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2006 Phys. Med. Biol. 51 R155

(http://iopscience.iop.org/0031-9155/51/13/R10)

INSTITUTE OF PHYSICS PUBLISHING PHYSICS IN MEDICINE AND BIOLOGY

Phys. Med. Biol. **51** (2006) R155–R167 doi:10.1088/0031-9155/51/13/R10

REVIEW

The development of mammography

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Received 27 October 2005, in final form 31 March 2006
Published 20 June 2006
Online at stacks.iop.org/PMB/51/R155

Abstract

This review traces the development of mammography physics over the last 50 years, concentrating mainly on technological changes and their inter-relations. It has been written for physicists with no specific mammography experience but a general interest in radiology, as much as for those with recent involvement in mammography. Topics covered include industrial film, xerography, intensifying screens, x-ray tube developments, image quality test objects, patient dose and performance checks. Some of these developments were necessary before population screening of healthy women could be considered, while others have resulted from increased opportunities for equipment manufactures which screening programmes created. The standpoint of this review is that of a physicist with long experience in a UK centre where mammography was performed on dedicated equipment well over 40 years ago and where screening has been performed continuously for 30 years.

Introduction

Mammography is the examination of the female breast by the use of x-rays to demonstrate low contrast and fine detail in the same film. As practised now, it normally requires a dedicated x-ray tube with special anode materials and rather small focal spots, operating at a tube voltage around 25 to 32 kV, and carefully chosen films and screens in dedicated cassettes. Moving grids are used as in other branches of plain film radiography, and yet despite that it can now fairly be described as a low dose procedure.

Fifty years ago mammography, where it existed at all, was in a primitive condition compared to what it is now, and also compared to general radiography of the period. At least in those days the film types were carefully chosen, though very different in type from those used now, but everything else in the first paragraph was different.

Mammography c.1956

It was recognized from the early days of radiography that reducing the x-ray tube voltage improved radiographic contrast. Unfortunately, because of poorer tissue penetration, it also

required greater tube output and led to greater dose to the patient. For mammography therefore, the kV was reduced to the minimum available. On many ordinary diagnostic x-ray units this will have been 50 kV, but some units did go down to 45 or 40 kV. Most x-ray departments of any size will have had at least one such tube, and this will have been used for whatever mammography was required. Demand for breast films was not particularly high, and only the largest departments could justify a dedicated mammography installation or the space for it.

To demonstrate fine detail, non-screen industrial film was used. This was supplied in envelope-wrapped form. Screens and cassettes were not used because they reduced image sharpness, and this led directly to a relatively high patient dose. Even when automatic film processing (typically requiring 7 to 8 min) had become general in large departments, this was not appropriate for industrial film, which was processed by hand using ordinary wet techniques. By the late 1960s, in one centre at least, two envelope films of different type were used for each exposure, stacked one above the other. The two films were of different speed so that one provided a 'well penetrated' image of breast tissue while the other less penetrated film showed the skin edge and less dense features.

In a few larger departments, x-ray units could be found which were used solely for mammography, and these would usually go down to around 25 to 30 kV. Often this was achieved by modifying the electrical circuits of the generator, possibly by centre-tapping the transformer. That resulted in a tube kV half what was displayed on the control unit. In the 1950s and 1960s, and even later, x-ray tube kV was difficult to measure or control, and much mammography was unknowingly performed at too high a kV.

Focal spot sizes in that period were generally over 1 mm, even for fine foci. Given the slow speed of the film being used, smaller foci could not have delivered the tube output required. Short focus–skin distances, sometimes less than 40 cm, were used to reduce this problem despite the image distortion this produced.

Beam limitation was often of the simplest kind. Even in general radiography, although continuously adjustable diaphragms had become common, field illumination (i.e. light beam diaphragms) was by no means universal. In mammography, copper cones extending from the tube housing right down to the level of the breast were often used. These would be available in a range of sizes, each with a semi-circular or elliptical vent on the patient side, to accommodate breasts of any size or shape. These cones provided both x-ray scatter reduction and some measure of patient localization/immobilization.

Breast compression, now regarded as an absolute essential, was primitive where it existed at all. The copper cones helped in some cases. In at least one unit, after 1972, an inflatable balloon was contained within each cone, and pumped up after the patient had been positioned. Doubtless this was better than nothing, but it was not compression as we now know it.

The first Code of Practice for the control and reduction of staff and patient radiation dose was introduced in the NHS in 1957 and revised in 1964. One of its prime requirements was the fitting of filters to all diagnostic x-ray tubes to remove soft x-rays (which were absorbed in the patient and never reached the film) in order to reduce unnecessary patient dose. For tube potentials below 70 kV, a minimum of 1.5 mm Al was required. This was inappropriate for mammography, and led to problems where mammograms could only be obtained on ordinary x-ray units at their lowest kV. An exception was allowed for general purpose tubes which were also used for soft tissue work such as mammography if the filter was removable, in which case 0.5 mm Al or its equivalent was permitted. This was sometimes provided by the glass envelope or window of the tube itself; in other cases, a 1 mm beryllium window was supplemented by an added sheet of 0.5 mm Al. In those days no interlocks or warning lights were required for such an arrangement.

Xerography

One alternative imaging system to non-screen industrial film was xerography. It is in the nature of xerography to enhance edges in the image, and this makes it advantageous in visualizing both fine detail, such as micro-calcifications, and low contrast masses. The patient dose, however, is comparable with that of non-screen industrial film and thus relatively high. Once screens came into use for mammography, xerography needed to demonstrate superior image quality. For some time it appeared that it might do so. The images appeared on paper and were viewed direct, not requiring an illuminated viewing box. Images could be presented in negative mode, i.e. where opacities appeared pale as in ordinary radiographs, or in positive mode where opacities appeared dark. A simple switch allowed the user to choose between these for each exposure. However, by the early 1980s it was clear that xerographic image quality was no better than could be obtained with the best film–screen combinations which were then available, either in positive or in negative mode. Both modes gave similar quality. Although it retained distinguished supporters for some time, its higher patient dose could not normally be justified, and it was generally out of use by the early 1980s.

Technical developments in the 1970s

The first and perhaps most important of these was the introduction of molybdenum target tubes. With a tungsten target tube, operated at mammographic voltages, there is virtually no line or characteristic radiation. The K-edge at 69 keV is well above the operating voltage, and the L-radiation, at around 9 keV, is largely absorbed in the target and filter or in superficial tissue layers. The x-ray tube thus emits only a continuous spectrum having a broad maximum at around 15 to 20 keV. The K-edge of molybdenum is at about 20 keV and most of its characteristic radiation lies around 19 keV. This is close to the optimum energy for breasts of average thickness or less. If in addition a molybdenum filter is used, this characteristic radiation is enhanced relative to the continuous spectrum, resulting in a beam much more appropriate for mammography than can be obtained with a tungsten target.

Molybdenum target tubes started to become available in the early 1970s and by 1987–1988 when equipment was being ordered for the start of the NHS Breast Screening Programme (NHS BSP), virtually all x-ray units then available had them.

The second main development in this period was the introduction to mammography of intensifying screens, with a substantial reduction in patient dose as a direct consequence. Mammography cassettes, however, were not introduced at this time, coming into general use only in the late 1980s. Because the fine-grain industrial film previously used was supplied in sealed wrapping, screens could not be used directly with that film. In any case, film has to be matched with screens: screens emit light of a fairly narrow wavelength spectrum (normally blue, but green for rare-earth screens) and film must be chosen which is sensitive to that wavelength range. For these reasons, film and screen were loaded manually into black plastic envelopes or bags. This was done in the darkroom, prior to each x-ray exposure. In order to maximize close contact between film and screen, which is essential for high definition in the eventual image, these black bags were then evacuated and sealed.

There were at least two different systems available for this vacuum packing. In the first, the black bags had a nozzle in one corner to which a small hand pump could be connected. These bags were reusable, the film being extracted after exposure when the vacuum was released, again in the darkroom. There may have been more than one model of this type of equipment available on the market. In the second type of system, the film and screen were loaded into a black bag or envelope which was open at one end; this assembly was then placed

in a special box and its lid closed, whereupon the envelope was automatically evacuated and heat sealed. After exposure one side of the envelope was cut open with a guillotine and the film processed. Envelopes were larger than the film-screen size and could be re-used three to five times. That size was by this time becoming standardized at 18 × 24 cm.

In general radiography, films normally have emulsions on both sides of the film base and both a front and a back screen are fitted in each cassette. In mammography, films are always single sided and used with a back screen only. This is to avoid any possibility of 'parallax unsharpness' which may arise from the two images in double sided film. This was the case with evacuated envelopes and with the cassettes which later replaced them, and it remains the case to this day.

With the change of film type, and the general introduction of automatic processing, wet processing went out of use at around this time, for mammography as for other procedures and film types. Film loading prior to exposure, and unloading prior to processing, continued to be done in darkrooms. Daylight loading and processing did not become general much before 1990.

All systems of the kind just described were of course rather primitive compared with what we now have, but they were a great advance on what had gone before. Even so, grids were not used until the 1980s.

A second development occurred in relation to breast compression. A band of heavy-duty polythene was stretched across the x-ray beam above the breast; after the band had been mounted on the x-ray set its tension was increased manually by the radiographer. When the patient was correctly positioned, the radiographer lowered the band manually onto the breast to the desired degree of compression. As with the black envelopes, this also was crude and primitive compared to what we now have, but again it was a considerable advance on previous practice.

X-ray tubes and generators specifically designed for mammography now started to become available, with nominal tube voltages down to around 25 kV or even lower, in steps of 1 kV. However, they continued to have only tungsten targets with aluminium or glass filtration. Tube kV was still not very well controlled, and a case is known of a dedicated mammography tube operating at 8 kV above the nominal values for several months before the combined suspicions of radiologist and physicist led to its correction.

Blue emulsion film

In the mid-1970s it was suggested that radiographic contrast could be improved by using blue-emulsion[1] films and viewing them in orange light. Viewing boxes having both orange and white light became available at reasonable cost, but processing was specific to the blue films, and perhaps for this reason the idea was not widely pursued in general radiography. Even for mammography it was only practicable where there was dedicated mammographic processing, but up to the mid to late 1980s it was the modality of choice in some larger centres and in some early screening trials. Only one manufacturer (Agfa) took it up, but trials with phantom films suggested that for image quality their Medichrome Blue system was the best film–screen system available, with doses no greater than with the best alternatives. However, with the more-or-less simultaneous arrival of mammographic film cassettes and the NHS Breast Screening Programme in the UK, it could not retain market-share and the film was withdrawn by 1989.

[1] These are not to be confused with black and white emulsions on clear film base having a slightly blue tinge.

Developments in breast screening

Although breast cancer screening is scarcely a technical development in itself, to omit mention of it altogether would distort any proper account of such development over the last 20 years.

The first screening programme of any significance recorded in the literature was the Health Insurance Plan (HIP) study in New York, which started in 1963 (Schapiro *et al* 1971). A later screening programme on which a number of others were to some degree modelled was the Swedish Two County Study (Tabar and Gad 1981).

In the UK, at least one major employer organized screening for its female staff in the 1970s but this was on a small scale and results were not reported. A pilot trial for population screening commenced in Edinburgh in 1975, again on a small scale and intended to demonstrate feasibility. In 1979 a UK trial for the early detection of breast cancer began in which two centres (Edinburgh and Guildford) used x-ray mammography, two others used breast examination and four others served as controls. Edinburgh and Guildford used Medichrome Blue Film, which was a single emulsion film used with a back screen as before. For the first few years of this trial, which ran to 1987, the x-ray tubes in Edinburgh continued to have tungsten targets and aluminium or glass filtration.

This trial led directly to the NHS Breast Screening Programme which began in 1988 but was not fully implemented with all centres running until the early 1990s. This programme was set up following the Forrest Report of 1986. Several major technical developments occurred in the mid to late 1980s, just in time for the start of this programme. These will be described in the following sections. A similar programme started in Holland at about the same time.

The degree of success achieved by these and other screening programmes is a complex and even now a somewhat controversial subject, which must fall outside the scope of this review.

Major technical developments in the 1980s

In this period, focal spot sizes were reduced. At the start of the NHS BSP the Department of Health stipulated nominal focus sizes of 0.5 mm (broad) and 0.2 mm (fine). The actual sizes of the broad foci were often somewhat larger, up to 0.8 mm in length, and some manufacturers made full use of the generous relationship allowed by the International Electro-technical Commission (IEC) between nominal and actual focus sizes. Nevertheless, these broad foci were better than their predecessors, and later tubes installed after about 1995 mostly complied very well with these requirements. For whatever reason, the fine foci rarely suffered from this problem.

Another major development in the mid-1980s was the introduction of anti-scatter grids to mammography. These had long been in general use in most forms of plain-film radiography, but had been excluded from mammography, probably mainly on grounds of dose, since grids increase dose by a factor typically of 3 or more. Most of these grids had 32 lines inch^{-1} (12.6 cm^{-1}) and a ratio of lead strip height to spacing of 5. Different x-ray unit manufacturers may have obtained them from a single source. Their use had become general by the time of the start of the NHS BSP.

A third significant development in the 1980s was the introduction of automatic exposure control (AEC) systems. In these, an ion chamber or other radiation detector is placed beneath the film cassette and connected electrically to the exposure time control circuit. When a pre-set amount of radiation has been detected, the exposure is automatically terminated. Systems of this type had been coming into use in general radiography over a fairly long time. In their absence, the radiographer used her judgement and experience in choosing exposure factors to achieve optimum film density. Experienced radiographers became very good at this, but

AEC systems helped greatly in their work. Without them it would have been more difficult to introduce the NHS BSP and train the necessary numbers of radiographers in a short period.

In mammography, the AEC detector was made much smaller than the breast, which usually does not cover the whole area of the film and cassette, but does cover the area of the detector with a generous margin. With some breasts, a dense structure (or a thin one) may chance to lie directly over the detector, leading to sub-optimal exposure. AEC detectors can be placed in one of two or three positions selected by the radiographer before exposure, and she will use her experience to do this or if necessary repeat the film with the detector repositioned.

With manual selection of exposure factors, the radiographer chooses not only kV but also a combination of tube current (mA) and time (s) to achieve the desired exposure (mAs). When AEC systems were first introduced, the radiographer had no means of knowing after the exposure what mAs value had been used. Various difficulties can arise from this, particularly in fault conditions. Post-exposure mAs meters were accordingly introduced, but shortly after AEC systems rather than before them. In some cases these mAs meters were fitted to x-ray units already in use. They had become general by the time the NHS BSP started. They were essential not only for radiographers but also for physicists carrying out checks to monitor equipment performance, and for both staff groups when assessing patient dose.

By the early 1980s, there were a number of films and screens available for mammography. Most of the major manufacturers produced at least one of each, and it was usually assumed that film and screen were best matched when made by the same maker. The development of test objects will be discussed later, but once a suitable test object for mammography was available it was natural that the leading contenders in films and screens should be compared for their imaging performance, using the same x-ray set and as far as possible the same processing, though that was not possible for blue film. Results suggested that there was no great difference between the best three or four combinations though some others were relatively poor (Kirkpatrick and Law 1987). Combinations of mixed manufacturer were tried but yielded no great gains. Even if differences between the best were not substantial, every gain in image quality was usually considered worthwhile, because radiologists were conscious of working at the limits of their perception, and maximizing cancer detection rate and diagnostic accuracy was the first priority. Much of the work of this kind was done some years before the NHS BSP started, so that the field of choice for films and screens was usefully narrowed when that programme was established.

Developments in film processing and related topics

With cassettes in general use, automatic daylight loading and unloading followed in mammography as it had done slightly earlier in general radiography. This happened from the late 1980s onwards, just in time for the earliest years of the NHS BSP.

At around that time there was some variation of opinion as to whether film processing, and checks to monitor its performance, should fall within the physicist's remit as well as within the radiographer's, but that doubt did not persist for very long. At the start of the BSP it was generally accepted that AEC systems should be set to give an average film density only a little above 1.0, or 1.0 above the base + fog level, itself typically about 0.2. This was thought to place the region of interest firmly on the straight-line portion of the characteristic curve of the film, so that higher densities would offer no gain in contrast. In a classic paper (Young *et al* 1994) it was shown that the cancer detection rate could be increased simply by adopting a mean film density of around 1.6, or at least within the range 1.4 to 1.8. This paper's conclusions were adopted widely and rapidly.

Film processing

Two important parameters in film processing are film speed, i.e. exposure required to reach a standard density such as 1.0 or 1.6, and contrast, i.e. the density difference between two known exposures within the straight-line part of the characteristic curve. Speed has a direct effect on patient dose, and contrast has a direct effect on image quality. By the mid-1980s sensitometric equipment was becoming available. This provided standard light exposures through a photographic 'wedge', a series of filters in steps, resulting in typically 10 or 20 standardized increments of density when the film was processed. By this means film speed and contrast could be tracked from day to day and month to month. Daily checks of this kind were instituted, especially in BSP centres from 1988 onwards. All this was a great help in maintaining consistent standards of performance, for example when processors were cleaned or chemicals were changed, and when fresh supplies of film were used. It was found that emulsion speed could sometimes vary by 20% or more between batches of the same brand of films.

All routine checks of this kind were performed by radiographers, but physicists would check the results for consistency on their visits, or in the BSP would have results sent to them from all centres in their territory every week. Physicists also used sensitometry checks during many of their own research projects.

Test objects for image quality assessment

Test objects (TOs) have been used in diagnostic radiology, in a variety of forms, for a long time. Up to the mid-1970s there was no TO specifically designed for mammography and commercially available. A few had been designed and constructed in medical physics departments but few if any reports of their successful use appeared. Early in 1974, the Diagnostic Radiology Topic Group of the Hospital Physicists Association (HPA, now IPEM) were planning a UK-wide survey of mammographic systems in hospitals in an attempt to identify best current practice and equipment. For this purpose a good TO was essential. Their eventual design was used not only for that investigation but in later years in centres conducting screening trials and elsewhere. Design details were published by White and Tucker (1980).

Test objects, whether in mammography or in general radiology, tend to fall into one of two main groups. The first group attempts to measure limiting resolution in line pairs/mm, and limiting contrast for objects of stated size in a quantitative way. This approach facilitates comparison with theoretical calculations. The second group concentrates on arrays of features which mimic the sort of detail looked for by the radiologist. These are made in decreasing sizes and contrasts, and a 'film score' is derived simply by counting the total number of these details which can be seen in a film. Many phantoms try to include features of both types. An essential point is that no imaging system under test should achieve a full score, and that size variations should be small enough that different scores are actually obtained on systems of different imaging capability, otherwise the TO is too insensitive to be useful. Furthermore, a TO which has adequate sensitivity and range when first designed may lose these qualities as imaging performance improves with new equipment.

The TO used in the HPA Topic Group's investigation was sometimes referred to as the 'Barts Phantom' because Drs White and Tucker worked at that hospital. In the mid-1970s when it was made it had more than enough sensitivity for the imaging equipment then in use in the UK, and it was still getting some use 20 years later, but for the inception of the NHS BSP a more advanced design was required. The Leeds Medical Physics Department had much experience in general x-ray TO design and were commissioned by the Department of Health

to produce a suitable design and construct it in sufficient numbers. The first result was the TORMAX plate, and its simplified version the TORMAS, both of which included at least one high contrast bar pattern, a low contrast bar pattern, and a range of 'realistic' details. These TOs were widely used from the start of the BSP, and still are in use, but already in their early years they were felt to lack something in sensitivity as imaging equipment performance advanced. This problem was soon removed with the appearance in 1992 of the Leeds TORMAM plate, which is made up entirely of realistic details and had more than enough sensitivity. It has for some years been the first choice TO for investigative work in mammography physics (Cowen *et al* 1992).

Alternative TOs include one designed by Ackermann and marketed by Dupont, which is like the TORMAX in including line-pair patterns and realistic details. This was thought to have greater sensitivity than the TORMAX, and was adopted by a few regions in the BSP before the TORMAM became available (Law 1991, Robinson and Underwood 1991). To that extent it remains in routine use. A very few other TOs were available but their use has not been widely reported.

Instrumentation for performance checks

Up to the mid-1960s, measuring equipment specifically for x-rays of mammographic energies scarcely existed, though ion chambers and dosemeters designed for general diagnostic x-ray work could be used down to 25 kV with no appreciable error (Osborn and Burrows 1958, Clayton *et al* 1970). Measurement of kV was difficult (as described earlier) until the advent of the Ardran–Crooks penetrameter in 1968 (Ardran and Crooks 1968). Although principally intended for the 60–120 kV region, it proved quite satisfactory for mammographic energies if a thinner copper filter was used. This instrument was a great advance, in that a single exposure yielded a measurement within a few minutes once the film had been processed, compared with 1 or 2 h with earlier methods. A calibration service for these instruments, in both energy ranges, was offered by the National Physical Laboratory from about 1975 and this was another great advance.

By 1988, just in time for the start of the BSP, digital direct-reading kV meters became available for the mammographic energy range. These instruments provided an immediate display, to 0.1 kV, after each x-ray exposure. The next exposure then over-rode the previous one so that the user could check every kV setting without needing to move from behind the protective screen. Within a short time, remarks were heard that film penetrameters were too slow. The underlying principle of these instruments was an electronic version of a penetrameter, with detectors under a step-wedge having only a few steps. Calibration turned out to be generally well within 1 kV, reproducibility was to 0.1 kV, and these features were found to hold over periods of years rather than months. At the same time that these devices came into use, manufacturers achieved remarkable improvements in the reproducibility and calibration of x-ray units. Any failings on that score would have been shown up very quickly by these kV meters, but an instance is known of an x-ray unit giving a reading of 28.1 kV for 28 kV set on every check at 3 months intervals for its first 2 years in quite intensive use for screening. The best-known kV meter in the UK in this period was the RMI 232 (Radiation Measurements Inc, WI); its convenience and reliability made it everyone's favourite (Underwood *et al* 1996).

The Adrian-type ion chambers remained much the most widely used in the UK at mammographic energies until just before the NHS BSP started, when a new range of chambers and dosemeters became available. There is little of note to record about these instruments except that their calibrations were generally found to be correct and stable to within a few per cent, their readings were highly reproducible, and they were much lighter to carry than

their predecessors, which was no small point for BSP work. As with kV checks, these features were matched by remarkable improvements in consistency of x-ray tube output.

For the measurement of focal spot size, a simple pin-hole in a sheet of lead was the most widely used method up until the mid to late 1980s. These devices were usually made manually in the local physics dept. workshops, and little attention was generally given to the precise size of the pin-hole or to any correction for this size. This was probably not unreasonable when focus sizes were typically 2 mm, and the purpose of a measurement was to check if it had increased to over 3 mm. With mammographic foci of 0.2 to 0.6 mm better methods were needed. Pin-holes of known size in gold were available commercially by the mid-1980s and could be mounted in a lead shield. There remained the problem of mounting this assembly on the x-ray tube housing so as to ensure that an image of the focus did appear on the film without appreciable distortion due to mis-alignment. Experience showed that this was by no means a trivial exercise. The problem reached its most acute form on mobile units in the BSP, none of which had film processing, this being done at the screening centre. The centres were often within a half-hour drive of their vans, but in rural areas distances of 50 to 100 miles were not unknown. Fortunately, alternative methods for estimating focus size were available, using radiating or tapering bar-patterns of variable line frequency. A simple film could normally be obtained reliably, and return visits to repeat these were rare. Also, jigs to hold pin-holes or bar patterns in correct position were made in hospital physics workshops, and accounts of two such devices were published (Ramsdale *et al* 1989, Law 1993a), though no such device ever became commercially available in the UK. With experience, and the parallel use of at least two methods on every x-ray tube, bar patterns tended to be regarded as giving the best size estimates, but pin-hole images remained valuable for indicating focal spot (and hence filament) condition, which could provide some rough prediction of future tube life.

For sensitometry checks on film processors, a sensitometer with highly reproducible light exposures is absolutely essential, and this point is very difficult for the user to check. Not every instrument of this kind always passed this crucial test, and the X-rite 383 model came to be the one most generally favoured, at least up to the mid-1990s (Law 1996).

Patient dose

The relatively high dose of the early years, and its reduction due to new films and screens, has already been mentioned. Early measurements of dose cannot easily be related to present day levels, as the current emphasis on mean glandular dose did not arise until the mid to late 1980s. Until that time, patient dose in mammography was usually described in terms of surface entrance dose, because that was what could be measured with relative ease. In the 1950s and 1960s it was often specified in roentgens, the unit of what later came to be called ‘exposure’. To derive mean organ dose was more difficult; the standard radiotherapy depth dose tables would have required interpolation and their validity in this context was not clear. In the late 1980s it became recognized that the glandular tissue was the region mainly at risk, and models were developed to enable simple calculations of mean glandular dose from measurements of entrance air kerma (Dance 1990). The published factors were further refined in the late 1990s (Dance *et al* 2000).

In the early years of the UK screening trial a mean glandular dose of 1 mGy per film was sometimes taken as a reasonable rough estimate for discussion purposes. At that time 4.5 cm was thought to be the average compressed breast thickness, but this had been based on a small sample of women. Once the screening programme had started it was realized fairly quickly that the true mean was just over 5.5 cm, and estimates also became available of numbers of repeat films required, numbers of breasts too large for a single film of 18 $\times$ 24 cm,

and the true range of breast thickness. The National Physics Centre established at Guildford under the NHS BSP has conducted several national dose surveys, and mean glandular tissue dose, averaged over all women screened, now seems to have stabilized at about 2.5 mGy for the lateral oblique view and 2.0 mGy for the cranio-caudal view (Young *et al* 2005). Two-view screening was introduced into the BSP, for the first screening round only, around 1995. Following a trial of two-view screening which showed a 24% rise in cancer detection rate (45% for small cancers) compared with single view (Wald *et al* 1995), the BSP decided about the year 2000 to introduce two-view screening on all screening rounds, so that 4.5 mGy is now taken as the average mean glandular dose to breasts of average size.

The balance of benefit and radiation risk

Even before screening trials began, it was recognized that there was some risk of x-ray induction of breast cancer. This risk was considered to be small but probably not zero. At that time, benefit in terms of mortality reduction was barely predictable, and discussion tended to concentrate on a comparison of numbers of cancers detected and numbers likely to be induced at the dose level thought to be correct at that time. A relatively early calculation suggested that the detection/induction ratio probably lay between 100 and 1000 for most women. It was recognized that a small minority of women had more than one film per breast per screening round but it was believed that this would not increase the risk more than ten-fold for any single woman. Also, the trial showed that, even at a 2 year screening interval, the cancer detection rate was virtually constant in each screening round. Thus the benefit/risk ratio could be considered for each round independently and the cumulative dose from successive rounds was not a cause for concern (Law 1987).

With more screening experience, the small proportion of women having extra films could now be estimated, and the risk for a woman in the worst case scenario, i.e. all possible causes of extra films occurring in a single individual, could be assessed. On this basis, there could be no guarantee (contrary to initial optimistic thinking) that benefit would exceed risk for every single woman screened. However, it was possible to estimate the proportion of screened women for whom risk of cancer induction might exceed probability of detection and this was generally extremely small unless screening were to commence at a younger age or be done more often (Law 1993b, 1997).

All such discussion requires a knowledge of numerical values for the numbers of cancers induced per mGy, preferably stratified by age in 5 year bands, since detection rates increase considerably with age and are also published in 5 year bands. This remains a point of some controversy to this day, and a number of approaches have been tried. It is most unlikely that numerical values can yet be established to better than a factor of 2 or 3 in either direction (Young *et al* 2003).

With greater experience of screening in a number of countries, more information is now available on mortality reduction which may actually be achieved. Numerical estimates of this vary from 6 to 60%, depending mainly on total duration of the screening programme and the basis of the calculation. For example, when set against risk of radiation induced cancer, benefit should be calculated for women actually screened, whereas in a discussion of whether benefit justifies the resources expended, benefit has to be calculated for the whole population to whom screening is offered. As with the radiation risks, quantitative estimates of benefit also remain uncertain. However, claims that benefit could be zero or negative, even in women over 50, seem to have been effectively refuted.

The cancer detection/induction ratio is a valuable indicator of benefit/risk, not least because the numbers can be estimated with relative ease (detection rates especially), but they

are not numerically equal, though they are unlikely to differ by as much as a factor of 10, and probably less. At the time of writing, the best discussion of this topic in a UK context is given in NHS BSP Report 54 (Young *et al* 2003). The implications for benefit/risk of the move to two-view screening have been considered by Law and Faulkner (2002).

It is important for physicists to recognize that there are a number of risks and benefits in screening beyond those discussed above, and for which they have no specific expertise.

A new generation of x-ray sets

By the early 1990s it was recognized that the optimum x-ray tube kV varied with breast thickness, optimum in this case being given by a maximum ratio of primary to scattered radiation on the beam-exit side of the patient. At that time choice of kV was left to the radiographer. At about the same time it was also recognized that molybdenum targets and filters, while excellent for breasts of average size, were not the best choice for thicker breasts, for which rhodium would provide a better x-ray spectrum.

Manufacturers now began to produce x-ray sets which offered automatic selection both of kV and of the optimum target/filter combination. Different makers used different methods to achieve this. In the Siemens 3000 unit it was done solely by detecting the compressed breast thickness, while in the IGE DMR and 800T units an initial extremely short x-ray exposure was detected, and its percentage transmission through the breast used to determine factors for the main exposure which followed a few milliseconds later. Neither user nor patient would note the very short extra time required. In addition to selecting kV, such units might select an optimum target/filter combination from a range including Mo/Mo, Mo/Rh, Rh/Rh or W/Rh. By means such as these, image quality could be improved and patient dose reduced simultaneously.

New x-ray sets with this kind of feature became available around 1995 and by 2000 were dominating the market. They appear to have played some part in keeping breast dose down at a time of increasing film density, and prior to the general introduction of two-view screening in 2003–2004.

Digital imaging techniques

These have been tried out in general radiology, and rather cautiously so far in mammography. No particular system has as yet been adopted to any significant extent for breast imaging. Much work remains to be done to identify optimum viewing conditions for imaging displayed on VDU screens. Initial assessments of image quality achievable with digital systems suggest fairly clearly that resolution as indicated by line-frequency bar patterns is considerably reduced, but that image scores from 'realistic' TOs are significantly increased. This may seem surprising at first, but the two findings are not necessarily in conflict.

Conclusion

Fifty years ago mammography was extremely primitive, a kind of Cinderella in radiography. The procedure is now as sophisticated as any, perhaps more so than most. In achieving this transformation much credit should go to x-ray equipment manufacturers. They often seem slow or reluctant to modify existing equipment in ways which appear obvious, simple and beneficial to the user. Nevertheless they have done well in producing improved models, in time for the screening programmes of the late 1980s and which put into practice more recent research conclusions. For this they deserve credit which they do not always receive.

In this account, the main emphasis has been placed on advances in equipment and technology, and on how some of those advances have been interrelated, so that these interrelations have determined both the sequence and the pace of change.

In the short bibliography below, some landmark publications are listed which do not appear in the reference list which follows. They are recommended reading for tracing the development of mammographic physics. Further references will be found in all these publications.

Acknowledgments

In preparing this review I have consulted a number of senior colleagues in order to confirm or to supplement my own records and memories. These include Mrs J Coupar, Dr D R Dance, Dr K Faulkner, Dr A E Kirkpatrick, Dr J L Price, Miss D A Shaw, Mr A Watt and Dr K C Young. I apologize to anyone else whom I may have omitted from this list. It has become clear to me how variable memories can be, and also that paper records even of relatively recent periods are being discarded by libraries and departments as well as by those like myself who are retired. I can only hope to have avoided major errors of chronology.

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