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X-RAY CALIBRATION QUALITIES

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Since the recent publication of IAEA Technical Reports Series No. 374 "Calibration of Dosimeters Used in Radiotherapy", there have been a number of queries about the origin of, and the rationale behind, the X-ray qualities recommended for calibration purposes as listed in Tables II and III of that publication.

The simple answer is that these are the qualities derived at the UK National Physical Laboratory (NPL) in 1971 for the calibration of therapy-level dosimeters and which are still in use for that purpose. As some SSDLs may have difficulties in adopting these exact combinations of kV and filtration, it may be helpful to discuss the basic ideas involved, and how to go about deriving a different series of qualities. But first, a brief historical review might be of interest.

Brief history

From the early 1900s NPL tried to respond to the requests of British radiotherapists to calibrate the dosimeters they used for standardising the dose delivered to patients. In those days electrical (or electrostatic) methods of measuring dose were rather unreliable, and the dosimeters in general use were "pastilles" - chemicals which changed colour when irradiated. Calibration was little more than standardisation, so that radiotherapists could exchange information about suitable dosages.

The main problem hampering progress was the absence of a suitable quantity and unit for the measurement of X-ray "intensity". This was solved by the decision by the International Congress of Radiology in 1928 to define the roentgen in terms of the amount of ionisation produced in a unit volume of air. Within a few months NPL had constructed a free-air chamber to realise this quantity and unit, and began to use it to calibrate radiation dosimeters.

From the beginning, the particular kVs chosen to generate the X-ray beams at NPL were intended to match those used in clinical radiotherapy, which in those days were generally in the range 100 kV to 150 kV. As the years passed by, X-ray technology improved, and the range of qualities used for radiotherapy expanded. It increased upwards in energy to 300 kV as radiotherapists demanded X-ray generators capable of giving greater depth doses. It also extended downwards in energy because a variety of skin diseases (not just malignant) were treated by radiotherapy at X-ray voltages down to 10 kV using special beryllium-window X-ray tubes.

In attempting to meet the demand for a wider range of X-ray qualities for the calibration of radiation dosimeters, NPL added qualities on a piecemeal basis, by devising each quality in response to a request from a radiotherapist and then adding that quality to the list of those generally available. In consequence, by 1970, although the range of qualities was quite wide, it bore little resemblance to logic or convenience. In particular, the exposure rates used for the different qualities differed widely, as did the spectral widths. This gave rise to difficulties when users wanted to interpolate between different qualities in order to calculate the calibration factors for the qualities used in a particular hospital. Therefore, in 1971 it was decided to rationalise the scheme and to derive a completely new range of X-ray qualities.

Specification of X-ray quality

For many years hospital physicists had been using half-value layer (HVL) in order to specify the quality of X-ray beams. It was decided therefore to adopt this concept and to specify the energies of low energy X-ray beams in terms of HVL in aluminium up to 4 mm Al HVL (about 100 kV), and in terms of HVL in copper for the higher energy X-ray beams up to 4 mm Cu HVL (about 300 kV). A total of nineteen qualities were chosen, at standardised values of HVLs spaced as evenly as possible, so that it would be easy for users to interpolate between them. That decision was easy, but much less obvious was the combination of kV and filtration that should be used for each quality.

Choice of kV-filter combinations

As the basic criterion was that the conditions should match those used in radiotherapy as far as possible, a review of the radiological literature was carried out to try to discover what combinations of kVs and filters radiotherapists actually used. There was a slight problem. Before about 1935 X-ray technology was not able to provide the highest and lowest energies that radiotherapists really wanted. After about 1955 the main interest of radiotherapists was concentrated on using the new opportunities offered by the development of ^{60}Co and ^{137}Cs teletherapy units and megavoltage X-ray generators. During this period there was the second world war. However, it was assumed that the requirements for low- and medium-energy X-ray therapy had not changed significantly since that time.

Interestingly, the review indicated that there were two extreme views. On the one hand there were those who used high kVs and low filtrations; these had the advantage of high exposure rates enabling large numbers of patients to be treated in the shortest possible times, but had the disadvantage of a high skin dose relative to the tumour dose, thus often preventing the required tumour dose to be delivered because of unacceptable skin reaction. The other extreme was to use highly filtered beams, the main advantage of which was to reduce the skin dose, but needed long treatment times, thus making radiotherapy rather expensive. It appeared however that most radiotherapists steered a middle course between these two extremes, and it was these conditions that were felt to be most appropriate for the new NPL calibration qualities.

The new NPL X-ray qualities

Taking this into account, together with a decision to try to keep the same kerma rates over the range of qualities, after a certain amount of trial and error the X-ray qualities listed in TRS 374 were derived, shown here as Tables 1 and 2. Over the range 0.35 mmAl HVL to 4.0 mmCu HVL, these all give air kerma rates of about 100 mGy/min at 75 cm from the target, keeping the tube current fixed at the maximum allowed by the manufacturer. For lower X-ray energies, calibrations at NPL are usually carried out at 50 cm from the target, thus increasing the kerma rate, but below about 0.5 mmAl HVL the kerma rate decreases with energy, partly because of the effect of air attenuation.

As an added bonus it was found that these conditions gave rise to very similar relative spectral widths over the whole range of qualities, i.e. the width of the photon energy spectrum divided by the mean photon energy was approximately constant.

TABLE 1. LOW-ENERGY X-RAY QUALITIES
(Table II of TRS 374}

Tube voltage (kV)	Added filtration (mm Al)	HVL at 50 cm (mm Al)
Typical inherent filtration: 1 mm Be		
8.5	None	0.024
10	0.025	0.036
11.5	0.05	0.05
14	0.11	0.07
16	0.20	0.10
20	0.30	0.15
24	0.45	0.25
34	0.47	0.35
41	0.56	0.50
44	0.74	0.70
50	1.01	1.00

A new concept of radiotherapy qualities

A year or two later it was noticed that if the kVs were plotted against the HVLs on log-log graph paper, they fell on straight lines. It was also noticed that if the same plots were made for the qualities provided by some other primary standardising laboratories for calibrating therapy-level X-ray dosimeters, these fell on almost the same straight lines, although with rather more scatter around the lines. It was felt therefore that this was the most satisfactory method of deciding whether a set of qualities is appropriate for calibrating therapy-level dosimeters, rather than just listing a set of kV-filter combinations. This is the reason for the recommendation contained in Fig. 3 of TRS 374 (Fig. 1 in this note).

If similar graphs are plotted for X-ray qualities suitable for calibrating protection-level dosimeters, keeping constant kerma rates over the whole range of qualities, their kVs also fall on straight lines when plotted against HVL, but on different straight (or almost straight) lines. An example is given in Fig. 2.

TABLE 2. MEDIUM ENERGY X-RAY QUALITIES
(Table III of TRS 374)

Tube voltage (kV)	Added filtration (mm)			Half-value layer (mm) (mm)	
	Sn	Cu	Al	Al	Cu
Typical inherent filtration: 1 mm Be					
32	0	0	0.47	0.35	-
39	0	0	0.56	0.50	-
43	0	0	0.74	0.70	-
50	0	0	1.01	1.00	-
*Typical inherent filtration: 2.5 mm Be + 4.8 mm PMMA**					
50	0	0	0.7	1.0	0.030
75	0	0	1.5	2.0	0.062
100	0	0	3.4	4.0	0.15
105	0	0.10	1.0	5.0	0.20
135	0	0.27	1.0	8.8	0.50
*Typical inherent filtration: 4 mm Al equivalent + 4.8 mm PMMA**					
180	0	0.42	1.0	12.3	1.0
220	0	1.20	1.0	16.1	2.0
280	1.4	0.25	1.0	20.0	4.0

* PMMA: polymethylmethacrylate

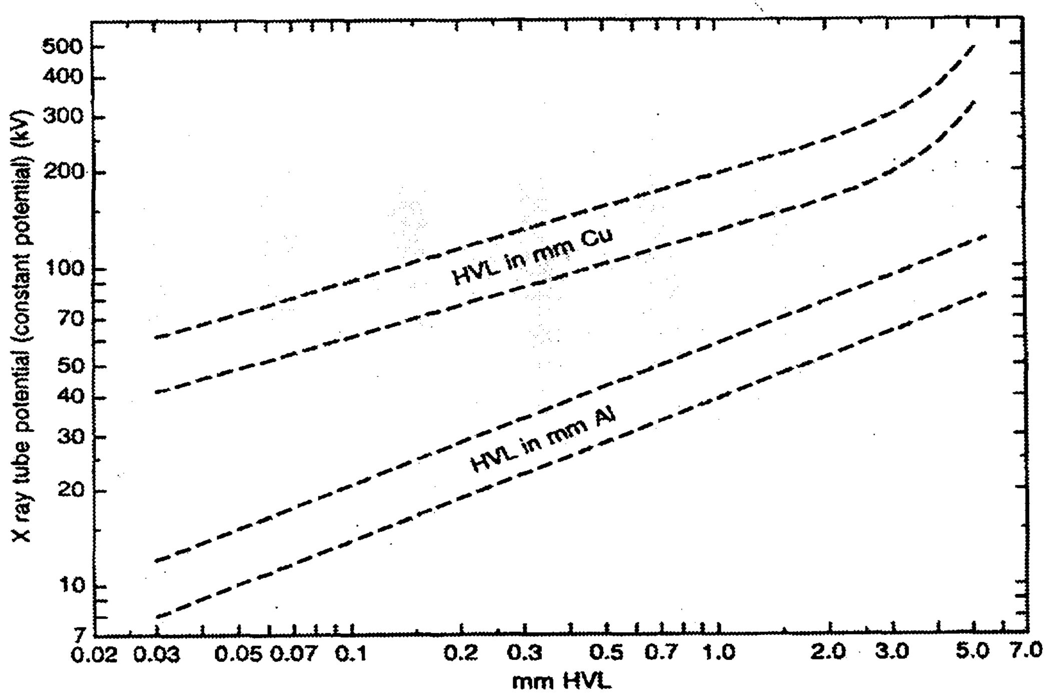

Fig. 1. Ranges of acceptable HVLs at various tube voltages (Fig. 3 of IAEA TRS 374).

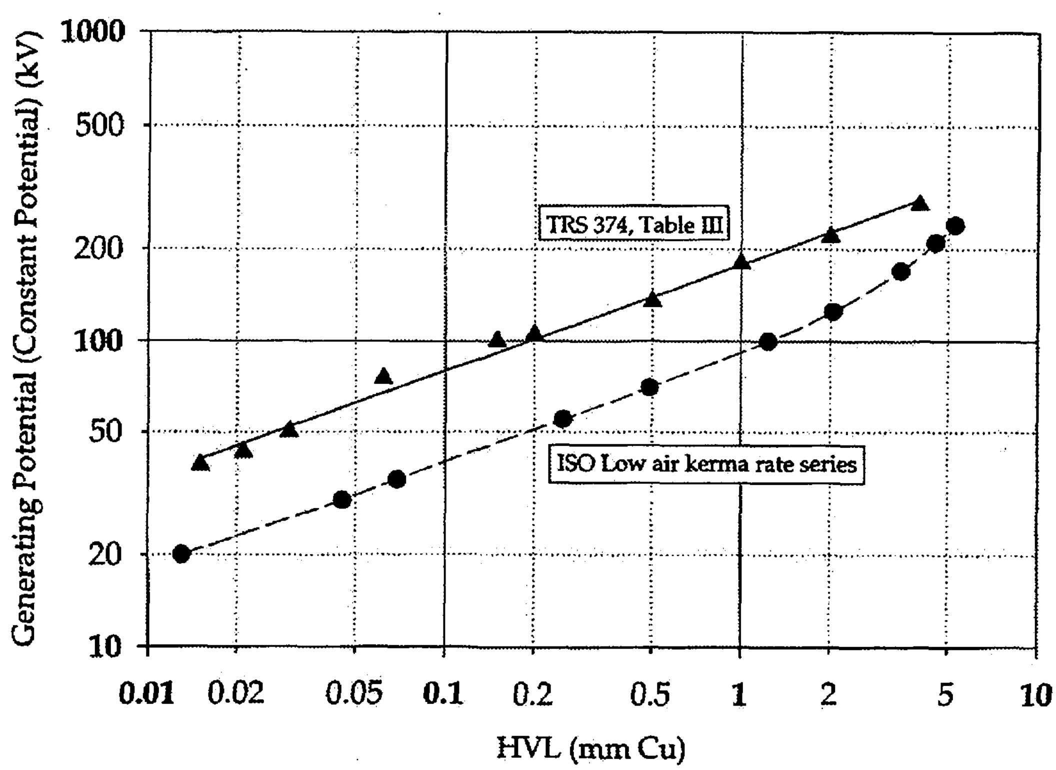

Fig. 2. Comparison of X-ray beam qualities suitable for calibrating dosimeters used in radiotherapy (taken from IAEA TRS 374) with beam qualities suitable for calibrating dosimeters used in radiation protection (taken from ISO Standard 4037).

Problems in devising new qualities

As mentioned earlier, the NPL qualities (and therefore those in TRS 374) are at standardised values of HVLs. This makes it easiest for users to interpolate between the qualities, but it does entail using some apparently strange kVs and filtrations, for example 0.5 mmAl HVL is obtained by using 41 kV and a 0.56 mmAl filter. If an SSDL found that this combination of kV and filtration did not give exactly 0.5 mmAl HVL, then it might be tempted to find a different combination. If so, a word of caution is necessary. This procedure is very time consuming, as it involves successive changes of kV and filtration, together with measurements of HVL and kerma rate, until the correct combination is found. Remember that increasing the kV increases both HVL and kerma rate, whereas increasing the filtration increases the HVL but decreases the kerma rate. Even when one has carried this out for a few qualities and become familiar with the procedure, to derive the correct combination for a single quality will still take not less than about three hours - about half a day's work.

This procedure also assumes that the SSDL possesses sheets of pure aluminium and copper and tin with a wide range of thickness down to at least 0.1 mm, and also an X-ray generator whose kV is continuously adjustable (i.e. not in steps). If the range of thickness is not available, then a quicker procedure is to take the nearest thickness available and to adjust the kV until it gives the required kerma rate, which must have been decided previously, and to check that the quality is within the range recommended in Fig. 1. If on the other hand various thickness of filters are available but that only fixed kVs are available on the X-ray generator which have been preset by the manufacturer, then choose the nearest kV and adjust the filtration until it gives the required kerma rate. Both of these procedures will give HVLs that are not standard values, but this is unavoidable. If the generator has pre-set kVs and only a few filtrations are available, then one can only try to find conditions within the suggested ranges given in Fig. 1, using the tables as a guide for kV-filter combinations.

Choice of filter material

Now a word about the choice of aluminium, copper or tin as filters. For qualities below 4.0 mmAl HVL, aluminium is the best material, because copper filters would be too thin and fragile. The aluminium should be at least 99.9% purity. For qualities above about 4.0 mm Al (0.15 mm Cu) HVL, aluminium becomes less effective in hardening the beam, and copper is a better material. ("Hardening" the beam means attenuating the lower photon energies more than the higher energies). However, copper has a K-absorption edge at 9 keV which allows it to transmit photons with a range of energies just below 9 keV, so a 1 mm thick aluminium filter must be added after (i.e. further from the target than) the copper filter in order to absorb the unwanted photons.

Similarly, for qualities above about 2.5 mm Cu HVL, copper becomes less effective at hardening the beam, so tin should be used instead. Because tin has a K-absorption edge at 29 keV, a copper filter (0.25 mm thickness would be satisfactory) should be added after the tin filter, followed by a 1 mm thick aluminium filter as before.

Inherent filtration

Finally, the tables in TRS 374 give typical inherent filtrations for the X-ray tubes. These are mainly for guidance when ordering the tubes. It is a feature of these X-ray tubes that the inherent filtration may gradually change during the lifetime of a tube because of target material being sputtered on to the X-ray window. It is necessary therefore to check about every six months that the beams are still giving the same HVLs and kerma rates that were determined when the conditions were set up. Slight adjustments to the kV or filtration may then be necessary to restore the original HVL. If large changes are found, this may mean that the surface of the target has been corroded by the electron beam, and the X-ray tube needs to be replaced.

Protection-level qualities

In principle it is easier to devise a set of qualities for calibrating protection-level dosimeters, because users do not normally want to interpolate between different HVLs. The first thing to do is to choose a convenient series of kVs, and the lowest kerma rate at which the secondary standard dosimeter will give repeatable results. Then at each kV increase the filtration until the kerma rate has been reduced to the chosen value. Start with aluminium filtration at the lowest kVs, then for increasing kVs move to copper, then tin, and then lead as the main filtration material, changing to a higher atomic number material when more than about 4 mm of the lower atomic number material would otherwise be required.

When it is necessary to use a higher atomic number material, some lower atomic number filtration should be left to absorb the photons transmitted through the K-absorption edge of the higher atomic number material, so that the order of filters along the beam starting from the target is lead, tin, copper and aluminium. As the work progresses the kVs should be plotted against HVL on log-log graph paper to confirm that they fall approximately on a straight line, except at the highest kVs when they will form a smooth curve similar to that shown in Fig. 2. Adjustments to the filtration can then be made if necessary.

However, some users may want their dosimeters to be calibrated using mean photon energy instead of HVL as the quality specifier. This can only be determined from a photon energy spectrum measured with a photon spectrometer, which may not be available. The alternative then is to use one of the sets of protection-level qualities published in ISO Standard 4037, which also contains the spectral widths and mean photon energies of the qualities. (ISO 4037: 1979. X and gamma reference radiation for calibrating dosimeters and dose-rate meters. International Organisation for Standardisation, CH-1211, Geneva 20, Switzerland)

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