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Protection of the Patient in X-Ray Computed Tomography
and
Further Statement on Radon Affected Areas

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AND

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VOLUME 3 NO 4 1992

National Radiological Protection Board
Chilton, Didcot, Oxon OX11 0RQ

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PROTECTION OF THE PATIENT IN X-RAY COMPUTED TOMOGRAPHY

ABSTRACT

The imaging modality of computed tomography (CT) has proliferated steadily in the UK over the last 20 years to form an integral part of medical radiology, with about 200 scanners in clinical use in 1989. The excellence of CT images has undoubtedly led to significant advances in patient care, although growth of the technique has taken place without full appreciation of the relatively high levels of patient dose involved. A recent national survey of CT practice in the UK has indicated that such procedures now represent about 2% of the annual total of all X-ray examinations, yet account for approximately 20% of the resulting collective dose. These data firmly establish CT as a major source of exposure from diagnostic X-rays for the UK population.

This document briefly reviews the principal results from the survey. Approximately 850 000 CT examinations were carried out in 1989 involving 600 000 patient attendances, with about half of all procedures being imaging of the head. Frequency distributions for the age of patients undergoing CT in general indicate a trend towards relatively elderly groups compared with the population of the UK. Typical patient doses for scanners in the survey were estimated from details of local practice using scanner-specific normalised organ dose data from Monte Carlo calculations for an anthropomorphic phantom and measured values of free-in-air axial dose. Factors of 10—40 were observed for the range of values of effective dose equivalent in a given type of examination over a sample of National Health Service scanners; this spread indicates the significant influence of variations in clinical practice on patient dose. Mean levels of dose from CT in the UK are generally large compared with those for many conventional X-ray examinations of similar regions of the body. The collective dose from CT for 1989 was estimated to be 4500 man Sv, with the major contribution provided by examinations of the abdomen. Analysis of quality assurance (QA) activities for participating scanners indicated a wide range in staff involvement and in the type and frequency of constancy tests undertaken, with only 7% of CT operators reporting any type of periodic dose measurements as part of their QA programme.

On the basis of the range of practice observed in the national survey, 17 general recommendations are made which are aimed at ensuring better control of patient dose from CT by promoting a more systematic approach to the justification and optimisation of all exposures. This advice relates to clinical practice, equipment and staff training, and is directed to the various professional groups involved with CT.

PREPARED BY P C SHRIMPTON

INTRODUCTION

1 Computed tomography (CT) is an X-ray imaging technique providing excellent radiographic contrast between soft tissues and high-quality clinical information for localised planes within the body. The world's first commercially available CT machine, the EMI brain scanner, was introduced into radiology practice in London in 1972. Considerable advances in scanner design have subsequently allowed the routine performance of more extensive and elaborate examinations. CT has replaced many other diagnostic techniques, often of a more invasive nature with a high morbidity, or even mortality. Many of these also involved considerable patient exposures. CT has found increasing use in the diagnosis and assessment of the treatment of cancer and other pathological conditions and has allowed significant advances in good patient care.

2 There has therefore been a worldwide proliferation of scanners over the last 20 years, with the number in clinical operation in the UK rising steadily – and with no apparent sign of saturation – to around 200 in 1989; this total includes 39 different models from 10 manufacturers, with nearly 90% based within the National Health Service (NHS). The corresponding level of provision for CT in the UK of about four scanners per million inhabitants nevertheless remains at the lower end of the rates observed in developed countries: it is, for example, about half the rate for the former Federal Republic of Germany and some ten times less than that for Japan.

3 Notwithstanding the undoubted benefits of CT in health care, growth of the technique has taken place without full appreciation of the relatively high patient doses involved. As part of a continuing programme of work by the National Radiological Protection Board (NRPB) to monitor exposure of the UK population from medical radiology, a national survey of CT practice has been carried out in collaboration with the Institute of Physical Sciences in Medicine (IPSM). The objectives were to assess the frequency and types of CT procedure, the typical patient doses and the quality assurance (QA) activities undertaken by scanner operators; full details of the methods and results are given in a series of three comprehensive publications[1-3] covering various aspects of the study.

4 The survey has firmly established CT as a significant source of exposure to diagnostic X-rays for the UK population and hence an important area in the radiation protection of patients. Current UK legislation[4,5] already requires that diagnostic X-ray equipment should be designed, constructed, installed, maintained and used so that all examinations are carried out with the minimum amount of radiation consistent with a proper clinical purpose. This document presents a brief summary of the principal results of the survey and makes general recommendations, arising from the range of practice observed, for promoting a more systematic approach to the justification and optimisation of exposures in CT.

UK CT PRACTICE

Frequency of CT

5 Nationally representative data on CT practice were obtained from a questionnaire completed by over 80% of all NHS CT installations[1]. Typical patient attendances reported for individual scanners varied from 5 to 153 patients per week, with a mean

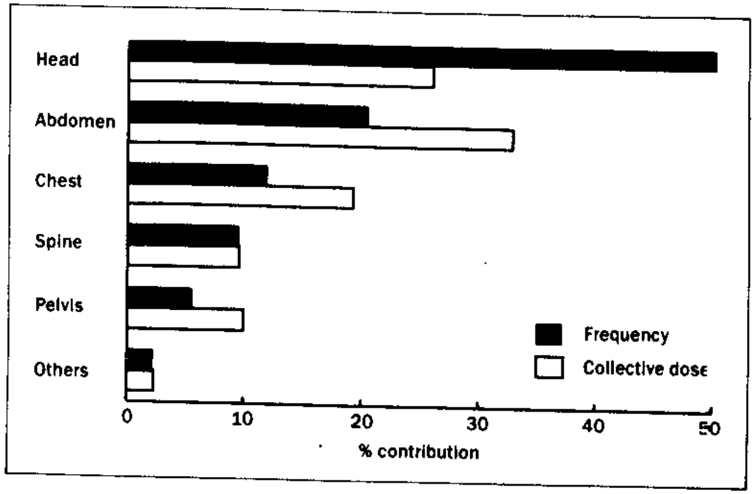
for the sample of around 65. About one-third of scanners were utilised quantitatively in the planning of treatments for patients undergoing radiotherapy, the typical workload for such procedures ranging from 0.2 to 16 patients per week, with a mean value of 5.2.

6 The questionnaires also provided estimates of the frequencies with which discrete types of examination were performed at each scanner. Analysis of these data indicates an annual total of 850 000 CT examinations for the UK in 1989 from the 200 scanners in operation, involving 600 000 patient attendances. This represents an increase by nearly a factor of four over the examination frequency estimated for CT in 1983 during a comprehensive review of UK radiology practice[6], or **an average increase of 24% per annum**. That review also indicated an average rate of increase of 2.3% per annum in the number of medical and dental X-ray examinations of all types, and an annual total of 35 million for 1983. It is not clear whether this trend has been maintained, but the present estimate for the total number of CT procedures would be about 2.4% of this most recent UK total.

7 The corresponding *per caput* frequency for CT in the UK is about 15.2 examinations per 1000 inhabitants. This is larger than the average figure of 10 CT procedures (out of a total of 800 X-ray examinations) per 1000 population assumed for developed countries by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in its 1988 review[7]. However, practice in the UK remains very much below the level of 123 CT examinations per 1000 population reported for Japan as long ago as 1979[7].

8 Frequency data for different types of examination indicate that about 50% of all procedures in the UK in 1989 involved imaging of the head: this is illustrated in Figure 1, which also includes contributions to the collective dose from CT as discussed in paragraph 29. The frequency analysis confirms the diversification of practice away from this initial application of CT, which in 1983 accounted for 90% of investigations[6]. The next most important region of the body in terms of examination frequency is the abdomen, which represents 20% of all procedures, with smaller contributions from the chest (12%), spine (10%), and pelvis (6%). Such a distribution is generally similar to analyses for scanners in Denmark[8] and Canada[9], although scans of the head and neck accounted for nearly two-thirds of all examinations in both of these studies.

FIGURE 1 *Contributions to UK CT practice by examination type*



Age and sex of CT patients

9 Representative information on the age and sex of patients undergoing CT has been obtained from a sample of 58 400 patient records[1]. Figure 2 shows age distributions for males and females observed for all types of CT examination: the first age band embraces patients with ages from 0 to 4 years inclusively, the second those from 5 to 9 years, and so on. After an initial fall, the numbers of patients in each band generally increase with age, rising to a maximum for the 65–69 years age band before falling rapidly. The figure also indicates a relatively increased frequency of CT for the lowest age range and a preponderance of males between ages 55 and 75 years, features that are discussed below.

10 Similar analyses by type of procedure indicate distributions for examinations of the chest and of the abdomen that are even more biased towards the elderly than in Figure 2, with more males than females for all but the youngest and oldest ages. Examinations of the pelvis and pituitary both appear to be predominantly on females, with the mode for the latter occurring in the 30–35 years age group. **Compared with the general pattern for CT, frequency distributions for examinations of the head and neck indicate relatively more patients of younger age, particularly children in their first year of life.** However, the profiles for special examinations of the orbits are fairly flat for patients with ages between 15 and 74 years. The modal frequencies for CT examinations of the spine lie in the age range 40–45 years, whereas investigations of the limbs most often involve patients in the age range 20–29 years, particularly males. Many of these patterns of use reflect the primary application of CT

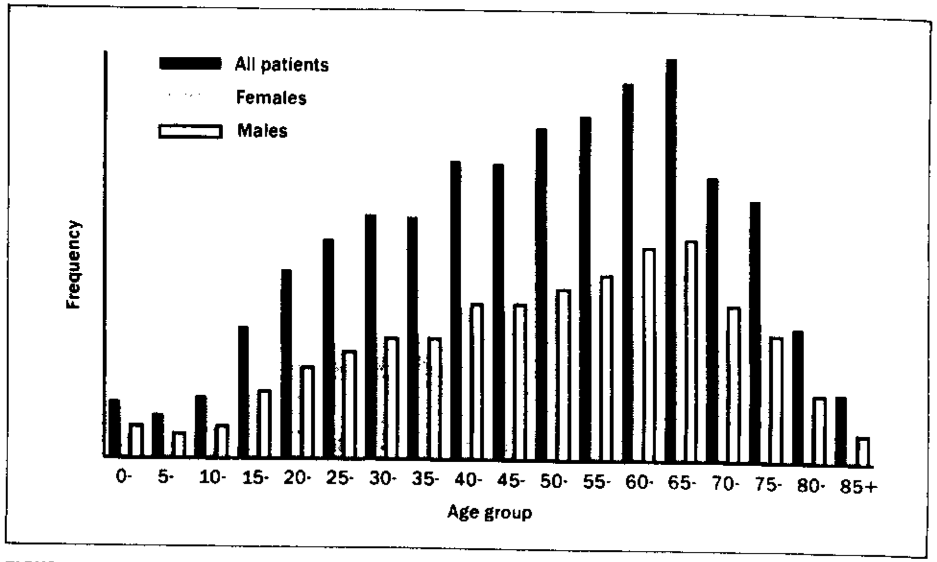


FIGURE 2 *Age distributions of patients undergoing CT (all types of examination)*

imaging in the diagnosis and treatment of malignancies and hence the incidence of various conditions by age and sex of patients, such as teratomas and lymphomas in males and gynaecological malignancies in females.

11 The shapes of the general distributions in Figure 2 for patients undergoing CT indicate a bias towards relatively elderly persons compared with the general population of the UK; the trend is similar to, but more pronounced than, that for patients undergoing conventional medical X-ray examinations[9]. This is illustrated by the cumulative age distributions for CT patients, X-ray patients and the general population in Figure 3, which indicates the percentages of each population group below particular ages. The cumulative distribution for CT patients rises more slowly with age than does that for either of the other population groups.

12 In the present analysis, the percentages of CT patients aged over 44 years and over 64 years are 60% and 30%, respectively, in close agreement with similar data for the USA[10]. The corresponding figures for X-ray examinations generally in the UK[9] are 50% and 23%. The significant number of older patients undergoing CT has important implications for the expression of delayed radiation effects, leading to a reduction in the risk per unit dose for this selected population compared with the UK population. However, relatively higher risk factors will be appropriate for CT examinations on younger patients, particularly small children.

Patient dose

Dosimetric method

13 CT examinations are characterised by the irradiation of thin (generally transverse) slices of the patient by a rotating fan beam of X-rays. Conditions of exposure are quite different to those in conventional X-ray imaging; this has required the development of specific techniques for assessing patient dose from CT[4]. Standard dosimetry for CT has generally involved the use of phantoms designed primarily to monitor scanner performance for the purposes of quality assurance. This approach often leads to dose descriptors that are inappropriate for assessing patient risk or for the optimisation of examination procedures. Proper assessment of the radiological risk from CT requires knowledge of the dose to all the radiosensitive organs of the patient arising from the highly localised patterns of exposure for the various techniques of scanning in clinical use.

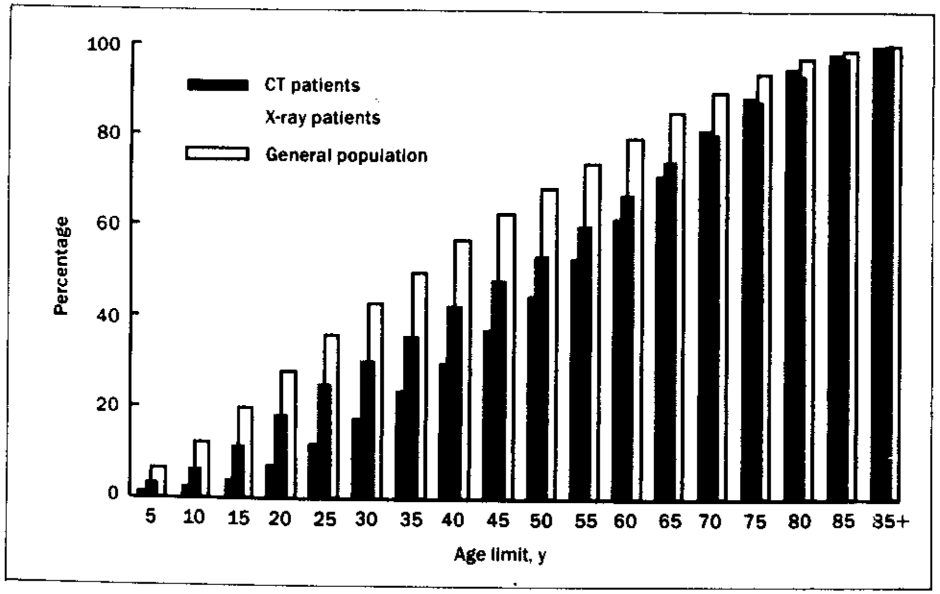


FIGURE 3 *Cumulative distributions by age of CT patients, X-ray patients and the general population*

14 In practice, it is convenient to estimate typical doses by calculation of the energy deposition in an anthropomorphic mathematical phantom under defined conditions of irradiation using Monte Carlo techniques. Series of such calculations have been carried out at NRPB[5] for 23 sets of exposure conditions appropriate to 27 common models of CT scanner from 5 manufacturers, which between them account for about 85% of all NHS scanners. For ease of use, the calculations provide doses to 27 organs or regions of an adult hermaphrodite phantom for the individual irradiation of 208 contiguous 5 mm thick transverse slabs that span the phantom from the top of the legs to the top of the head. These doses are normalised to unit dose on the axis of rotation of the scanner in the absence of the phantom. Simple measurements of free-in-air axial dose for scanners at the exposure settings used in clinical practice allow estimates of typical patient dose from selections of normalised dose data appropriate to local scanning protocols.

15 This approach formed the dosimetric basis for the CT survey in the UK, allowing information on scanning technique provided in each questionnaire to be interpreted in terms of typical patient dose for various types of examination on individual scanners[7]. The method has also been implemented during similar national CT surveys in several other European countries[11]. In order to promote more widespread patient dosimetry in CT, the normalised organ dose data appropriate for a range of scanners are available on microdisk for use with computers operating under MS-DOS[12].

Inherent differences between scanners

16 The predicted dose distributions within transverse slabs of the mathematical phantom vary between types of scanner owing to differences in both the geometry and radiation quality of the X-ray beam. These are influenced in turn by the distance between the X-ray focus and the axis of rotation of the scanner, the applied potential, and the amount and type of filtration; of particular importance is the use of complex shaped filters often known as bow-tie filters. Such differences in design between the scanners considered in the calculations result in variations in normalised dose by a factor of five for the simulated irradiation of similar isolated slabs of the phantom. However, this inter-scanner range reduces to a factor nearer two when considering larger sections of the phantom more relevant to complete CT examinations.

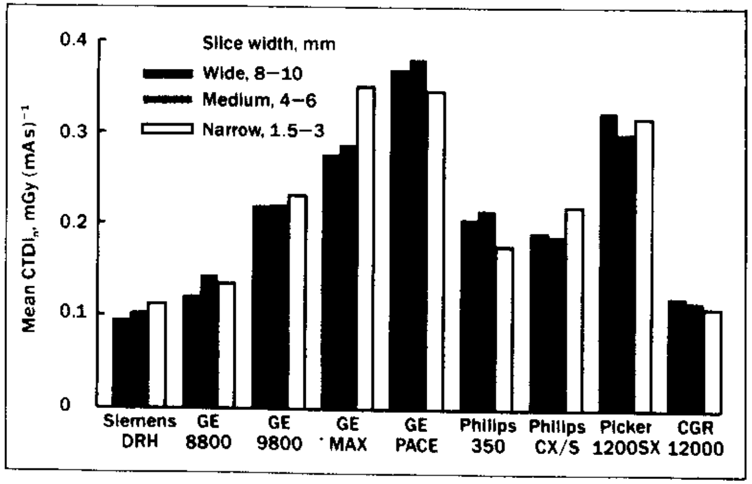
17 Utilisation of the normalised organ dose data requires some appropriate measure of free-in-air axial dose for scanners which takes account of the inevitably imperfect collimation of the X-ray beam relative to the nominal slice width. The dose profile arising from the imaging of a single slice in air is dependent on the settings of applied potential, nominal slice width and, if these may also be varied, focus-to-axis distance and filtration; the dose can also be assumed to vary linearly with exposure setting

(mA s). The computed tomography dose index (CTDI) provides a suitable way of characterising the radiation output from individual CT scanners that is compatible with the mathematical modelling described above[2]. CTDI is defined as the linear integral along the axial direction of the dose profile for a single slice in air divided by the nominal slice width. The value of CTDI calculated for a profile can be considered to represent the peak dose for a perfectly collimated CT scan where the primary beam is constrained to lie uniformly within the nominal slice width. The ratio R of CTDI to the observed peak dose for a profile is a measure of the build-up in dose from the overlap of nominally contiguous slices.

18 As part of the national survey, a programme of free-in-air CTDI measurements using thermoluminescent dosemeters was carried out for a representative sample of 75 scanners[2]. Selected mean levels of CTDI normalised to the radiographic exposure setting (mA s) and signified by $CTDI_n$ are illustrated in Figure 4, which indicates variation by a factor of 3.5 between models of scanner owing, once again, to differences in design. However, variations of up to a factor of 2 were also observed between mean results for individual scanners of the same model under similar conditions of measurement. Estimates of R for individual profiles ranged from 0.87 to 4.7, with the mean values for each type of scanner generally increasing with decreasing nominal slice width. Typical values of 1.3 to 1.5 for many of the smallest settings have serious implications for increased patient dose when imaging narrow contiguous slices.

19 Some of the inherent variation in normalised organ dose and $CTDI_n$ data between scanners discussed above is offset in practice by the differences in exposure settings necessary to achieve a given level of image quality; for CT, noise in the image is related inversely to X-ray exposure, slice width and spatial resolution. Values of effective dose equivalent calculated for standard examinations varied by up to a factor of three between models under the assumption that the settings of radiographic exposure and nominal slice width selected for each model gave comparable image quality.

FIGURE 4
Typical levels of free-in-air axial dose for selected types of scanner



Representative data

20 The levels of dose occurring in clinical practice will depend not only on the model of CT scanner but also on the volume of the patient imaged and the level of image quality required. The dose for each patient will therefore be strongly influenced by the number and width of slices imaged, the couch increment between slices, the use of contrast medium and the radiographic exposure (mA s) resulting from settings of tube current and speed of scan. The critical importance of local examination technique is confirmed by analysis of typical values of effective dose equivalent for common types of examination estimated for each of the NHS scanners in the survey[7]. **The dose for a given type of examination varied by factors of 10 to 40 over the whole sample, although smaller differences by factors of 5 to 20 were observed when each scanner model was considered separately.**

21 Table 1 summarises the arithmetic mean values for selected patient dose quantities over all scanners in the survey; further results for other organs and for individual models of scanner are given in NRPB-R249[7]. Mean levels of effective dose equivalent ranged from 0.44 mSv for complete examination of the internal auditory meatus (IAM) to 10.2 mSv for examinations of the liver. Individual values of effective dose equivalent in excess of 20 mSv were recorded for most types of procedure involving the trunk.

TABLE 1
Selected mean values of patient dose from the UK CT survey

	Mean values of dose for sample of NHS scanners					
CT examination	Eyes (mGy)	Uterus (mGy)	Ovaries (mGy)	Testes (mGy)	H_E[(a)] (mSv)	E[(b)] (mSv)
Routine head	50	*[(c)]	0	0	3.4	1.8
Posterior fossa	53	*	*	0	1.2	0.72
Pituitary	60	*	*	0	1.1	0.57
IAM	2.6	*	*	0	0.44	0.35
Orbits	50	*	0	0	1.2	0.64
Facial bones	9.0	*	*	0	0.77	0.68
Cervical spine	0.62	*	*	0	1.7	2.6
Thoracic spine	0.04	0.02	0.02	*	6.6	4.9
Routine chest	0.14	0.06	0.08	*	8.4	7.8
Mediastinum	0.11	0.03	0.04	*	7.8	7.6
Routine abdomen	*	8.0	8.0	0.70	9.2	7.6
Liver	*	1.0	1.2	0.03	10.2	7.2
Pancreas	*	0.35	0.41	0.01	7.0	4.8
Kidneys	*	1.1	1.3	0.03	9.3	6.3
Adrenals	*	0.10	0.12	*	4.2	3.4
Lumbar spine	*	2.4	2.7	0.06	5.6	3.3
Routine pelvis	*	26	23	1.7	9.2	7.1

Notes
(a) The symbol H_E stands for effective dose equivalent.
(b) The symbol E stands for effective dose.
(c) The symbol * indicates that the dose lies between 10[illegible] and 5 10[illegible] mGy.

22 Mean values of absorbed dose to the eyes averaged over all scanners in the survey were above 50 mGy for most types of examination of the head, with individual doses for some examinations on particular scanners exceeding 150 mGy. However, these doses have been calculated on the assumption that the X-ray beam is always normal to the long axis of the phantom. In clinical practice, the gantry may be tilted from the normal to image other planes of the patient and, since this excludes the eyes from the primary beam, it can lead to a marked reduction in dose to the eyes during certain examinations of the head[13].

23 Absorbed doses to the gonads were largest for routine examinations of the abdomen and pelvis; mean doses to the testes for these examinations were 0.70 and 1.7 mGy, with maxima of 15 and 7.7 mGy, respectively. Corresponding mean ovary doses were 8.0 and 23 mGy, with maxima of 41 and 73 mGy. Estimates of dose to the uterus were similar to those for the ovaries. Typical ovarian and uterine doses in excess of 1 mGy were also estimated for the protocols used by some scanners in the survey for examinations of the liver, pancreas, kidneys and lumbar spine. As with any X-ray examination of the female abdomen or pelvic region, special care should be exercised when such CT examinations are to be undertaken on patients of child-bearing age[14].

24 In its 1990 Recommendations[15], the International Commission on Radiological Protection defined a new weighted-dose quantity called effective dose for controlling the exposure to radiation of workers and members of the public. Effective dose has weighting factors for a larger number of specified organs and is likely to be a better indicator of the risk of stochastic effects than effective dose equivalent. It is illuminating therefore to consider the differences that would arise if this quantity were adopted to summarise the exposure of patients from the highly non-uniform irradiations encountered in CT. A comparison of values of effective dose and effective dose equivalent in Table 1 indicates ratios of about 0.5 for examinations of the head, 0.6 for the lumbar spine, 0.7–0.9 for the trunk, and 1.5 for the neck. This pattern reflects the relative importance of particular organs in the calculation of these weighted-dose quantities.

25 The questionnaires on CT practice indicate that about 80% of CT examinations include non-tomographic scan projection radiography (SPR) of the general anatomical region of interest for the purposes of positioning subsequent rotational scans. This type of CT image is similar to conventional radiography in that the X-ray tube is held stationary during the exposure, although for SPR the patient is moved through the gantry and is scanned by the narrow fan beam of X-rays. Typical levels of effective dose equivalent from common SPR exposures are shown in Table 2, together with representative doses for rotational CT (excluding any component from SPR) and conventional X-ray examinations in the UK; data for CT are mean values from the present survey derived from considerations of collective dose, whereas the doses for conventional procedures are those determined in an earlier national patient dose survey[16]. Comparison of the data indicates that SPR typically represents only 1–2% of the total patient dose for a complete CT examination. Doses from SPR are also lower than those from corresponding X-ray films of similar field sizes apart from chest radiography, although it must be remembered that the two types of imaging are carried out for different purposes.

TABLE 2 *Comparison between typical levels of patient dose from scan projection radiography (SPR), rotational CT and conventional X-ray (CONV) procedures in the UK*

	Typical effective dose equivalent (mSv)		
Examination	SPR[a]	CT[b]	CONV[c]
Head	0.02	3.5	0.2
Cervical spine	0.03	1.9	–
Thoracic spine	0.14	7.8	0.9
Chest	0.14	9.1	0.05
Abdomen	0.16	8.8	1.4
Lumbar spine	0.08	6.0	2.2
Pelvis	0.14	9.4	1.2
Intravenous urography	–	–	4.4
Barium meal	–	–	3.8
Barium enema	–	–	7.7
Cholangiography/ cholecystography	–	–	1.2
	Typical mean dose to fetus (mGy)		
Pelvimetry	0.05–0.35 AP[d] 0.01–0.07 Lat[d]	0.07–0.24[e]	0.11 AP[f] 0.07 Lat[f]

Notes
(a) Data for single antero–posterior (AP) projection with a Siemens DRH scanner and a typical scan projection radiography exposure factor[7] (SPREF) of 2 mA s.
(b) Representative data for complete rotational CT series in the UK taking into account the variations in both dose and utilisation between scanners in CT survey.
(c) Average data for complete examinations from a previous national patient dose survey[16].
(d) Ranges for AP and lateral projections relate to overall spread in practice observed in CT survey and assume 50% of fetus exposed.
(e) Range relates to overall spread in practice observed in CT survey and assumes 3% of fetus exposed per 10 mm slice.
(f) Data for rare earth screens and air gap, with 50% of fetus exposed[17].

26 More importantly, Table 2 demonstrates that **the typical levels of patient dose from CT are relatively large compared with those for many conventional X-ray examinations of similar regions of the body;** the mean dose to the fetus from CT pelvimetry (SPR or rotational) is, however, broadly similar to doses achievable with rare earth screens in cassettes and good technique[17]. Such a superficial comparison of imaging modalities ignores the superior clinical information available from CT, although it serves to illustrate that doses from modern digital techniques of radiography are not inherently low. The potential implications of high doses in CT examinations have already been highlighted in a joint report from the Royal College of Radiologists (RCR) and NRPB, which recommended that all patients for CT should be individually referred by experienced radiologists[18].

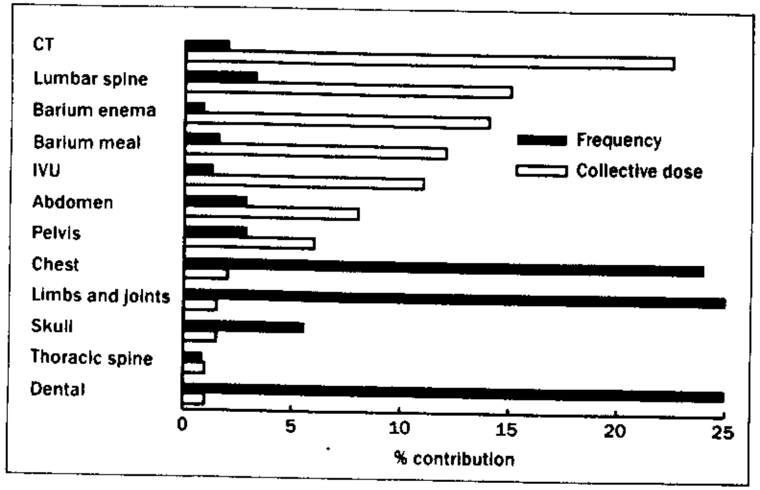
27 Frequency and dose data for the sample of NHS scanners have been combined so as to assess the collective dose to the UK population from CT. Mean values of effective

dose equivalent per examination (Table 2), derived from these collective doses, take into account the variations in both dose and utilisation between scanners and are generally within 10% of the corresponding arithmetic means for the sample of scanners (Table 1).

28 The collective effective dose equivalent from the 200 scanners operating in the UK in 1989 has been estimated at about 4500 man Sv, on the assumption that NHS scanners account for 90% of practice. This total dose is nine times larger than the figure of 500 man Sv previously assessed for 1983[19]. The consequent average effective dose equivalent per CT examination of 5.3 mSv is larger than the general figure of 1 mSv assumed by UNSCEAR in 1988[7]. In general terms, each scanner in the UK gives rise to a collective dose of about 20 man Sv a year. Attention has already been drawn to the level of such contributions from ever-increasing numbers of CT scanners and the suggestion made[20] that about two-thirds of the workload of a scanner at an average District General Hospital would be better undertaken, on clinical grounds, by magnetic resonance imaging (MRI) with considerable concomitant savings in collective dose.

29 Contributions to the collective effective dose equivalent from CT by examination type are shown in Figure 1. Whereas examinations of the head represent one-half of all CT procedures (paragraph 8), they account for only one-quarter of the collective dose which, not surprisingly, is dominated by examinations of the abdomen. The collective effective dose equivalent for the UK population from conventional X-ray examinations was assessed at 15 500 man Sv in 1983[19]. Techniques of radiology continue to evolve and usage changes, so there is some uncertainty in combining data from different periods of time. Nevertheless, the available data would suggest a revised total annual collective effective dose equivalent from all medical and dental X-rays of 20 000 man Sv, of which approximately 20% is accounted for by CT. Figure 5 illustrates the relative importance of the various X-ray techniques. **This assessment makes CT a major source of exposure from diagnostic X-rays in the UK and hence an examination technique worthy of particular attention in terms of radiation protection to ensure proper control of all exposures to patients.**

FIGURE 5
Contributions to UK diagnostic radiology practice by examination type



QA activities in CT

30 Information on CT practice from over 80% of NHS scanners has also provided a useful indication of the mode of operation and the provisions for quality assurance at scanners in the UK[1]. The proportion of purpose-built head-only machines has fallen to a mere 5%, although 25% of scanners were considered primarily to be for neuroradiological applications rather than for general-purpose radiology. The median scheduled hours of operation indicated for scanners was 40 hours per week. The oldest scanner in operation at June 1989 had been installed 15.7 years earlier, although the median age of 3.3 years reflects the significant numbers of machines installed during the last few years.

31 An assessment of the typical rates at which CT scans have to be repeated as a result of inadequate initial images indicates an overall value of about 4%; this is at the lower end of the range of 3% to 15% observed for conventional X-ray examinations in the UK[18].

32 All CT users reported regular servicing for their scanners and an involvement in a range of important QA tasks. The manufacturers' engineers play the major role in all aspects of QA for most scanners, generally as part of a comprehensive maintenance contract. Local radiographers and hospital physicists also share in the responsibility for the performance, analysis and review of QA tests, although less than one-fifth of users indicated that a hospital physicist worked regularly on the unit, for instance conducting measurements at least monthly. Radiologists were reported to take little part in QA activities, but it is recognised that final responsibility to ensure that such tasks are undertaken rests with the clinical head of the department.

33 Approximately 40% of users carried out some type of QA measurement with a test phantom to monitor constancy of scanner performance on a daily basis; these were generally assessments of image noise, reproducibility or uniformity. A further 20% of users included some weekly procedure, although the most common frequency of all types of test was monthly. Advice from IPSM[21] (currently under revision) for the daily appraisal of noise and sensitivity appears largely to have been ignored, whereas recommendations for the monitoring of reproducibility and uniformity (monthly), contrast scale (six-monthly), resolution (yearly) and alignment (as required) would appear to be followed fairly well. **Only 7% of users reported any type of periodic dose assessment.**

34 Comprehensive QA programmes are essential in all radiology departments in order to meet and demonstrate compliance with UK legislation on radiation protection[4,5]. The complexity of equipment and the relatively high levels of exposure in CT underline the particular need for strict control of both image quality and patient dose for such an important medical imaging modality. Periodic evaluation of typical levels of patient dose for local scanning protocols therefore represents a crucial element of the routine QA measurements necessary for all scanners. The dosimetry techniques[12] and wealth of data[2] provided by the UK survey will enable staff operating CT scanners to assess the performance of their equipment and procedures against national practice.

RECOMMENDATIONS

35 The steady growth in CT and its present importance in terms of collective dose for the UK population necessarily make it a focus of increased attention for the radiation protection of patients. CT can clearly be of substantial benefit to patients, particularly those who have serious medical conditions such as malignancy and who may go on to receive much higher doses in radiotherapy. However, there is a need to ensure that for all patients CT scans are clinically justified and properly carried out in order to avoid unnecessary exposure of the population. The following general recommendations are based on the range of practice observed in the national survey and are intended to promote better control of patient dose from CT. This advice is directed to the various professional groups involved with CT and relates to clinical practice, equipment and staff training. It is complementary to previous advice[18] from RCR and NRPB on patient dose reduction in diagnostic radiology.

Clinical practice

1 In view of the potential for high patient doses, CT examinations should only be carried out after there has been proper clinical justification for the examination of each individual patient by an experienced radiologist. Examinations on children require a higher level of justification, since such patients are at greater risk from radiation than are adults.

2 When clinically appropriate, the alternative use of safer non-ionising techniques (such as ultrasound and MRI where available) or of low dose X-ray techniques should be considered. This reinforces the previous recommendation[18] that increasing the availability of ultrasound and MRI would reduce reliance upon techniques involving X-rays.

3 The Royal College of Radiologists should extend existing guidelines on referral criteria for conventional X-ray examinations to include the use of CT.

4 Each CT examination should be conducted with the minimum exposure settings (tube current and scan time) to give adequate image quality, and with the minimum number of slices and minimum irradiated volume compatible with the clinical purpose. In particular, CT of the chest region may often be possible with radiographic exposure (mA s) settings lower than those for the abdomen, unless the use of high image quality is specifically justified.

5 The relatively low dose technique of scan projection radiography (SPR) over the region of interest should be used where appropriate to aid positioning and limit the amount of subsequent cross-sectional scanning.

6 CT examinations should not be carried out on the abdomen or pelvis of pregnant patients without sound clinical reasons and particular attention to low dose techniques.

7 Properly conducted CT pelvimetry using either rotational or SPR techniques leads to mean fetal doses that are similar to those achievable by conventional radiography with good technique and rare earth screens. When clinically indicated, X-ray pelvimetry should always be carried out using low dose techniques.

8 Care should always be taken to minimise exposure of the eyes, particularly for patients likely to undergo multiple examinations. Dose to lens tissue can often be substantially reduced by angulation of the gantry to exclude the eyes from the primary beam during examinations of the head.

9 Persons clinically and physically directing examinations should be aware of the potential build-up in patient dose when imaging a series of nominally contiguous slices, particularly for the narrowest settings of slice width.

Equipment

10 Manufacturers should be more aware of likely levels of patient dose when designing new scanners and should make available more comprehensive details of construction in order to assist in the mathematical modelling of patient dose. NRPB intends to monitor the types of scanner in common use and review periodically, and as necessary publish, further normalised organ dose data for CT.

11 Manufacturers should also attempt to match closely the sensitivity profile to the dose profile in designing the collimation of the X-ray beam for each nominal slice width setting. In this respect, emphasis should be on the use of pre-patient collimators. Manufacturers should clearly indicate to users the implications for increased patient dose when significant post-patient collimation has been employed in scanner design to reduce the width of the imaged slice.

12 Manufacturers and the Department of Health[22] should include measurements of free-in-air axial dose (CTDI) in performance tests of new types of scanner to allow better indication of patient dose. Aspects of patient dose should form an integral part of the criteria under consideration when a new scanner is to be purchased.

13 Comprehensive QA programmes should be performed for all scanners in clinical use covering all aspects of operation, including regular quality control measurements of imaging performance according to the recommendations of manufacturers and IPSM[21].

14 It is essential that such QA programmes include some periodic assessment of patient dose. Free-in-air axial dose profile measurements should be made so that the dosimetric method referred to above may be used to estimate typical levels of patient dose for all commonly-used local scanning protocols. In order to promote the central collation of these further data, consideration should be given to extending the IPSM/NRPB/CoR national protocol for patient dose measurements in diagnostic radiology[23] through the publication of an additional protocol for CT.

15 In order to encourage optimisation of patient dose in CT, hospital departments should compare typical levels of dose for their local procedures against practice observed in the national survey. For this purpose, NRPB intends to develop and promulgate suitable reference dose levels for CT.

Staff training

16 All staff clinically and physically directing CT examinations should have received adequate special training in the imaging modality leading to an appreciation of the relatively high levels of patient dose. In support of this aim, NRPB is preparing, as previously recommended[18], a booklet which deals with the radiological risks associated with medical X-ray procedures including CT and sets them in context.

17 Effective quality assurance in CT can only result from a determined managerial effort and should be a multidisciplinary activity involving all staff associated with providing the service. Final responsibility to ensure that QA tasks are undertaken rests with the radiologist who is the clinical head of the department.

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RADON AFFECTED AREAS: DERBYSHIRE, NORTHAMPTONSHIRE AND SOMERSET

ABSTRACT

Board advice on radon in homes issued in 1990 specifies that areas of the UK where 1% or more of homes exceed the Action Level of 200 becquerels per cubic metre of air should be regarded as Affected Areas. Results of radon measurements in homes in Derbyshire, Northamptonshire and Somerset are mapped and used to delineate Affected Areas in these counties. The Department of the Environment is advised to consider which localities should be delimited for precautions against radon in future homes. Advice on other areas will be proffered as data become available.

PREPARED BY J C H MILES, B M R GREEN AND P R LOMAS

INTRODUCTION

1 In January 1990 the National Radiological Protection Board recommended that the Action Level for radon in existing homes should be 200 Bq m^{-3} averaged over a year[1]. Parts of the country with 1% probability or more of present or future homes being above the Action Level should be regarded as Affected Areas: such areas should be identified from radiological evidence and periodically reviewed[2]. In October 1990 the Board assessed the radiological evidence for Cornwall and Devon[3] and advised that the whole of these counties should be regarded as an Affected Area.

2 This document has an assessment of Affected Areas in the counties of Derbyshire, Northamptonshire and Somerset. Details are given of the proportions of homes in these counties estimated to exceed the Action Level, and Affected Areas are identified. The five English counties that have now been surveyed for Affected Areas are shown in Figure 1. Further documents assessing Affected Areas will be issued as sufficient information becomes available.

DATA COLLECTION AND ANALYSIS

3 In order to map Affected Areas, data are analysed by 5 km squares of the National Grid. Radon measurements are required across the whole of the area to be mapped: for this assessment the aim was to obtain five or more results in each 5 km grid square. NRPB had carried out various surveys of radon in homes in Derbyshire, Northamptonshire and Somerset using passive etched-track detectors over at least 3 months. Most of the measurements were funded by the Department of the Environment (DoE) and were performed at the request of the householder. Households requesting measurements were not evenly spread across the counties, and when the results were mapped by 5 km grid squares some areas were seen to have insufficient data. In order to fill the gaps, NRPB wrote to householders in these areas offering a radon measurement. The numbers of homes surveyed in each county are

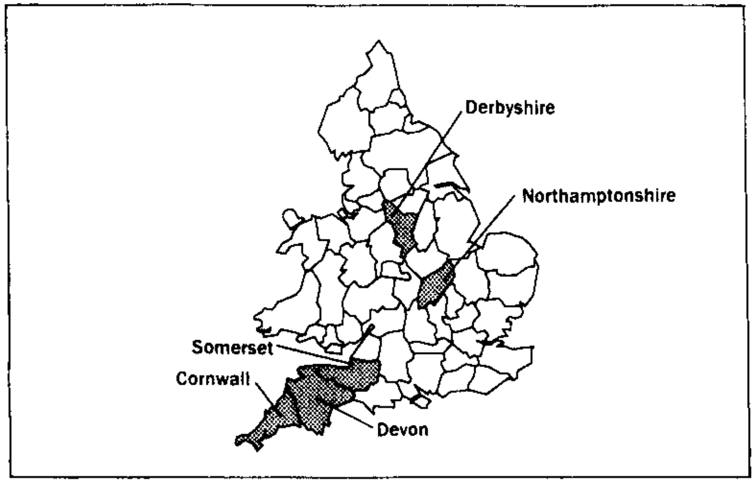


FIGURE 1
English counties in which Affected Areas have been assessed

given in Table 1. The differences in numbers surveyed has been caused largely by differences in local publicity about radon. There are about 13 000 results in the three counties.

4 Indoor radon concentrations are affected by indoor and outdoor temperatures, by winds, ventilation conditions and other factors. The seasonal variation in average radon concentrations had been previously assessed for the country as a whole[4] and used to derive correction factors for measurements lasting 3 or 6 months (see Table 2). These factors are applied here in estimating annual average radon concentrations in homes.

5 The national survey of radon in homes[4] showed that householders living in detached and semi-detached houses were more likely to participate in a radon survey than those in terraced houses or flats. As radon levels are generally higher in detached and semi-detached houses, this introduces a bias in the estimate of average radon concentrations. In the national survey it was found that the average radon concentration in homes surveyed was 9% higher than it would have been if the homes had been fully representative of the national housing stock. Since the measurements on which this report is based have been subject to the same type of selection bias, all results have been corrected by the percentage found in the national survey.

6 The distribution of radon concentrations in homes is approximately log-normal, whether the sample is taken from the whole housing stock or a single grid square[3,5]. It

TABLE 1
NRPB surveys of radon in homes in Derbyshire, Northamptonshire and Somerset as of July 1992

County	Numbers of homes	Numbers of grid squares
Derbyshire	2840	121
Northamptonshire	6505	115
Somerset	3550	164

TABLE 2
Correction factors for 3 and 6 month measurements of radon in homes. The measured radon concentration is multiplied by the factor given

Starting month of measurement	Correction factor	
	3 month measurement	6 month measurement
January	0.74	0.90
February	0.83	1.05
March	0.96	1.20
April	1.15	1.33
May	1.45	1.35
June	1.64	1.27
July	1.59	1.14
August	1.28	0.96
September	1.04	0.85
October	0.88	0.80
November	0.76	0.79
December	0.73	0.83

has been shown that the distribution of radon concentrations nationally conforms much more closely to a log-normal distribution if the mean outdoor radon concentration (4 Bq m^{-3}) is subtracted from each result[5]. This subtraction was therefore performed for all radon concentration values in this work. An appropriate addition was subsequently applied when estimating the fraction of homes exceeding the Action Level.

7 If the geometric mean (GM) and geometric standard deviation (GSD) of a log-normal distribution are known, the fraction of the distribution exceeding any threshold can be calculated. In the previous designation of Affected Areas in Cornwall and Devon[3], this property of the distribution was used to allow the fraction of the housing stock exceeding the Action Level in each grid square to be estimated. In that assessment, values of GM were smoothed between adjacent squares to remove anomalies due to the small numbers of results in some squares. No variation of GSD with GM was found, and a single value of GSD of 2.4 was used for all grid squares. Later measurements in 70 000 more homes in Cornwall and Devon showed a good correspondence between the predicted and measured fraction exceeding the Action Level. The same techniques were used to estimate the fraction of the housing stock exceeding the Action Level in each grid square in Derbyshire, Northamptonshire and Somerset. The GM values for all squares in the three counties were geometrically smoothed once with the GM values of adjacent squares.

8 The variation in GSD values within these counties has been examined for this document. For Northamptonshire and Somerset, no variation with radon concentration was found, and weighted mean GSD values of 3.0 and 2.65, respectively, were calculated for the two counties. The data for Derbyshire fell into two groups: squares with GM values less than 60 Bq m^{-3} had a mean GSD of 3.0, whereas squares with GM values more than 60 Bq m^{-3} had a mean GSD of 3.5. This difference is attributed to differences in geology: high radon levels are found mainly in the areas of the county underlain by permeable karstified limestone. Soil gas bearing radon is drawn into homes by underpressure, which varies from home to home. Where the underlying rock is highly permeable, variations in underpressure will cause greater variations in the quantity of soil gas drawn in than where the permeability is low: hence more variation in radon levels would be expected in areas with underlying rock of high permeability. The foregoing values of GSD were therefore used to estimate the fraction of the housing stock exceeding the Action Level in the three counties: for Derbyshire, the alternative values of GSD used were determined by the GM value for each square.

9 In the north of Derbyshire and the west of Somerset some grid squares had few or no results because of the low population density. For Somerset the data were supplemented by extending the mapped area over the county border into Devon, where more results were available. Blank squares could then be infilled using the techniques described previously[3]. This procedure could not be applied in the case of Derbyshire as there were insufficient extra data in grid squares adjacent to the blank ones.

10 The results are shown in Figures 2–10, grouped by county. Figures 2, 5, and 8 show the numbers of measurements in each 5 km grid square in the counties: they range from a few to a few hundred. Figures 3, 6 and 9 show the estimated proportion of

FIGURE 2
Numbers of homes in which radon was measured in each 5 km grid square of Derbyshire

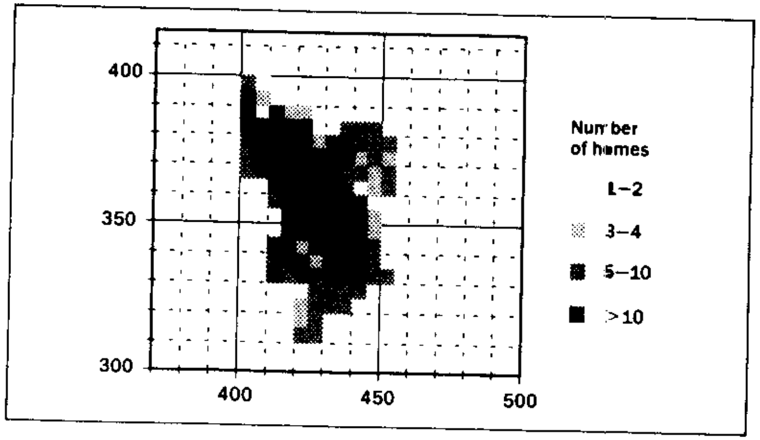


FIGURE 3
Estimated proportions of homes exceeding the Action Level in each 5 km grid square of Derbyshire. Data not smoothed

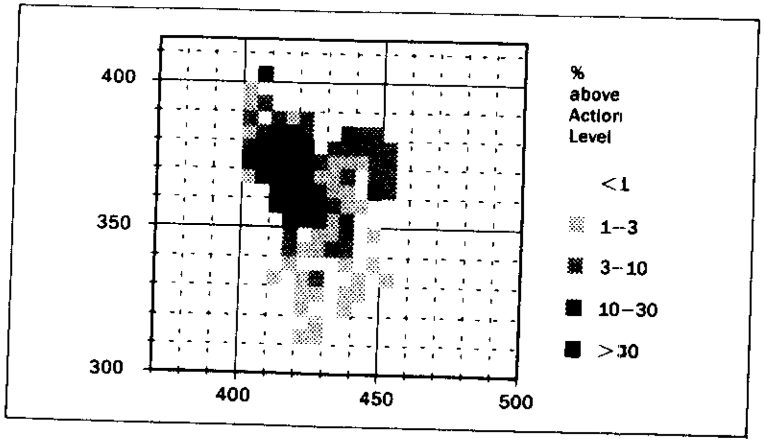


FIGURE 4
Estimated proportions of homes exceeding the Action Level in each 5 km grid square of Derbyshire. Data smoothed

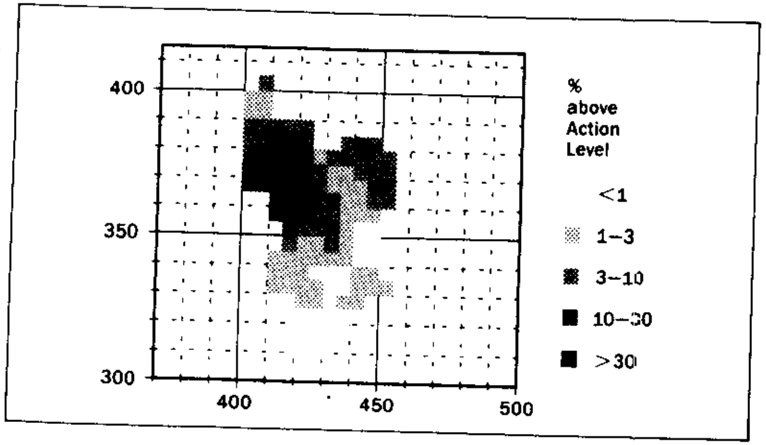


FIGURE 5
Numbers of homes in which radon was measured in each 5 km grid square of Northamptonshire

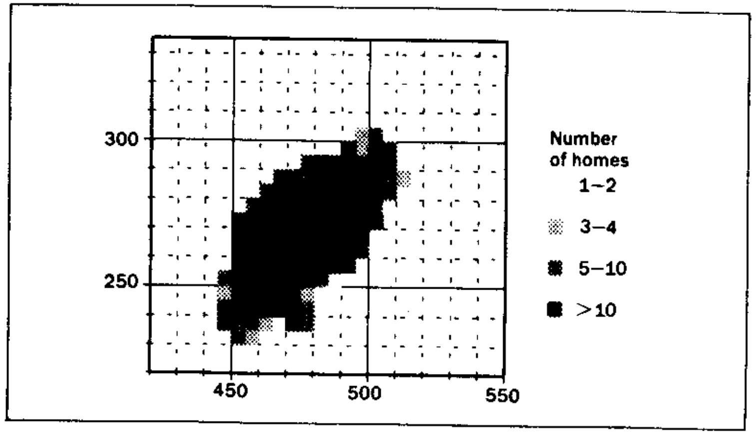


FIGURE 6
Estimated proportions of homes exceeding the Action Level in each 5 km grid square of Northamptonshire. Data not smoothed

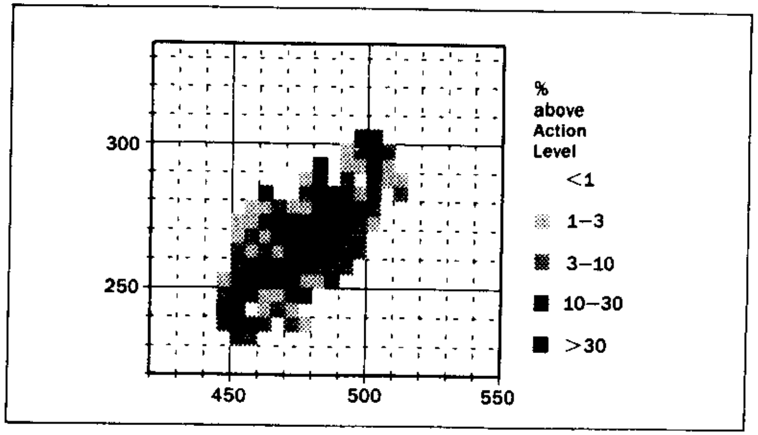


FIGURE 7
Estimated proportions of homes exceeding the Action Level in each 5 km grid square of Northamptonshire. Data smoothed

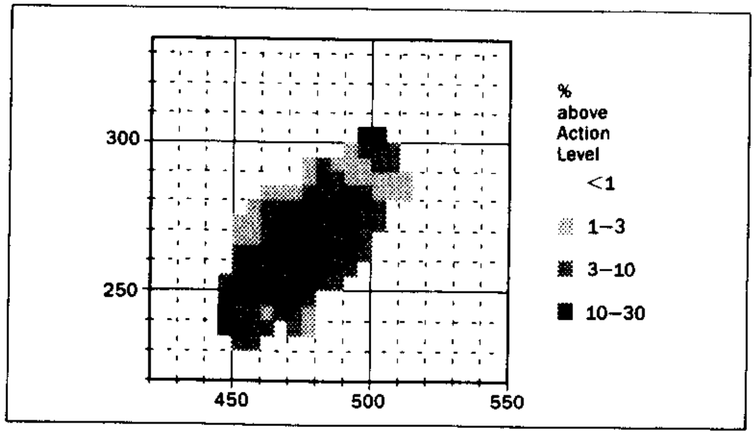


FIGURE 8 *Numbers of homes in which radon was measured in each 5 km grid square of Somerset*

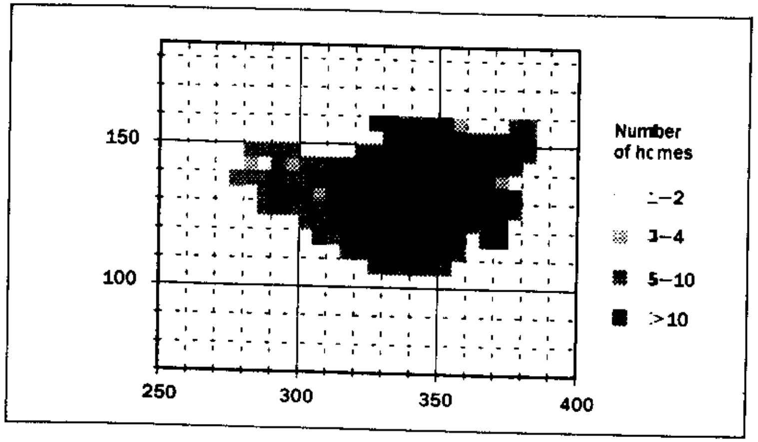


FIGURE 9 *Estimated proportions of homes exceeding the Action Level in each 5 km grid square of Somerset. Data not smoothed*

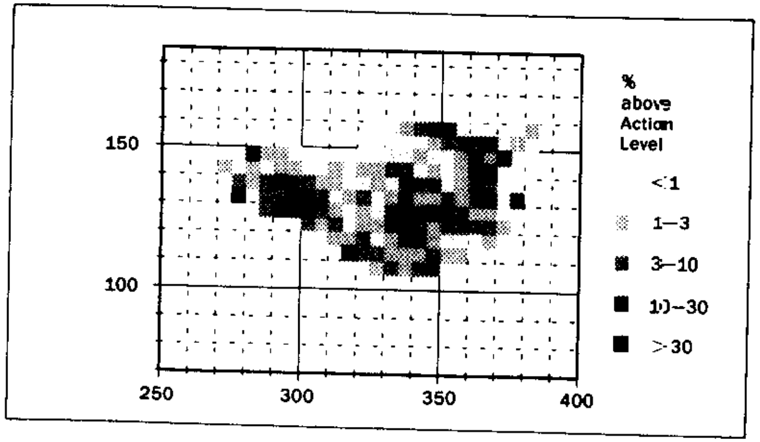
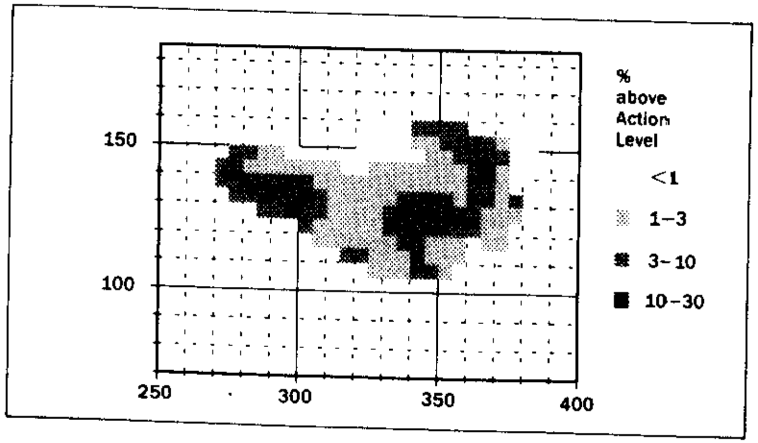


FIGURE 10 *Estimated proportions of homes exceeding the Action Level in each 5 km grid square of Somerset. Data smoothed*



homes in each square with radon concentrations exceeding the Action Level of 200 Bq m^{-3} these figures are based on the unsmoothed estimates for each square – the proportion ranges from below 1% to above 30%. Figures 4, 7 and 10 show the same information after the GM value for each square has been smoothed with those in surrounding squares.

INTERPRETATION

11 In order to use the data in Figures 4, 7 and 10 to define Affected Areas and facilitate the delimitation of localities where precautions against radon are required in new homes, they have been redrawn in Figures 11–13 on maps showing the outlines of the three counties and the major towns. Here the borders between areas with different proportions of homes above the Action Level have been drawn by hand on the basis of the data in Figures 4, 7 and 10, which broadly accord with the local geology. The parts of the counties shown in Figures 11–13 as having 1% probability or more of homes being above the Action Level should be regarded as Affected Areas.

12 Since the analysis in this document is performed on 5 km grid square maps, the position of borders between different areas cannot be defined to an accuracy greater than 5 km. For this reason no attempt has been made to draw borders around areas of one or two grid squares that differ from the surrounding squares.

13 In Derbyshire there is a clear relationship between radon levels and geology. An area with more than 10% of homes above the Action Level is associated with the

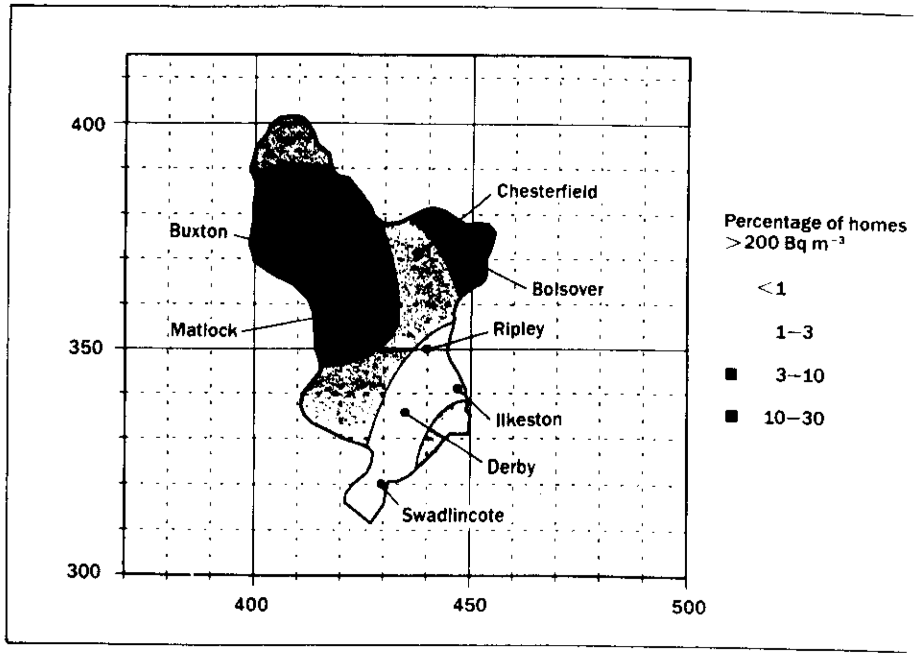


FIGURE 11 *Estimated proportions of homes exceeding the Action Level in parts of Derbyshire*

Carboniferous Limestones in the west of the county. In the east an area with 3–10% of homes above the Action Level is underlain by Permian Limestones. Homes in the south of the county are underlain by mudstones and sandstones of the Permo-Trias, and have lower radon levels. All of the north of the county must be regarded as a radon Affected Area, but parts of the south of the county with less than 1% of homes above the Action Level need not be designated as Affected Areas.

14 The results in Northamptonshire show a distinct pattern with the highest values along a northeast–southwest trend that is parallel to the regional strike of the rocks. Much of the area with the highest radon levels is on the Northampton Sand Formation and the Lower Estuarine Series. These rocks comprise phosphatic ironstones, sandstones and limestones. The whole of the county must be regarded as an Affected Area, with the centre of the county having more than 10% of homes above the Action Level. The area with more than 10% of homes affected has been drawn to include Northampton and Kettering and to exclude Wellingborough following separate examinations of the distributions of results for these towns.

15 In Somerset there is again an association of higher radon levels with limestone, with high values found over Carboniferous and Mesozoic Limestones in the northeast. In the west of the county high values are associated with Devonian rocks, mostly sandstones and shales. Although most of Somerset has less than 3% of homes above the Action Level, a substantial part of the county meets the criterion for Affected Areas.

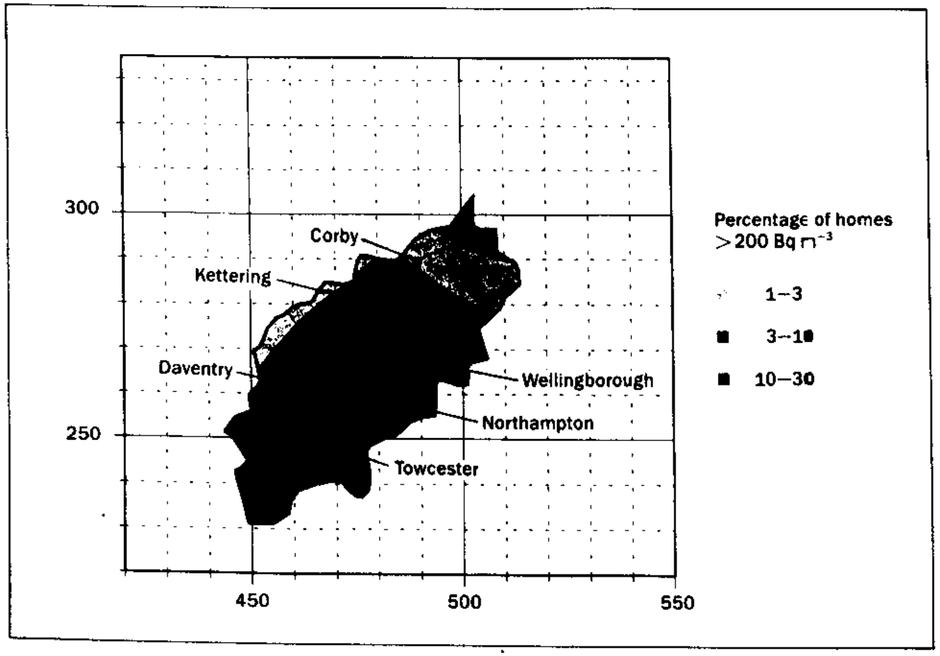


FIGURE 12 *Estimated proportions of homes exceeding the Action Level in parts of Northamptonshire*

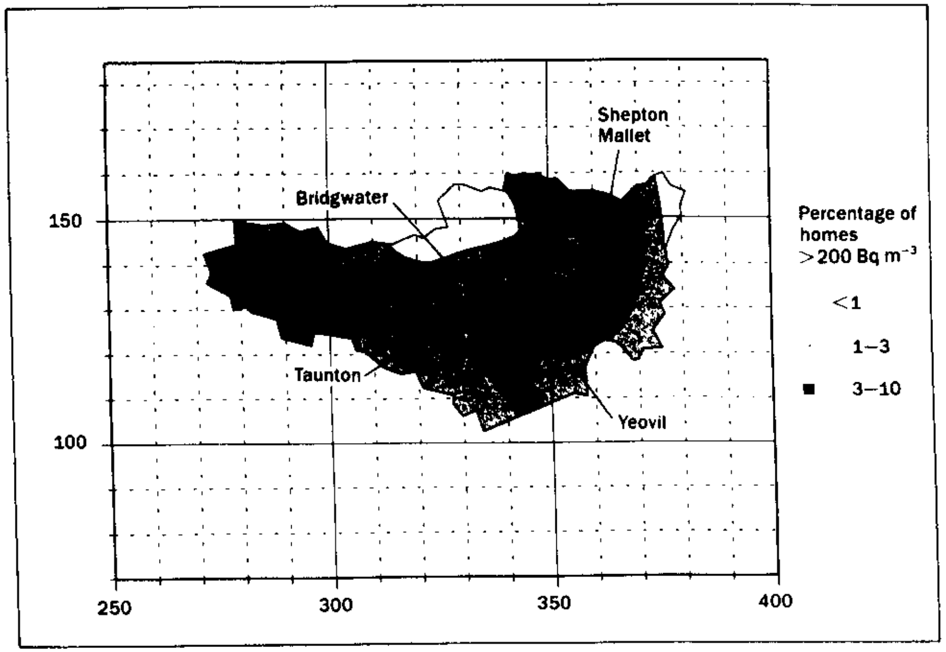


FIGURE 13 *Estimated proportions of homes exceeding the Action Level in parts of Somerset*

16 It has to be recognised that the geological formations which provide the potential for high radon levels in homes extend across county borders. Radon measurements funded by the Department of the Environment will continue to be available on request to householders in areas which may have high radon levels. In order to clarify which other areas are at risk, a systematic survey of the whole country will be undertaken.

RECOMMENDATION

17 The parts of the counties of Derbyshire, Northamptonshire and Somerset shown in Figures 11–13 with 1% probability or more of homes being above the Action Level should be regarded as Affected Areas for the purposes of the Board Statement on radon in homes[1]. The appropriate government authorities should delimit localities within these areas for preventive measures against radon in new homes.

ACKNOWLEDGEMENTS

18 We wish to thank C R Muirhead for his advice on statistical aspects of this work, and T K Ball of the British Geological Survey for advice on geological aspects of this work.

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