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CALIBRATION OF PHOSWICH DETECTORS FOR ASSESSMENT OF PLUTONIUM IN LUNGS: THE METHODS OF FOUR LABORATORIES COMPARED

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Increasingly, laboratories engaged in nuclear energy projects are becoming equipped with X-ray detectors for the assessment of plutonium in lungs. This technique is potentially subject to large errors of calibration, owing to the low energies of the relevant X-rays (13-20 keV) and their consequent severe attenuation in the body. During 1978, three such laboratories in the UK were concerned to know to what extent their assessments might differ if, hypothetically, each were asked to estimate easily detectable lung deposits of ^{239}Pu in the same contaminated subjects. The three laboratories were (i) Atomic Energy Establishment, Winfrith (AEEW), (ii) Atomic Energy Research Establishment, Harwell (AERE) and (iii) National Radiological Protection Board, Harwell (NRPB). In such an exercise, if it could ever be performed, differences were to be expected, since the procedures of these three laboratories differed in important

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respects: their detectors viewed different regions of the thorax, and their assumed calibration factors (i.e. detector response per unit activity in lungs) were derived by different methods (Table 1). There had been indications that the differences ought not to be major, from previous collaboration, notably in studies with the same experimental subjects containing ^{103}Pd as a simulator for plutonium in lungs; however, these inferences were indirect, and it was of interest to compare estimates of ^{239}Pu itself.

In the absence of suitable contaminated subjects to participate in such an intercomparison, these laboratories considered the alternative scheme of circulating a phantom thorax containing plutonium-loaded lungs. The most suitable for these purposes was the phantom (Gr79) produced by the Lawrence Livermore Laboratory (LLL), specifically for use in calibration studies relevant to the assessment of low-energy photon emitters in male subjects. The phantom was constructed of materials closely matching the corresponding tissues in their X-ray attenuation properties, and every effort was made to ensure that it was anatomically realistic in such respects as the shapes and relative sizes of its organs, and the pattern of variation of tissue thickness in the chest wall. These attributes would be of obvious importance in any comparison of data from detectors which viewed different regions of the chest. LLL's phantom had another attraction: it was possible to vary the thickness of its frontal chest wall, and, to a limited extent, the relative amounts of muscle-and adipose-tissue substitutes in the chest wall, so that data for a range of physiques could be compared. LLL undertook to make the phantom available to the other laboratories, and collaborated in compiling and supervising an agreed program

of investigations.

Investigations with the Livermore phantom

In its basic form, the phantom (Gr79) possessed a frontal chest wall of 19-mm (average) thick muscle-equivalent material, with an embedded rib cage and sternum. Various close-fitting overlayers were provided so that other, thicker chest walls could be simulated, with the compositions set out in Table 2. A pair of lungs loaded uniformly with ^{239}Pu was provided. This plutonium contained small amounts of other Pu isotopes, the total plutonium content producing L X-ray emissions equal to those from 5.14 μCi ^{239}Pu. Approximately 18 ppm by weight of ^{241}Am, ingrown through decay of the ^{241} Pu impurity, was also present.

The three UK laboratories used their phoswich detectors (Table 1) to record photon energy spectra, typically covering the range 10-120 keV, from the basic phantom, with and without its various accompanying overlayers. The detectors were positioned according to each laboratory's contemporary practice (Table 1) in the routine assessment of plutonium in humans, except at AEEW. AEEW generally monitors subjects with a combination of phoswich and proportional counters viewing both the anterior and posterior surfaces of the chest. Since only the phantom's anterior chest wall thickness could be adjusted, data for the intended range of physiques could not be obtained with this combination. We shall present AEEW's data for a single phoswich only, viewing the frontal surfaces of the phantom (Table 1).

All of these spectra showed the expected peaks at 17 keV, from the L X-rays, and at 60 keV from the gamma rays of ^{241}Am. Duplicate measurements, but with

the phantom fitted with a different set of lungs containing only a known quantity of ^{241}Am, were made; these enabled net spectra (i.e. from plutonium only) to be derived from the first series of measurements. Each laboratory integrated its corrected spectra over an appropriate energy region encompassing most, or all, of the 17-keV X-ray peak. The resulting count rate was due predominantly to L X-rays from plutonium, but included scatter contributions from the K X-rays (∿100 keV) and 52-keV gamma rays of ^{239}Pu, whose relative importance increased with the thickness of material overlying the basic phantom.

Results and Discussion

The results are summarized in Table 2, for five values of mean chest wall thickness (CWT) between 19 and 43 mm. With the larger thicknesses, data are given both for muscle-equivalent material, and for a combination of muscle-and adipose-tissue substitutes. Note that the proportion of adipose tissue envisaged with these combinations increased with increasing total CWT, in a manner which may not be typical of humans.

The columns headed 'A' in Table 2 show each laboratory's assumed calibration factors, i.e. those considered appropriate to subjects of the total CWTs indicated. None of the laboratories habitually adjusted its calibration according to any estimate of the proportion of adipose tissue in the chest wall. To derive a calibration factor for a particular subject, AEEW ordinarily adjusts the factor indicated by its own phantom, the adjustment depending on the extent to which a subject's mean thickness of soft tissue overlying the rib cage (MSTT) differs from an assumed MSTT for the phantom (Ra67). For the pre-

sent purposes, AEEW's existing assumptions, concerning calibration factors as a function of MSTT, were adjusted to produce an assumed relationship with CWT. An empirical relationship (Ra67) between MSTT and the ratio Weight/Height ($^{W}/H$), and a correlation (unpublished) between CWT and $^{W}/H$ from ultrasonic measurements of LLL, together suggested that CWT and MSTT (both expressed in mm) were connected as follows

$$CWT = 0.77\ MSTT + 10.4 \quad \ldots\ldots \quad (1)$$

and this was used as a crude means of effecting the transformation required.

The data under 'B' in Table 2 are the calibration factors indicated by measurement of the Livermore phantom, containing in its lungs the L X-ray emitting equivalent of 5.14 μCi ^{239}Pu. The values of C (=$^{A}/B$) indicate the laboratory's assumed calibration factors relative to those indicated by this phantom. (It is implied in Table 2 that the LLL value for C is one.) Alternatively, if AEEW, AERE and NRPB regarded the Livermore phantom as a contaminated subject whose lung content was to be assessed by reference to existing calibration data, the reciprocals $^{1}/C$ would indicate these assessments, expressed as fractions of the actual burden.

The differences between A and B are most marked in AEEW's data. This laboratory's phantom predicts somewhat higher efficiencies for small values of CWT than does LLL's phantom; for large CWT, the reverse applies. We would expect to find higher efficiencies overall for AEEW's phantom, since its lungs (volume 2.5 l) are smaller than those in LLL's (3.9 l). In this situation, AEEW's phoswich, covering only a small region of the thorax, would view a greater proportion of the activity in the AEEW phantom than in the LLL phantom. The reversal of these

expected discrepancies, to give C<1 for large CWT, arises from the use of Equation 1 as a rough method of transforming AEEW's MSTT-based calibration into an assumed function of CWT. The foregoing discussion with regard to the size of the lungs does however invite a question of wider significance: whether one should expect, using any single basic phantom, to produce calibration data valid for subjects of all physiques, merely by adjusting for assumed differences in Livermore are also relevant in this connection. When the standard thickness (anterior-posterior) of the phantom's ^{241}Am-loaded lungs was reduced by 4 cm and 6 cm, there were increases of 13 per cent and 26 per cent respectively in the counting efficiency for 60-keV photons detected with 125-mm-diameter phoswiches viewing the anterior surfaces of the upper thorax. Larger increases in the efficiency for 13-20 keV photons would be expected, if the experiment were to be repeated with plutonium-labelled lungs.

NRPB's phantom indicated higher calibration factors that LLL's in most situations. The phantom lacked intrathoracic organs apart from the lungs; the absence of liver, heart and mediastinum could certainly produce greater X-ray emission from the phantom, leading to the effect found (C>1). We note also that Temex (St61) was used to represent the soft tissues of the chest wall. Temex is a good substitute for 'average' chest wall containing typical amounts of adipose tissue, but attenuates 17 keV X-rays less effectively than does muscle alone (Ne78c). This may explain why, in Table 2, NRPB's values of C are closest to unity for chest walls containing adipose-tissue substitute.

Two sets of values for C are given for AERE. We first consider the smaller numbers, ignoring the larger values C' in parentheses. If we regard C as an indication of how closely AERE's contemporary assumptions were supported by its

measurements of Livermore's phantom, there appears to be very good agreement in all cases, except for large CWT. This agreement is partly fortuitous. AERE's values of A in Table 2 were derived from measured X-ray detection efficiencies for volunteers containing ^{103}Pd, by methods outlined in Table 1. They therefore indicate only the true X-ray contributions to be expected from ^{239}Pu in lungs, whereas the values B recorded from LLL's phantom include the effects of scattered K X- and gamma rays which are substantial for large CWT. If these proportionate scatter components are assessed roughly from AERE's spectra of ^{239}Pu in LLL's phantom, and the values of A are correspondingly incremented before division by B, the values C' in parentheses are obtained. With their data revised in this way, AERE's calibration appears less consistent than previously with that indicated by LLL's phantom for chest walls whose soft tissue is wholly muscle-equivalent; however, it is now more consistent than before for chest walls containing adipose tissue. This is entirely reasonable, since the volunteers in AERE's calibration studies would have contained adipose tissue. The soft tissues of the human chest wall are reported (Do73) to contain typically 22 per cent of adipose tissue; in the four instances (Table 2) where adipose-tissue substitute was present in the phantom's chest wall, the adipose/muscle ratio increased from 11 per cent for CWT = 24.5 mm, to 28 per cent for CWT = 43.4 mm.

Viewing the project as an investigation of the consistency of calibration procedures at AEEW, AERE and NRPB, we see no reason to be discouraged by the outcome. The values of C in Table 2 (C' in the case of AERE) show much less than a factor of two interlaboratory variation, except for the thinnest and thickest chest walls considered. Much larger interlaboratory differences emerged

from a previous comparison of calibration techniques, which included methods based on commercially produced phantoms (Ne78a). We do not know whether the results in Table 2 reflect the relative assessments of easily detectable ^{239}Pu which AEEW, AERE and NRPB would make in the same contaminated humans. We have noted the difficulties of translating AEEW's MSTT-based calibration into a function of CWT, and we have commented that the size of the lungs is one potentially important factor affecting X-ray counting efficiencies, particularly for laboratories using detectors of small area. Another such factor, with a similar bearing on the practical relevance of this comparison, is the extent to which the uniform distribution of plutonium in the LLL phantom's lungs reflected a 'typical' distribution of plutonium present in human lungs, if indeed a 'typical' distribution could be said to exist. An unrealistic distribution in the phantom, through its effect on the pattern of variation of X-ray flux over the surface of the chest, could distort the relative response of detectors viewing different regions.

AERE's values of C^1 (Table 2) are close to unity in the instances of most relevance. These embody the results of calibration studies in vivo and so it is tempting to conclude that in all important respects, including the pattern of distribution in the lungs, the LLL phantom is satisfactory; other data (Ne80) for a different geometry, showing close agreement between X-ray detection efficiencies for ^{103}Pd in vivo and those for ^{103}Pd in the phantom, would appear to support this. However these latter data in particular relate to detectors of large areas, and they may conceal local inconsistencies in the regions viewed by the smaller detectors of AEEW and NRPB.

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TABLE 1

SUMMARY OF METHODS EMPLOYED BY UK LABORATORIES IN THIS INTERCOMPARISON

LAB	EQUIPMENT AND MEASUREMENT GEOMETRY (in all cases detectors were positioned as close as possible to the body)	BASIS OF CALIBRATION
AERE	200-mm-diameter phoswich, central over mid-sternum of supine subject	X-ray count rates were recorded from volunteers whose lungs contained independently known amounts of ^{103}Pd incorporated in 5-μm polystyrene particles (Ne78a); adjustments were made for the body's differential attenuation of X-rays from ^{103}Pd and ^{239}Pu (Ne78b); the resulting calibration factors were correlated with chest wall thickness.
AEEW	125-mm-diameter phoswich, central over mid-sternum (normal counting regime employs a more sensitive system of phoswich detectors and proportional counters viewing anterior and posterior surface of thorax - see text)	X-ray counts recorded from a phantom (Sp64) with lungs uniformly loaded with ^{239}Pu. Ordinarily, the resulting calibration is adjusted according to the subject's mean thickness of soft tissue (MSTT) overlying the rib cage, estimated from correlations (Ra67) between. MSTT and anatomical parameters; modified procedures were necessary in these investigations (see text).
NRPB	Two 125-mm-diameter phoswich detectors, one viewing each lung, located tangentially to clavicle and sternum	Interim calibration according to chest wall thickness, obtained with an incomplete phantom (Fr77). Phantom consists of lungs with distributed point sources of ^{239}Pu, inside a human thoracic cage, with adjustable thickness of Temex (St61) as chest wall. No other intra-thoracic organs.

TABLE 2

CALIBRATION DATA FOR ASSESSMENT OF ^{239}Pu IN LUNGS

MUSCLE mm	ADIPOSE mm	ADIPOSE / TOTAL	AEEW (12-25 keV) A	AEEW B	AEEW C	AERE (10-33 keV) A	AERE B	AERE C (C')	NRPB (11-25 keV) A	NRPB B	NRPB C
19.0	0	0	82	41	2.0	85	87	1.0 (1.1)	148	98	1.5
24.5	0	0	40	22	1.8	50	50	1.0 (1.2)	84	55	1.5
21.7	2.8	0.11		24	1.7		52	1.0 (1.1)		58	1.4
30.0	0	0	19	14	1.4	29	27	1.1 (1.3)	48	30	1.6
24.5	5.5	0.18		16	1.2		33	0.9 (1.1)		37	1.3
35.4	0	0	9.2	7.7	1.2	17	18	0.9 (1.3)	29	18	1.6
27.2	8.2	0.23		12	0.8		24	0.7 (0.9)		25	1.2
43.4	0	0	3.2	4.2	0.8	7.5	9.8	0.8 (1.3)	15	9.2	1.6
31.2	12.2	0.28		6.4	0.5		14	0.5 (0.8)		14	1.1

A = Counts/min/μCi ^{239}Pu assumed by laboratory for a subject of the same total chest wall thickness as the phantom

B = Counts/min/μCi recorded by laboratory from known ^{239}Pu activity in the Livermore phantom

C = A/B

C' = See text