5.2 Types of radiograph and examination

It is recommended that dose measurements be made on those types of radiograph and examination that make a significant contribution to the collective population dose from medical X-ray examinations. Table 1 shows the relative frequency of various types of examination in the UK and, more importantly, their percentage contribution to the UK collective effective dose equivalent from all medical and dental X-ray examinations.

TABLE 1 Relative contribution of examinations to UK frequency and collective dose

Examination	% frequency	% collective dose
Computed tomography	2.0	20
Lumbar spine	3.3	15
Barium enema	0.9	14
Barium meal	1.6	12
Intravenous urography	1.3	11
Abdomen	2.9	8
Pelvis	2.9	6
Chest	24	2
Limbs and joints	25	1.5
Skull	5.6	1.5
Thoracic spine	0.9	1
Dental	25	1

The methods of dose measurement recommended in this protocol are not suitable for CT examinations (see reference 8 for appropriate methods). One or both of the recommended methods will be suitable for the other types of examination in the table and, where possible, measurements should be concentrated on those towards the top of the table that make the greatest contribution to the collective dose. This recommendation should not be taken to imply that dose assessments are not needed for other, less frequent procedures, particularly if the individual patient doses are high. Such procedures are best subject to special studies.

To obtain sufficient measurements (ie on at least ten patients of suitable size) in a reasonable time, it is likely that the sample will also have to be restricted to those types of radiograph and examination that are frequently carried out on the facility being monitored. Within this restriction the types of *radiograph* for entrance surface dose measurements should preferably be selected from the following:

Lumbar spine	AP
	Lat
	LSJ
Abdomen	AP (including IVU pre-contrast KUB)
Pelvis	AP
Chest	PA
	Lat
Skull	AP/PA
	Lat

Again within the above restriction the types of *examination* for dose–area product measurement should be selected from the following:

Lumbar spine
Barium enema
Barium meal
Intravenous urography
Abdomen
Pelvis

It is important that examinations that are terminated at an unusually early stage on account of, for example, unforseen difficulties with the patient, not be included in the sample of measurements from which the average dose is calculated.

Measurements for types of radiograph or examination other than those listed above which would provide useful information on the performance of a particular X-ray facility are not to be excluded from quality assurance programmes that follow this protocol. For the majority of standard radiographic or fluoroscopic facilities, however, patient dose monitoring should be concentrated initially in the above areas.

5.3 Frequency of measurements

Representative measurements of entrance surface dose and dose–area product should be made periodically, at least once every 3 years, on each piece of X-ray imaging equipment in a department or whenever changes to equipment or its performance or to examination procedures are likely to lead to significant changes in patient dose. These periodic measurements should be regarded as an essential part of the medical audit or the quality assurance programme that ought to be in operation in all X-ray departments.

If sufficient numbers of dose–area product meters are available, continuous patient dose monitoring on the most frequently used equipment will become possible, which will aid compliance with the recommendations and regulations discussed in Section 2. Otherwise, dose–area product

meters should be rotated around the X-ray sets in a department so that each one is monitored at regular intervals.

In any event, measurements should be made with sufficient regularity so that radiologists and radiographers are kept aware of how the doses that they currently deliver to their patients compare with national norms, so that they can bring them into line with modern accepted practice and thus be able to reassure their patients that all reasonable steps have been taken to protect them.

6 Practical techniques of measurement and details to be recorded

6.1 Entrance surface dose per radiograph

It is envisaged that TLDs calibrated in the manner prescribed in Appendix C and capable of the required precision and accuracy will be available for radiographers from a number of medical physics departments and from NRPB. They should be suitably packaged in thin plastic sachets to protect them from dirt, grease, etc, so that they can be stuck directly to the patient's skin with short lengths of sticky tape – Micropore tape is probably the most suitable type. Figure 3 shows a radiographer sticking TLD sachets to a patient. The sachets should be attached to the skin as close as possible to the point where the central axis of the X-ray beam enters the patient.

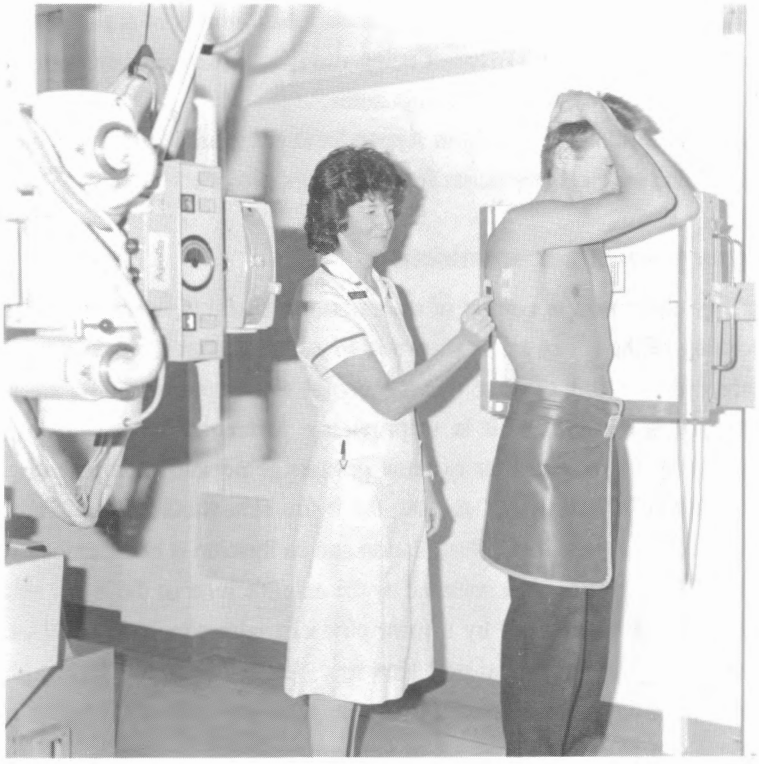

FIGURE 3 Sachets containing TLDs being attached to a patient's skin with adhesive tape

The *preferred* method is for a fresh TLD to be used to measure the entrance surface dose for each radiograph without exposing the same TLD more than once. A simple procedure for identifying the TLDs and for recording all the necessary details of each exposure is to stick the TLD to a form such as form 1(a) in Appendix D, after it has been exposed. A form of this type should be completed by the radiographer for each patient, together with one as form 1(b) in Appendix D

for each set of imaging equipment that is being checked. These will provide all the necessary information for the TLD laboratory to convert the TLD reading into dose and for the doses to be analysed locally to assess performance and to compare them with previous results and national norms. When the dose readings are added to forms 1(a), they will provide data in a suitable format for submission to the national patient dose collation centre discussed in Section 8.

An *alternative* method for obtaining the average dose for a representative sample of patients is to use the same TLD repeatedly for all measurements in the sample and to divide the final cumulative dose reading on the one TLD by the number of measurements. This provides a far more efficient use of TLDs but at the expense of losing much useful data on how individual doses vary with changes in exposure conditions. There is also a greater opportunity for losing track of the number of exposures actually made when the same dosemeter is being used for all measurements in a sample. This method is consequently recommended only if resources are so limited that, without recourse to this method, no measurements would be made at all.

If a radiograph is rejected after a dose measurement has been made, the measurement should be included in the sample only if the rejection was **not** due to incorrect exposure settings, that would lead to a different dose when rectified. For example, if rejection was due solely to patient movement, leading to a repeat radiograph under identical exposure settings, the dose measurement made on the first (rejected) radiograph would be acceptable. To be indicative of typical practice, the dose measurements should be for only radiographs of acceptable optical density.

It is essential that all other TLDs not being used for a particular measurement should not be left unshielded in the X-ray room during exposures.

The outlines of forms 1(a) and (b) in Appendix D are suitable for photocopying and direct use by radiographers and medical physicists following this protocol.

6.2 Dose–area product per examination

Dose–area product meters consist of an ionisation chamber, which is usually attached to the diaphragm housing of the X-ray set as shown in Figure 4, and an electrometer and display unit to which it is connected by a long cable so that the display can be positioned for easy access to read and reset. Printers are sometimes built in to provide a permanent record of display values, or suitable connections may be provided for external printers or personal computers.

Once installed on a particular X-ray set, the instrument should be calibrated according to the procedures described in Appendix C. Installation and calibration is best carried out by a medical physicist unless the instrument has been installed by the manufacturer of the X-ray equipment. Even then the calibration should be checked by a local physicist who should also be satisfied that the instrument is capable of the accuracy and precision specified in Appendix C. The physicist should ensure that instrument readings are corrected by the appropriate calibration factor before they are used in any subsequent performance analysis or comparison.

Corrected dose–area product meter readings integrated over a complete examination can be entered by the radiographer for each patient on to form 2(a), shown in Appendix D, which also includes space for all other relevant details of the examination. When completed, these forms, together with one as form 2(b) in Appendix D giving equipment details for each facility, will provide data in a suitable format for local assessment as well as for submission to the national patient dose collation centre discussed in Section 8. Printers or personal computers connected to the dose–area product meter may help to automate the collection of some of these details.

FIGURE 4 Ionisation chamber of a dose–area product meter being attached to the diaphragm housing

The outlines of forms 2(a) and (b) shown in Appendix D are suitable for photocopying and direct use by radiographers and medical physicists following this protocol.

7 Reference dose levels

7.1 Entrance surface dose per radiograph

Table 2 shows the minimum, quartile and maximum values of entrance surface dose for common types of radiograph from a national patient dose survey conducted by NRPB in the mid-1980s[2]. Until more recent data are collected, it is recommended that this survey, which covered 20 randomly selected English radiology departments, should form the basis for national reference dose levels. Figure 5 indicates the distribution of the mean entrance surface doses for samples of 10–20 patients at each hospital in the NRPB national survey for a given radiograph. The third quartile of these mean values is indicated on each bar chart in the figure and closely matches the corresponding rounded value of the third quartile for all the individual doses in the survey, which are shown in Table 3.

These rounded 3rd quartile values for entrance surface dose form the basis for UK reference doses previously quoted in the report on patient dose reduction in diagnostic radiology produced jointly by RCR and NRPB[1]. They also form the basis of European reference doses in a document produced by a Study Group of the Commission of the European Communities (CEC) entitled 'Quality Criteria for Diagnostic Radiographic Images'[16] and originally appeared as suggested guideline doses in a paper by Shrimpton *et al*[17]. The same concept is to be used for setting reference doses in this protocol.

TABLE 2 Distribution of individual entrance surface doses for adult patients at a random sample of 20 English hospitals

Radiograph		Entrance surface dose (mGy)				
		Minimum	1st quartile	Median	3rd quartile	Maximum
Lumbar spine	AP	0.83	5.65	7.68	11.2	59.1
	Lat	2.38	12.7	19.7	30.1	108
	LSJ	7.40	24.0	34.5	50.2	131
Abdomen	AP	0.71	4.69	6.68	10.5	62.4
Pelvis	AP	0.85	4.19	5.67	7.86	31.6
Chest	PA	0.03	0.13	0.18	0.26	1.43
	Lat	0.14	0.49	0.99	1.46	10.6
Skull	AP	0.73	2.97	4.02	4.97	13.9
	PA	1.82	3.26	4.25	5.49	13.1
	Lat	0.36	1.42	2.19	2.85	9.09

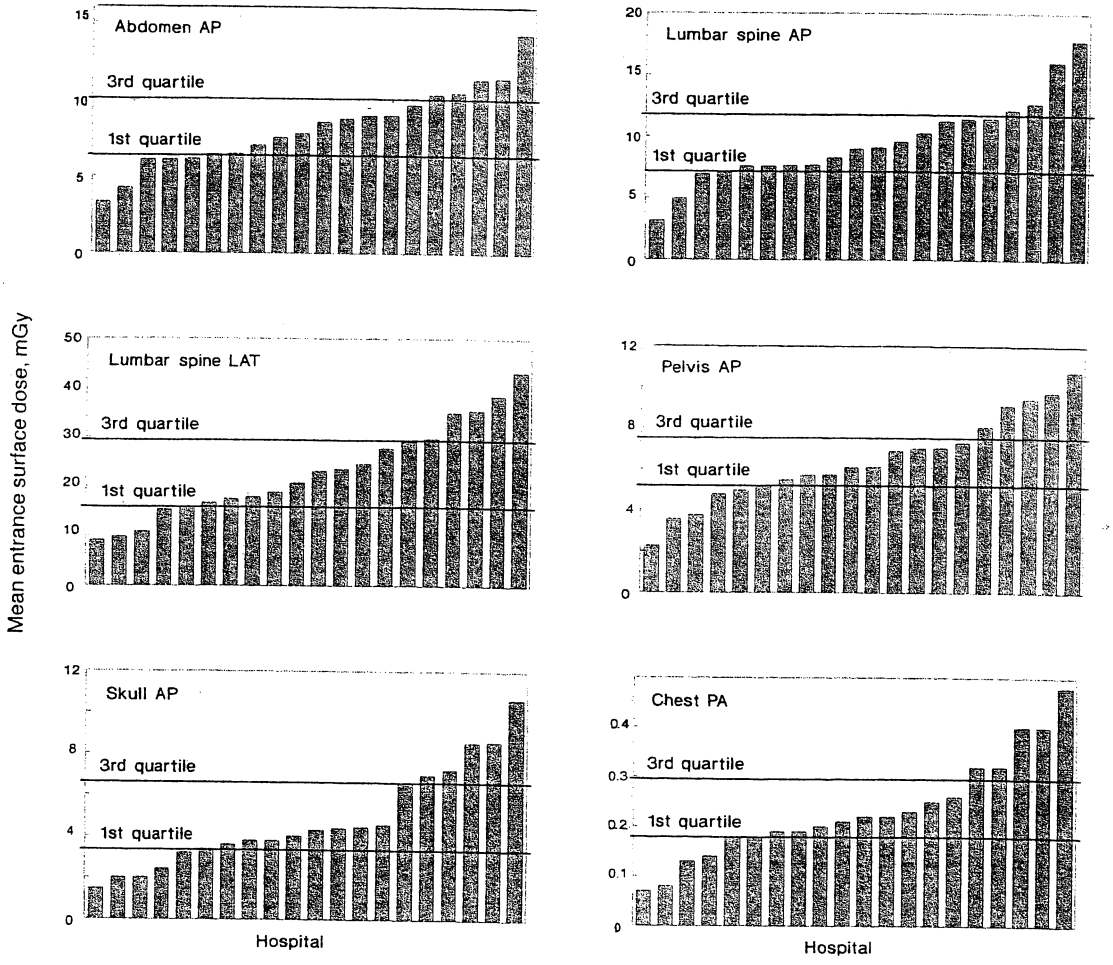

FIGURE 5 Distribution of mean entrance surface doses at 20 hospitals for 6 types of radiograph

TABLE 3 Reference values of entrance surface dose

Radiograph		Reference dose (mGy) (rounded value of 3rd quartile)
Lumbar spine	AP	10
	Lat	30
	LSJ	40
Abdomen	AP	10
Pelvis	AP	10
Chest	PA	0.3
	Lat	1.5
Skull	AP	5.0
	PA	5.0
	Lat	3.0

As an initial guideline, it is recommended that all radiology departments should aim to achieve mean dose levels that are less than the reference doses given in Table 3. Since 75% of radiology departments in the survey were apparently operating satisfactorily with mean doses below these values, it is recommended that those departments that are found to exceed this level should conduct thorough and immediate investigations into the reasons for their excessively high doses. The investigations either should lead to revisions in techniques or equipment to bring the mean dose into line with the majority or, exceptionally, should lead to a thorough justification of the need for high doses in that particular clinical circumstance.

The proposed reference doses should be seen as a practical aid to increase awareness of the significance of observed levels of patient dose and hence to the promotion of optimisation of radiation protection in medical radiology. The adoption of the third quartile values is a purely pragmatic approach to help identify those radiology departments in most urgent need of better quality control. The achievement of mean doses below the reference level should not, however, be construed as an indication of satisfactory or optimum performance. It may well be possible to reduce doses further without detriment to the diagnostic value of the examination and such reductions should always be pursued in line with the ALARA principle.

In its 1990 Recommendations[18] the International Commission on Radiological Protection states that, for medical exposures, 'Consideration should be given to the use of *dose constraints*, or investigation levels, selected by the appropriate professional or regulatory agency, for application in some common diagnostic procedures. They should be applied with flexibility to allow higher doses where indicated by sound clinical judgement'. The above reference dose levels could be construed as dose constraints that have been set at the national level.

In some X-ray departments, particularly those with modern, sensitive imaging equipment, it may be possible for a local group of professionals to establish practical dose constraints that are lower than the national reference values indicated in this document. This is to be encouraged so as to ensure that the full potential of the available equipment for patient dose reduction is realised.

It is well recognised that there are some circumstances in which over-zealous reductions in patient dose can have deleterious effects on image quality. Particular attention should therefore be paid to the checking of image quality if mean doses are seen to fall significantly below the first quartile values that are marked on the bar charts in Figure 5 and shown in Table 2. A brief review of simple methods for assessing image quality is given in Section 9.

All reference dose values will be reviewed periodically in the light of the national collation of patient dose data.

7.2 Dose–area product per examination

Table 4 shows the minimum, quartile and maximum values of individual measurements of dose–area product for common types of X-ray examination taken from the same national patient dose survey as the previous entrance surface doses. Figure 6 also shows the distribution of the mean dose–area products for samples of 10–20 patients at each hospital for a given examination. Once again, these data form the basis for national reference dose levels with the recommendation that the rounded third quartile values be used as an initial investigation level. Reference values of dose–area product per examination based on rounded third quartile values observed in the NRPB national patient dose survey are given in Table 5.

TABLE 4 Distribution of individual dose–area products for adult patients at a random sample of 20 English hospitals

	Dose–area product (Gy cm^2)				
Examination	Minimum	1st quartile	Median	3rd quartile	Maximum
Lumbar spine (3.4 films)	2.0	8.2	12	17	93
Barium enema (8.5 films, 224 s fluoro)	6.2	26	41	61	272
Barium meal (7.8 films, 193 s fluoro)	0.49	9.3	17	23	163
Intravenous urography (8.2 films)	3.3	13	29	42	251
Abdomen (1.4 film)	0.70	3.2	4.9	8.3	30
Pelvis (1.1 film)	0.49	2.6	3.8	5.0	19

Note The indicated numbers of films and fluoroscopy times are the mean values for the 20 hospitals.

These reference doses should be used, in the same way as those for entrance surface dose, as an initial guideline to help identify those radiology departments in most urgent need of better quality control for particular types of X-ray examination. Again they should be applied with flexibility, but allowing higher mean doses only with sound clinical justification. They should not be construed as target doses, or as an indication of optimum performance. Doses well below these reference levels may be reasonably achievable and efforts further to reduce patient doses should not be relaxed simply because these reference levels have not been exceeded. However, as before, particular attention should be paid to checking image quality if mean doses fall significantly below the first quartile values shown on the bar charts and in Table 4.

These reference dose–area product values will also be reviewed periodically in the light of the national collation of patient dose data.

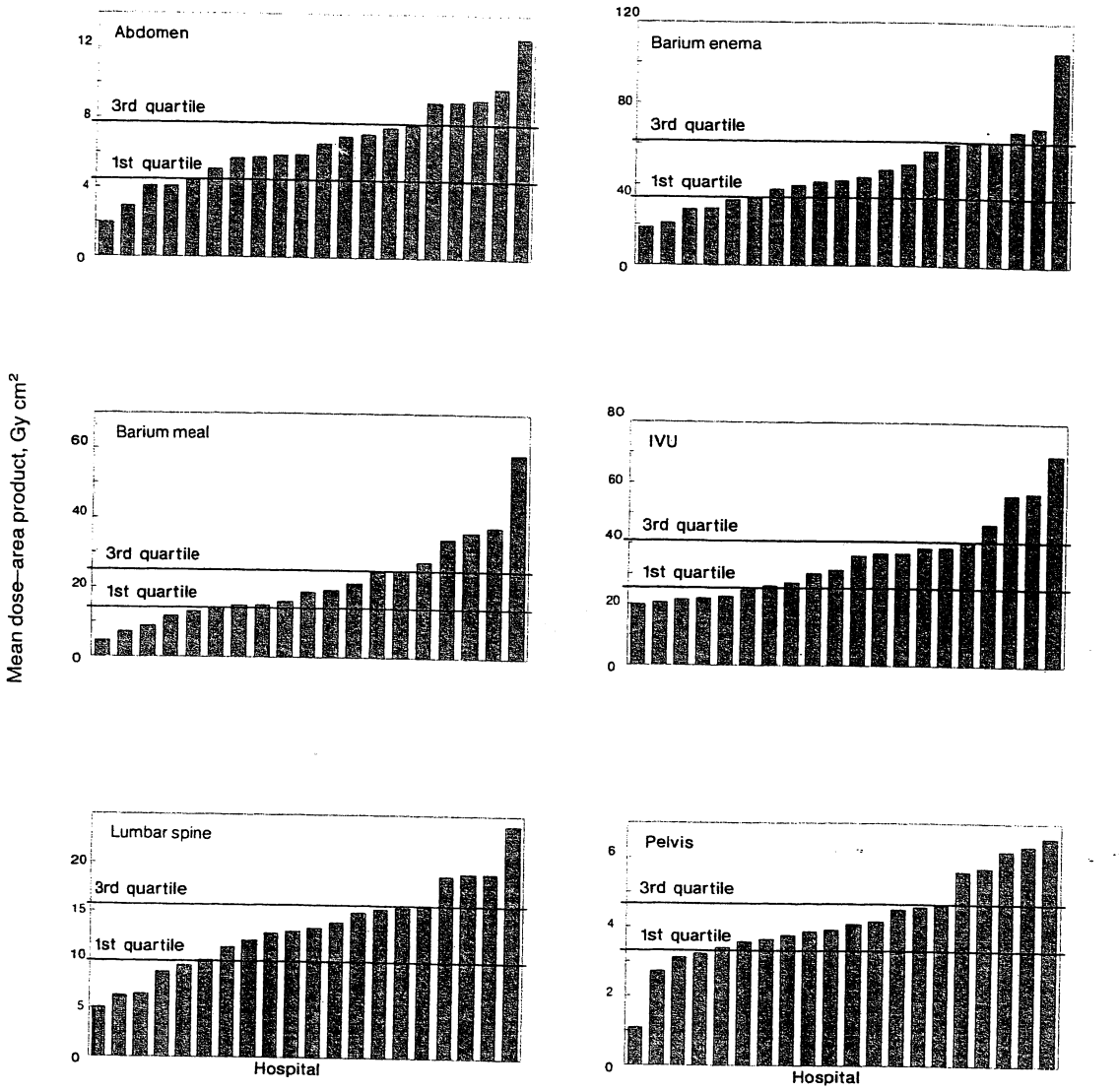

FIGURE 6 Distribution of mean dose–area product at 20 hospitals for 6 types of examination

TABLE 5 Reference values of dose–area product

Examination	Reference dose (Gy cm^2) (rounded value of 3rd quartile)
Lumbar spine	15
Barium enema	60
Barium meal	25
Intravenous urography	40
Abdomen	8
Pelvis	5

8 National collation of dose data

The value of patient dose measurements made and assessed at a local level will be considerably increased if they are forwarded to a single centre for national collation and assessment. Such assessment would provide timely evidence for national trends in patient dose and the effectiveness of patient protection in the UK. It will also allow for the periodic updating of national norms and reference dose levels.

NRPB, having already carried out a number of national patient dose surveys, is in a good position to collect and analyse these data. It will consequently set up a National Collation Centre in close collaboration with IPSM and CoR, with the approval and support of the Department of Health. Radiation Protection Advisers (RPAs), having collated and compared patient doses measured according to these protocols on a local level, are requested to send their results to the National Collation Centre at NRPB.

One convenient way of supplying the data would be in a manner corresponding to the forms shown in Appendix D, with the measured dose values included with the technical exposure details for each patient in the sample. It is important that as many as possible of the patient, examination and equipment details listed in Appendix D be included, but if the data are incomplete in only a few respects or are presented in a different format, they will still be acceptable. If, for example, resource limitations restrict measurements of entrance surface dose to the use of only one TLD for each sample of patients, or to the use of an ionisation chamber for a single free-in-air dose measurement under typical exposure conditions, so that individual patient doses are unknown, information in this form should still be forwarded to the National Collation Centre where it will be interpreted appropriately.

Information on all suitable types of X-ray examination and radiograph will be welcome, not just those recommended for initial measurements in Section 5.2. It is essential that measurements made on paediatric patients should include details of the age, weight and preferably also the height and thickness of each patient.

The data should be sent to:

National Collation Centre
Medical Dosimetry Group
NRPB
Chilton
Didcot
Oxon
OX11 0RQ

It is known that many local patient dose surveys have been conducted in the few years prior to the publication of this protocol, generally following the methods of the NRPB survey in the mid-1980s. Results from these surveys will be of great value to the National Collation Centre to review trends during this period, and those responsible for such surveys are encouraged to supply whatever data they have.

Periodic reports on the data received at the National Collation Centre will be issued so as to show trends in patient doses in the UK. The results will be published in such a manner that it will not be possible for readers to determine the performance of identifiable radiology departments and the anonymity of patients will, of course, be preserved.

9 Image quality checks

It is important to ensure that efforts to reduce patient doses do not also reduce doses to the imaging system to such an extent that the diagnostic quality of the images is seriously degraded. Image quality can be affected by low doses in three distinct ways.

(a) In the non-digital imaging systems used in conventional radiography and fluoroscopy, the optical density or brightness of the image is proportional to the dose received by the image receptor. Too low a dose can simply result in images that are too faint and that cannot be clearly discerned.

(b) As medical imaging systems have become more sensitive, needing only low doses to achieve images of satisfactory density or brightness, there is an increased likelihood that random variations in the photon fluence rate reaching the image receptor will give a disturbing mottled appearance to the image. This so-called 'quantum mottle' can be a predominant source of image degradation in sensitive digital and non-digital imaging systems.

(c) The sensitivity of the imaging system can often be improved by increasing the thickness of the sensitive layer of the image receptor so that it absorbs more of the incident X-ray energy. Thicker sensitive layers, however, frequently result in wider spatial dispersion of the emitted light before the image is recorded, so that greater sensitivity, and hence the ability to use lower doses, is gained at the expense of poorer spatial resolution in the image.

It is a significant observation that in surveys where both image quality and patient dose have been assessed in practical clinical circumstances[16] there appears to be little correlation between dose and image quality. Whereas nearly all images were declared to be diagnostically acceptable, the patient doses varied enormously.

Unlike patient dose, which cannot be perceived directly, image quality is continuously being assessed, as radiographers and radiologists view and report on the images that they have taken. It could consequently be argued that there is not such an urgent need for carrying out additional checks on image quality as there is for monitoring otherwise undetectable patient doses.

Such continuous image quality assessment is often carried out subconsciously and is naturally rather subjective. However, since the diagnostic value of the images is realised only through the radiologist's skilled but subjective interpretation of the anatomical features that he or she can perceive in the image, purely objective assessment of image quality would be an incomplete measure of diagnostic value. Ultimately the radiologist reporting on the examination is the only person who can properly judge the diagnostic quality of the images but, as with all processes that rely upon human skill, it would be useful to have a simple means of checking performance against a recognised standard so that a level of uniformity can be established.

In the context of this protocol, concerned as it is with patient dose, there is a need for some simple procedures for checking that doses have not been reduced to such an extent that inadequate optical density, excessive quantum mottle or poor spatial resolution is preventing reliable diagnosis. Ideally the procedures should enable the clinical images produced in a department to be checked against a recognised standard. The minimum use of specialised test equipment is desirable if the procedures are to be widely adopted.

There are four types of image quality check that each go some way towards meeting these requirements.

(a) *Regular quality review by all radiologists in a department*

As a first step in widening the critical assessment of diagnostic images beyond the individual radiologist, it is useful to hold regular departmental meetings in which all radiologists review the diagnostic quality of the images produced in the department. This is an essential component of the more general quality audit now required of all hospital departments.

(b) *Checks on the visibility of critical anatomical features in clinical radiographs*

A CEC document on quality criteria for diagnostic radiographic images[16] provides image quality criteria for ten types of routine radiograph which can be checked purely by subjective visual assessment of clinical images and do not require any specialised test equipment. The necessary degree of visibility of anatomical structures that are important for accurate diagnosis is specified as well as the size of the smallest details that should be visible in the image. If all these criteria are met, it is unlikely that low doses are having an adverse effect on image quality.

(c) *Checks on contrast or detail detectability with appropriate test objects*

Test objects are available with features that cover a range of contrast and size which, when imaged, allow a subjective assessment to be made of the thresholds of detectability of the imaging system. Since the test objects are normally exposed under standard conditions that may not coincide with those used clinically, they provide only a relative test of the imaging capability of the equipment and not necessarily a measure of the diagnostic quality of clinical images obtained under realistic conditions. However, the detection of significant deterioration in imaging performance that may have been caused by excessive dose reduction might be possible if suitable test objects were used periodically under clinical exposure conditions.

Further guidance on the use of image quality test objects can be found in the six-part IPSM Topic Group report entitled 'Measurement of Performance Characteristics of Diagnostic X-ray Systems Used in Medicine'[19].

(d) *Checks on the extent and cause of rejected radiographs*

Whereas reject analysis says little about the quality of the images actually being used for diagnosis, evidence for an increase in the number of rejected radiographs may indicate when imaging systems are being operated under conditions resulting in marginal image quality. Investigation of the cause of rejection could reveal whether steps to reduce patient dose had resulted in extra numbers of underexposed, noisy or blurred images that were deemed unacceptable for diagnosis.

Further guidance on the implementation of reject analysis programmes can be found in quality assurance manuals published by the British Institute of Radiology[20] and the College of Radiographers[21].

10 Summary of recommendations

Whereas the following recommendations are mainly directed at radiographers and medical physicists who should collaborate to carry out the necessary measurements, it is the clinical directors of departments of radiology who are ultimately responsible for health and safety matters within their departments, including quality assurance and patient protection.

1 Radiology department staff, with advice and assistance from medical physicists, should carry out regular measurements of the radiation doses delivered to patients in their department.

2 To be comparable with measurements in other departments and with national norms, the measurements should be of the entrance surface dose per radiograph or the dose–area product per examination.

3 Thermoluminescent dosemeters attached directly to the patient and dose-area product meters attached to the diaphragm housing of the X-ray set are the most suitable types of dosemeter.

4 Dosemeters should be calibrated in the manner described in Appendix C and should be capable of performing within the recommended levels of accuracy and precision.

5 Direct dose measurements during the course of real examinations on real patients are preferred. A representative sample of at least ten patients should be measured for each type of radiograph or examination and on each X-ray set in the department.

6 Measurements should initially concentrate on those types of radiograph or examination that make a significant contribution to the collective population dose.

7 Measurements should be made at least every 3 years on each piece of imaging equipment, or whenever changes are made to equipment or procedures that are likely significantly to affect patient dose.

8 If measurements indicate mean doses in excess of the national reference doses recommended for particular radiographs and examinations, an immediate investigation should take place to establish the cause and to improve patient protection, unless the exceptionally high doses can be clinically justified.

9 Radiation Protection Advisers, having collated and compared doses at a local level, should send the results to the National Collation Centre at NRPB.

10 Simple methods for monitoring image quality are recommended, particularly if mean doses are found to fall below the first quartile values observed in the national surveys.

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APPENDIX A

Medium for Absorbed Dose

Values of absorbed dose to tissue will vary by a few per cent depending on the exact composition of the medium that is taken to represent soft tissue. All of the following have been used as tissue substitutes in radiation dosimetry: water, striated muscle[1], ICRP reference man soft tissue[2], ICRU sphere 'soft tissue'[3], and skeletal muscle[4]. The ratios of the absorbed doses in these different media to that in air are given by the ratios of their respective mass energy absorption coefficients which are also dependent on X-ray energy. Values of the ratios are given in Table A1 where the coefficients have been averaged over the X-ray energies present in typical diagnostic X-ray spectra, defined in terms of the peak applied potential (kV) and total filtration (mm Al).

TABLE A1 Ratio of absorbed dose in medium to that in air

Medium	50 kV 2.0 mm Al	80 kV 2.5 mm Al	120 kV 4.0 mm Al
Water	1.02	1.02	1.11
Striated muscle[1]	1.05	1.06	1.07
ICRP reference man soft tissue[2]	0.95	0.96	1.00
ICRU sphere tissue[3]	0.94	0.95	1.05
Skeletal muscle[4]	1.05	1.05	1.06

The ratios for the different media are almost all within 10% of air over the complete range of X-ray spectra likely to be met in diagnostic radiology. Water and the muscle substitutes are slightly higher than air and the soft tissue substitutes are slightly lower than air. In view of its central position, when the more recent tissue substitutes are taken into account, and because it is the usual medium in which dosemeters are initially calibrated, it would now seem sensible to take air as the recommended medium in which to express the entrance surface dose. This will result in differences of only about 6% between entrance surface doses measured in air and those measured in the previously recommended medium – striated muscle[5]. An additional drawback with muscle is that it differs by up to 11% from ICRU 1980 soft tissue which is the medium recommended for personal dosimetry in occupational exposures, whereas air differs by only about 5% from this soft tissue formulation.

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APPENDIX B

Backscatter Factors

The amount of radiation scattered back from the patient into a dosemeter placed on the skin is substantial, as Tables B1 and B2 of backscatter factors for various beam qualities and size indicate[1].

TABLE B1 Backscatter factors measured with TLDs and a water phantom

HVL (mm Al)	Field size (cm x cm)				
	10 x 10	15 x 15	20 x 20	25 x 25	30 x 30
2.0	1.26	1.28	1.29	1.30	1.30
2.5	1.28	1.31	1.32	1.33	1.34
3.0	1.30	1.33	1.35	1.36	1.37
4.0	1.32	1.37	1.39	1.40	1.41

TABLE B2 Backscatter factors calculated by Monte Carlo techniques in an anthropomorphic phantom

HVL (mm Al)	Peak applied potential (kV)	Total filtration (mm Al)	Projection		
			Lat LSJ (11 x 14 cm)	AP abdomen (26 x 35 cm)	PA chest (30 x 38 cm)
2.0	60	2.5	1.23	1.31	1.23
2.5	80	2.0	1.25	1.37	1.27
3.0	80	3.0	1.27	1.41	1.30
4.0	110	2.5	1.29	1.45	1.34

For the X-ray spectra and the beam sizes most commonly employed in diagnostic radiology, the dose is increased by between 20% and 40% when measurements are made on the patient as opposed to free in air. It is consequently essential that this backscattered radiation be completely included in the measurement and this is best achieved by using a dosemeter of small volume attached directly to the patient's skin.

If dose measurements are made with an ionisation chamber free in air, backscatter factors such as those above must be used to correct the reading to entrance surface dose.

Reference

1 IPSM. Patient dosimetry techniques in diagnostic radiology. York, IPSM, Report No. 53 (1988).

APPENDIX C

Calibration Procedures and Accuracy Requirements

1 TLDs for measuring entrance surface dose

Since TLDs do not provide a direct indication of absorbed dose, their response to radiation in the form of an emission of light has to be calibrated against a known standard of absorbed dose. It is essential that all TLD systems used to carry out the measurements recommended in this protocol be calibrated in a similar manner and be capable of performing within the recommended levels of precision and accuracy.

The sensitivity of TLD systems needs to be checked regularly (at least annually) by measuring the response to X-ray exposures of known magnitude and quality. The magnitude is to be determined in terms of the absorbed dose to air (or the air kerma) by a secondary or local reference (tertiary) standard instrument that has itself been calibrated in a manner that is traceable to the national primary standard of air kerma.

These regular TLD calibration measurements should be carried out at a dose and with an X-ray quality (energy spectrum) typical of those to which the TLDs will be exposed in the course of the patient dose measurements recommended in this protocol. An absorbed dose to air of about 10 mGy and an X-ray spectrum generated at around 80 kV with 3.0 mm Al total filtration will usually be appropriate.

The calibration of the secondary or tertiary standard instrument is unlikely to have been performed with diagnostic X-ray spectra since these are not yet available at the National Physical Laboratory or at NAMAS accredited calibration laboratories. NPL is considering plans to provide primary standards at diagnostic X-ray qualities and the John Perry Radiation Metrology Laboratory at St George's Hospital, London, has developed a calibration facility using diagnostic X-ray spectra for which NAMAS accreditation is being sought. NPL or NAMAS accredited laboratories should be used for the calibration of secondary or tertiary standard instruments at diagnostic X-ray qualities when they become available. In the meantime, it is sufficient that the secondary or tertiary standard instrument be calibrated at X-ray qualities and dose rates encompassing those for which the TLDs will be used so that their response can be determined with an uncertainty not exceeding 5% at the 95% confidence level for the exposure conditions prevailing for TLD calibration measurements. Corrections to the response of secondary or tertiary standard ionisation chambers for variations in atmospheric pressure and ambient temperature will obviously be required to meet this standard of accuracy, if they are open to the atmosphere.

In addition to the regular (at least annual) TLD calibration check, it will be necessary to make at least one series of measurements to establish how the response per unit absorbed dose to air varies over the entire range of doses and X-ray qualities for which the TLDs are to be used. Ideally this variation should be so small that if the response of the TLDs is determined at one suitable dose and X-ray quality it could be used without correction for measurements at any other dose or X-ray quality without exceeding the tolerance on overall uncertainty specified below. In practice this may not always be possible and appropriate energy response or other correction factors may have to be applied to keep the dosemeters within tolerance. Since the TLDs will be calibrated and read by a competent dosimetry laboratory this should not be a problem.

Warning

TLDs supplied by personal dosimetry laboratories for body or extremity monitoring may not be able to meet these requirements.

1.1 Tolerances on precision

The precision of the dose measurement made by a single TLD is a measure of how repeatable it is and thus depends on the random uncertainties in the method used to convert the TLD signal (usually a count displayed on the TLD reader) into a dose.

TLDs can be calibrated individually or as one of batch of TLDs that have been selected for closely matching sensitivities. In the latter case, all TLDs in the batch, or a sample (n) of them, are given the same calibration dose (d), and the mean count (c) for the batch is subsequently attributed to each TLD with the standard error of the sample counts ($S_c/\sqrt{n}$) providing a measure of the random uncertainty in c (where S_c denotes the standard deviation in the sample of n counts). If the TLDs are individually calibrated this source of uncertainty disappears.

Since unirradiated TLDs give off a background signal that has to be subtracted from the total signal prior to estimating the dose, the mean level and variation in this background count has also to be taken into account in estimating the total random uncertainty in any measurement. Background counts have to be subtracted both from the calibration exposure count (c) and from the count (X) for the TLD that is being used for the patient dose measurement. The mean count (b) for a sample of unirradiated TLDs from the same batch used in the calibration exposure, or the mean count (B) on a sample of unirradiated TLDs from the same batch used for the patient dose measurements, is commonly used as the appropriate background count. The standard error of the sample counts again provides a measure of the random uncertainty in the background measurements.

The calibration factor or sensitivity (ϕ) of the TLDs is given by

$$\phi = \frac{c-b}{d} \tag{1}$$

The estimate of the dose to a medically exposed TLD is given by

$$D = \frac{X-B}{\phi} \tag{2}$$

Hence

$$D = \frac{d(X-B)}{c-b} \tag{3}$$

There is a further source of random uncertainty in X, the count for the TLD used to make the patient dose measurement. This is a measure of the reproducibility of the count on a single TLD when repeatedly given the same dose. It is given by the standard deviation (S_X), rather than the standard error ($S_X/\sqrt{n}$), of the counts from a series of identical doses to the same TLD, since in this case it is the uncertainty associated with a single measurement and not the mean of a series of measurements that is required.

The overall standard error in D (S_D) is the quadrature sum of these individual standard errors with each one weighted by the relative contribution that it makes to the dose estimate. This is given by the appropriate partial differentiation of equation (3). Thus

$$\frac{S_D}{D} = \frac{1}{D}\left\{\left(\frac{\partial D}{\partial X}\right)^2 S_X^2 + \left(\frac{\partial D}{\partial B}\right)^2 \frac{S_B^2}{n_B} + \left(\frac{\partial D}{\partial c}\right)^2 \frac{S_c^2}{n_c} + \left(\frac{\partial D}{\partial b}\right)^2 \frac{S_b^2}{n_b}\right\}^{1/2} \qquad (4)$$

and hence

$$\frac{S_D}{D} = \left(\frac{S_X^2 + \frac{S_B^2}{n_B}}{(X-B)^2} + \frac{\frac{S_c^2}{n_c} + \frac{S_b^2}{n_b}}{(c-b)^2}\right)^{1/2} \qquad (5)$$

The standard error has been divided by D to express it as a fraction or percentage of the measured dose.

On the assumption that this overall error is normally distributed, $2 \times S_D/D$ can be taken as a good approximation to the total random uncertainty (U_D) at the 95% confidence level. Thus

$$U_D = 2\left(\frac{S_X^2 + \frac{S_B^2}{n_B}}{(X-B)^2} + \frac{\frac{S_c^2}{n_c} + \frac{S_b^2}{n_b}}{(c-b)^2}\right)^{1/2} \text{ at the 95\% confidence level} \qquad (6)$$

Some typical values for these parameters are given below for a TLD system using lithium borate dosemeters.

	Calibration series		*Measurement series*	
	Background	*Dosed*	*Background*	*Dosed*
Mean count	$b = 45$	$c = 4000$	$B = 45$	X
Standard deviation	$S_b = 9$	$S_c = 200$	$S_B = 9$	$S_X = 3\%$
No. of measurements	$n_b = 10$	$n_c = 10$	$n_B = 10$	$n_X = 1$
Dose (mGy)	0	$d = 10$	0	D

The corresponding overall random uncertainties at the 95% confidence level are shown in Table C1 as a function of the dose being measured. It can be seen that the uncertainty increases rapidly as the dose to be measured drops below 0.2 mGy. This is due to the overriding influence of the variability in background count when the count from the dose to be measured approaches it.

For the TLD systems used to carry out patient dose measurements according to this protocol it is recommended that:

Total random uncertainty $\leq \pm 20\%$ at the 95% confidence level

TABLE C1 Typical total random uncertainties at the 95% confidence level

Measured dose D (mGy)	Percentage total random uncertainty (%)	
	Group calibration	Individual calibration ($S_c = 0$)
0.1	19.5	19.3
0.2	12.3	11.8
0.5	8.5	7.9
1.0	7.5	6.8
2.0	7.1	6.4
5.0	6.9	6.1
10.0	6.9	6.1
20.0	6.8	6.0

1.2 Tolerances on accuracy

The accuracy of a given TLD dose measurement (ie the difference between the indicated and true dose values) depends on the non-random or systematic uncertainties in the method for converting the TLD response (count) to dose. Sources of non-random (systematic) uncertainty include:

Uncertainty in calibration of secondary or tertiary standard dosemeter and hence in calibration dose d

Energy response of TLD

Variations from linearity of TLD response with dose

Fading of TLD signal

Temporal variations in TLD reader performance

Corrections for these systematic sources of uncertainty can be made to a greater or lesser extent in any particular circumstance, but after suitable corrections have been applied the residual bounds of uncertainty will contribute to the inaccuracy of any measurement. A discussion of how non-random uncertainties should be combined to obtain the total systematic uncertainty is given elsewhere[1].

For the TLD systems used to carry out patient dose measurements according to this protocol it is recommended that:

Total non-random uncertainty $\leq \pm 10\%$ at the 95% confidence level

1.3 Overall uncertainty

When account is taken of all influence quantities and using all available correction factors it is recommended that:

Overall uncertainty $\leq \pm 25\%$ at the 95% confidence level

This should apply for all doses, dose rates and X-ray energies that are to be encountered, which are likely to cover the following ranges:

Doses	0.1 mGy	to 100 mGy
Dose rates	0.1 mGy/s	to 100 mGy/s
X-ray spectra	50 kV, 2.5 mm Al	to 120 kV, 5 mm Al

Random and non-random uncertainties are to be combined in quadrature in the manner recommended[1] to derive the overall uncertainty.

The overall uncertainty at low doses is primarily influenced by the random uncertainties due to the variability in background noise from unexposed TLDs (see Table C1). This may result in an unacceptably high overall uncertainty for measurements of the relatively low entrance surface doses for chest or paediatric X-ray examinations with some TLD systems.

2 Dose–area product meters

A method for calibrating dose–area product meters has been described in detail elsewhere[2,3].

It is essential that a separate calibration be carried out every time a meter is installed on a different X-ray set, whenever ionisation chambers and electrometers are interchanged, or at least once a year if the instrument is permanently installed on the same equipment. The response of the meter (ie the indicated value divided by the true dose–area product at the surface of the patient) will depend on whether the chamber is installed on an overcouch or undercouch X-ray tube since in the latter case the couch will attenuate the X-ray beam before it reaches the patient. Calibration should be performed with an X-ray field of about 10 cm × 10 cm at a position just above the couch, where a tertiary standard dosemeter and a film cassette can be conveniently positioned to measure the dose and field area effectively in the same plane perpendicular to the beam axis. Use of a small field ensures uniformity so that a dose measurement made at its centre can be accurately assumed to apply to the whole area.

As before, the tertiary standard dosemeter should itself be calibrated in a manner traceable to the national primary standard of air kerma and should have an uncertainty not exceeding 5% at the 95% confidence level for the X-ray qualities and dose rates used in the calibration. The beam area should also be determined with an uncertainty of no more than 5% at the 95% confidence level. This should be easily achievable by measuring the area bounded by the line on a suitably exposed radiographic film where the optical density falls to 50% of its maximum value, using a densitometer and a ruler. The product of these separate measurements of the absorbed dose to air (or the air kerma) and the beam area should be compared with the corresponding dose–area product value indicated on the meter to derive a suitable calibration factor or to adjust the sensitivity of the meter so that the indicated and measured values match. This type of regular calibration should be carried out at one or two sets of exposure conditions typical of those experienced in the course of the patient dose measurements recommended in this protocol (eg 80 kV, 3.0 mm Al filter and at dose rates typical of radiography and fluoroscopy).

Dose–area product meters are required to operate under a wide range of exposure conditions and users should satisfy themselves that the meters comply with the tolerance on overall uncertainty specified below for the complete range of exposure conditions that will be met in practice. Samples of the production instrument should have been type-tested in this manner by the manufacturer.

2.1 Overall uncertainty

In view of the fact that dose–area product meters will frequently be used by X-ray department staff who are not expert in radiation dosimetry, it would be preferable if the instrument remained within the tolerance specified below without the user having to make any corrections for the effect of influence quantities.

IEC Publication 580[4] specifies acceptable limits of uncertainty in the response of dose–area product meters when individual exposure parameters (influence quantities) vary to the maximum likely extent. Production instruments should perform within these limits, in which case the tolerance specified below on overall uncertainty will be achievable.

It is recommended that:

Overall uncertainty ≤ ±25% at the 95% confidence level

This should apply for all doses, dose rates and X-ray energies that are to be encountered, which are likely to cover the following ranges:

Dose–area products	10^{-2}	to	10^{3} Gy cm^2
Dose–area product rates	3 10^{-3}	to	3 10^{2} Gy cm^2 s^{-1}
X-ray spectra	50 kV, 2.5 mm Al	to	120 kV, 5 mm Al
Ambient temperature and atmospheric pressure	The ranges of temperature and pressure for which the meter will satisfy the tolerance on overall uncertainty should be determined and stated		

Random and non-random uncertainties are to be combined in the manner recommended[1] to derive the overall uncertainty.

3 References

1 NAMAS. The expression of uncertainty in radiological measurements. Teddington, NAMAS Executive, NPL, Information Sheet B0825 (1990).

2 Shrimpton, P C, and Wall, B F. An evaluation of the Diamentor transmission ionisation chamber in indicating exposure–area product (R cm^2) during diagnostic radiological examinations. Phys. Med. Biol., 27, 871-878 (1982).

3 Wall, B F. Quality control of dose–area product meters. IN Technical and Physical Parameters for Quality Assurance in Medical Diagnostic Radiology. London, BIR, Report 18 (1989).

4 IEC. Area exposure product meter. Geneva, IEC Publication 580 (1977).

APPENDIX D

Forms for Recording Data

1 Measurements of entrance surface dose per radiograph

(a) For each patient

Date: ..... Hospital: .....

X-ray room: .....

Patient data [No.] Sex: ..... Weight: .....

Age: ..... Height: .....

Examination data

Type of examination: .....

[If chest — reason for referral .....]

Radiographic data

Radiograph 1	**Radiograph 2**
Projection:	Projection: .....
FFD (cm):	FFD (cm): .....
Applied potential (kV):	Applied potential (kV): .....
Exposure setting (mA s):	Exposure setting (mA s): .....
AEC used: YES/NO	AEC used: YES/NO
Film size (cm x cm):	Film size (cm x cm): .....
Focal spot size (mm):	Focal spot size (mm): .....
Film density OK: YES/NO	Film density OK: YES/NO
ATTACH TLD HERE	ATTACH TLD HERE
Entrance surface dose ..... mGy	Entrance surface dose: ..... mGy
Radiograph 3	**Radiograph 4**
Projection:	Projection: .....
FFD (cm):	FFD (cm): .....
Applied potential (kV):	Applied potential (kV): .....
Exposure setting (mA s):	Exposure setting (mA s): .....
AEC used: YES/NO	AEC used: YES/NO
Film size (cm x cm):	Film size (cm x cm): .....
Focal spot size (mm):	Focal spot size (mm): .....
Film density OK: YES/NO	Film density OK: YES/NO
ATTACH TLD HERE	ATTACH TLD HERE
Entrance surface dose: ..... mGy	Entrance surface dose: ..... mGy

1(b) For each X-ray room

Date:	Hospital: ..... X-ray room: .....
Equipment data X-ray generator	Make: ..... Type: ..... Waveform: .....
X-ray tube	Make: ..... Type: ..... Target angle: ..... Total filtration: ..... mm Al
Anti-scatter grid	Grid ratio: ..... Strips/cm: ..... Stationary or moving: ..... Carbon fibre covers: YES/NO
Automatic exposure control (AEC)	YES/NO
Table top	Material: ..... Al equivalence: ..... mm Al
Film	Make and type: .....
Intensifying screen	Make and type: .....
Film/screen	Speed class: .....
Cassette	Carbon fibre front: YES/NO

2 Measurements of dose–area product per examination

(a) For each patient

Date: ..... Hospital: .....

X-ray room: .....

Patient data

[No.] Sex: ..... Weight: .....

Age: ..... Height: .....

Examination data

Type of examination: .....

[If chest – reason for referral .....]

Degree of difficuly of examination: (delete as appropriate) Easy Textbook Difficult

Film data

	Number of films by size and projection (cm x cm)						
Projection	35 x 43	35 x 35	30 x 40	24 x 30	18 x 24	Other (.....)	Applied potential range (kV)
AP:							
PA:							
Lat:							
Tomo:							
Other:							

Fluoroscopy data

Fluoroscopy time:

Applied potential range: ..... kV

Dose data

Total dose–area product: ..... Gy cm^2

2(b) For each X-ray room

Date:	Hospital: .....
	X-ray room: .....
Equipment data	
X-ray generator	Make: .....
	Type: .....
	Waveform: .....
Overcouch X-ray tube	Make: .....
	Type: .....
	Target angle: .....
	Total filtration: ..... mm Al
	Anti-scatter grid, Grid ratio: .....
	Strips/cm: .....
	Stationary or moving: .....
	Carbon fibre covers: YES/NO
	Automatic exposure control (AEC): YES/NO
Undercouch X-ray tube	Make: .....
	Type: .....
	Target angle: .....
	Total filtration: ..... mm Al
	Anti-scatter grid, Grid ratio: .....
	Strips/cm: .....
	Stationary or moving: .....
	Carbon fibre covers: YES/NO
	Automatic exposure control (AEC): YES/NO
Table top	Material: .....
	Al equivalence: ..... mm Al
Film	Make and type: .....
Intensifying screen	Make and type: .....
Film/screen	Speed class: .....
Cassettes	Carbon fibre fronts: YES/NO
Image intensifier	Make and type: .....
	Input phosphor diameter: ..... cm
	Automatic brightness control (ABC): YES/NO