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WHOLE BODY COUNTER EFFICIENCY CALCULATIONS FOR DISTRIBUTED SOURCES IN A HUMAN PHANTOM

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ABSTRACT

The space and energy dependence of the full energy peak efficiency of the 6" x 4" NaI/Tl/ detector of a whole body counter was calculated by computer from input data measured on point sources. By volume integration of this empirical function, the efficiency of the counter was evaluated for a BOMAB-type human phantom. Calculations were carried out for uniformly distributed sources with gamma energies of 0.1-2.0 MeV, in chair, arc and scanning geometries. The calculations were extended to cases of activity confined in geometrically well-defined organs within the phantom. Measurements performed to verify the calculated values showed a better than ± 4% agreement.

РЕЗЮМЕ

Опытным путем, с помощью ЭВМ, была определена зависимость эффективности 6" x 4" NaI/Tl/ детектора счетчика от энергии и координат места точечного источника. Путем интегрирования по объему этой эмпирической формулы была определена эффективность счетчика для фантома человека типа "BOMAB". Подсчеты были проведены также и методом стандартного кресла, дуги и скенирования в случае однородного распределения источников, в интервале 0,1-2,0 Мэв. Метод может применяться также и в случае неоднородного распределения, когда источник в фантоме расположен внутри геометрически хорошо описываемого органа. Разница между рассчитанными данными и результатами измерений, проведенных для проверки расчетов составила менее ±4%.

KIVONAT

Pontforrásokkal végzett mérések alapján számitógép segitségével empirikus uton előállitottuk egy egésztestszámláló berendezés 6" x 4" NaI/Tl/ detektorának teljes energia csucs hatásfokát az energia és a pontforrás helykoordinátáinak függvényében. Az igy nyert formula térfogati integrálásával meghatároztuk a berendezés hatásfokát egy BOMAB tipusu emberutánzó fantom esetére. A számitásokat homogén forráseloszlást feltételezve 0.1-2.0 MeV energiaintervallumban szék, iv és scanning geometriáknál egyaránt elvégeztük. Megmutatjuk a módszer alkalmazhatóságát olyan inhomogén eloszlás esetére is, amikor a forrás a fantomon belül csupán egy geometriailag jól meghatározható szervben található. A számitásokat mérésekkel is ellenőriztük. A mért és számitott hatásfokok közötti eltérés <± 4%-nak adódott.

INTRODUCTION

The calibration of whole body counters for given measurements is usually performed with a human phantom or, in favourable cases, in vivo. Such calibrations procedures are impracticable if one wants to establish the optimum measuring geometry or the counting efficiency as a function of variable parameters over a wide range of their values so as to be able to use the counter for a variety of measurements. In this case it is the most expedient to work out some calculation method permitting the efficiency to be evaluated in terms of the relevant parameters. The efficiency calculation to be described in the present report was formulated for the NS-206 Whole Body Counter of the Central Research Institute for Physics.[1] Using as input data values measured on point sources of different energies, the ICT-1905 computer was programmed to calculate the full energy peak efficiency of the 6" x 4" NaI/Tl/detector of the counter in terms of the energy and spatial coordinates of a point source P.[2] The function in three variables calculated by the computer has the form

$$\eta^{(P)}(r,\varphi,E) = \frac{1}{r^2}\left\{\exp\left[p_1 + p_2E + p_3E^2\right] - \varphi\cdot\exp\left[p_4 + p_5E + p_6E^2\right]\right\} + \frac{1}{r^4}\left\{p_7 + \frac{p_8}{E} + \varphi\left(p_9 + \frac{p_{10}}{E}\right)\right\} \qquad /1/$$

where p_{1-10} are constants, r and φ /20 cm $\leq r \leq$ 160 cm; $0 \leq \varphi \leq 0{,}44\pi$/ are the cylindrical coordinates of point P in a rectangular Cartesian coordinate system in which the origin O and the OX axis coincide with the geometrical centre and axis of symmetry of the detector, respectively. E is the gamma energy /100-2000 keV/.

This empirical function was already used to calculate and compare counting efficiencies for point sources in different geometries applied in whole-body counters.[3] Here the results obtained for distributed sources in a human phantom are reported.

CALCULATION

The calculation considers uniformly distributed sources and source-free attenuating media defined by the finite series $T_1, T_2, \ldots, T_j, \ldots, T_n$

and $T_{n+1},..,T_N$, respectively, in all possible detector positions $O_1,O_2,..,O_i,..,O_m$ determined by a well-defined geometry. For fixed i and j we can substitute $\eta_{ij}^{(P)} = \eta^{(P)}$ in eq./1/ for all $P/x,y,z/ \in T_j$.

For an arbitrary source, T_j, the full energy peak efficiency of the detector with geometrical centre O_i can be expressed as

$$\eta_{i,j}(E) = \frac{1}{V_j} \iiint_{T_j} \eta^{(P)}(r,\varphi,E) \exp\left[-\mu(E)\, s(x,y,z)\right] dx\, dy\, dz \qquad /2/$$

where $r = /x^2+y^2+z^2/^{1/2}$, $\varphi = \text{arctg}\,\frac{/y^2+z^2/^{1/2}}{x}$

V_j is the volume of T_j
μ is the total attenuation coefficient[4] /for water see Table 3/
s is the attenuation path length /the summed length of sections in the regions $T_k/k = 1,2,..,N/$ of the straight line O_iP.

The arithmetic means of the functions

$$\eta_i(E) = \frac{1}{V} \sum_{j=1}^{n} V_j\, \eta_{ij}(E) \qquad \left(V = \sum_{j=1}^{n} V_j\right) \qquad /3/$$

and

$$\eta(E) = \frac{1}{m} \sum_{i=1}^{m} \eta_i(E) \qquad /4/$$

give the full energy peak efficiencies for a cylindrical detector with fixed geometrical centre O_i for the series $\{T_j\}$ /:eq./3/:/ and for the system defined by the series $\{O_i\}$ and $\{T_j\}$ /:eq./4/:/, respectively.

Taking T_j to be an elliptic cylinder and the BOMAB-type human phantom to be composed of T_j elements $/1 < j < n = 10/$, considered as parts of the body /phantom dimensions are listed in Table 1./, then the full energy peak efficiency of the counter for chair /Fig. 1a/ and arc /Fig. 1c/ geometries can be approximated by function /3/. The efficiency for scanning geometry η^{sc} /Fig. 1b/ is given by function /4/. A more uniform positional dependence can be obtained with the so-called scanning-end-stop method, with which the full energy peak efficiency is approximated by a function of the form

$$\eta^{sce}(E) = \frac{1}{1 + 2\tau/t} \left\{\eta^{sc}(E) + \frac{\tau}{t}\left[\eta_1(E) + \eta_m(E)\right]\right\} \qquad /5/$$

where t is the scanning time, and τ is the measuring time at the end points. For $\tau = 0$, function /5/ obviously reduces to /4/.

Table 1. *Human phantom data*

body region	shape	dimensions (cm)			volume (l)
		2a	2b	m	
head	elliptical cylinder	14	19	20	4.18
neck	cylinder	13	13	10	1.33
upper trunk	elliptical cylinder	30	21	40	19.78
lower trunk	elliptical cylinder	36	20	20	11.30
arm (2)	cylinder	10	10	60	4.71
upper leg(2)	cylinder	15	15	40	7.07
lower leg(2)	cylinder	12	12	40	4.52

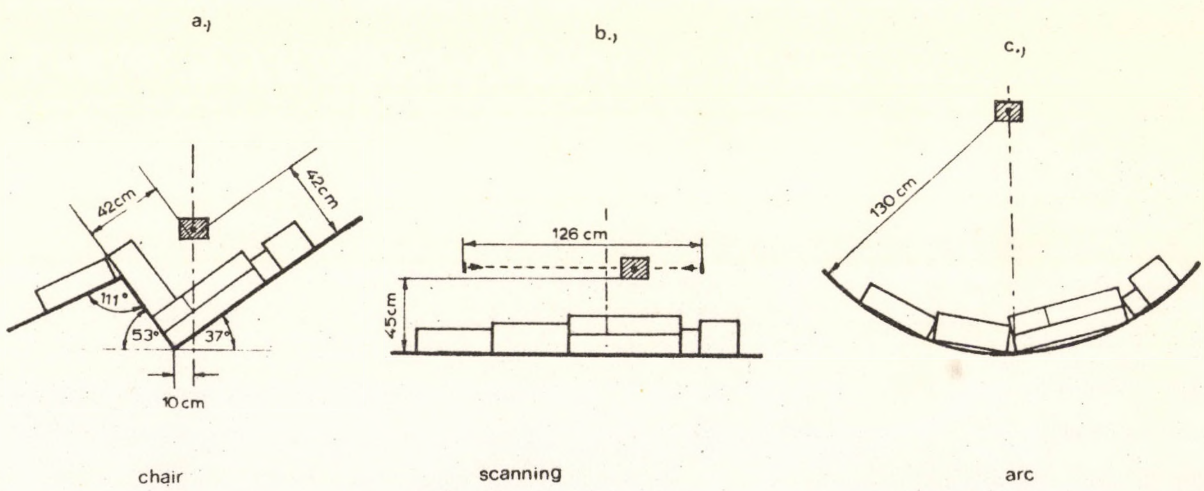

Fig. 1

Whole body counting geometries used in the calculations

The calculations were carried out for m = 16 at equidistant points of the 126 cm long scanning orbit at values of τ/t = 0 or 0,14.

Functions /3/ and /5/ were calculated by procedures worked out for ALGOL programs. Integrals of the form of eq./2/ over cylinders were reduced by coordinate transformation to integrals over 3-dimensional intervals, which were treated as a succession of simple integrals using, as a good approximation, Romberg's numerical quadrature method.

Expressions/3/ and /5/ apply to a large variety of systems. The efficiency calculation for a homogeneous system /uniformly distributed sources/ is achieved by taking N = n.

The efficiency calculation was also performed for an inhomogeneous system - a thyroid neck phantom /N > n = 1, i.e. a single distributed source with the rest of the body regarded as attenuation medium./

EXPERIMENTAL

The calculated efficiency values were verified by measurements performed in different geometries at a few energies on a polyethylene BOMAB phantom filled with a dilute solution of the standard source. The inhomogeneous system was simulated with the thyroid-neck phantom suggested by the National Bureau of Standards /USA/ measured along with the water-filled human phantom. The activity of the standard sources introduced into the phantom was found to be accurate to better than ± 2%. The full energy peak counts were determined by the method suggested by Hitchinson and Walker[5]. The overall error of the measurement arising from the statistical error and the inaccuracy of the full energy peak determination was less than ± 3%.

RESULTS

A comparison of the predicted and measured efficiency values at the energies used for the verification is presented in Table 2. The efficiency values calculated for uniformly distributed sources in human phantom considered in different measuring geometries and for energies from 100 to 2000 keV are listed in Table 3. The efficiency vs energy curve plotted from the calculated values is shown in Fig. 2.

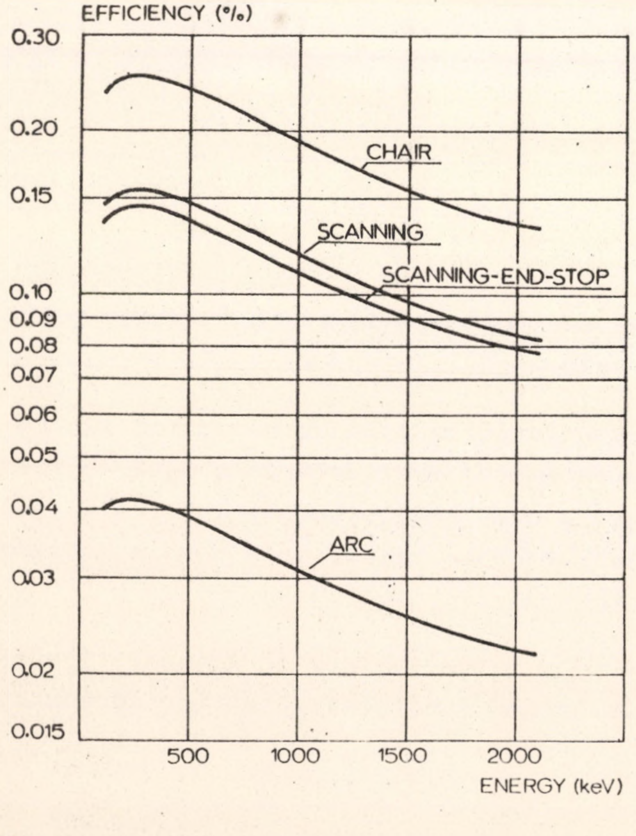

Fig. 2

Energy dependence of the calculated full energy peak efficiency for human phantom in different measuring geometries

Table 2

Comparison of the measured and calculated full energy peak efficiency values

geometry	E(keV)	efficiency (%)		rel.difference(%)
		measured	calculated	
chair	159	0.252	0.247	- 2.0
	364	0.258	0.250	- 3.1
	662	0.216	0.223	+ 3.2
	1460	0.161	0.160	- 0.6
scanning	662	0.135	0.138	+ 2.2
	1460	0.100	0.099	- 1.0
scanning--end-stop	662	0.132	0.128	- 3.0
	1460	0.091	0.093	+ 2.2
arc	1460	0.0253	0.0262	+ 3.6
chair, activity in the thyroid	364	0.546	0.557	+ 2.0

DISCUSSION

It can be seen from Table 2 that the efficiency of whole body counters can be predicted by the described method to satisfactory accuracy for any of the usual geometries and energies.

The curve of Fig. 2 can be used to directly read off the efficiency for contaminant activities of known energy presuming them to be uniformly distributed.

The calculations furnished highly interesting data on the geometry and energy dependence of the counting efficiency for the different body regions, but we can not go into details. Furthermore, it can be stated that this method of efficiency calculation is also suitable for predicting the counting efficiency for the activity of any geometrically well-defined organ embedded in the phantom.

Table 3. Calculated full energy peak efficiencies for uniformly distributed sources in human phantom

energy (keV)	total lin. attenuat. coeff. (cm^{-1})	e f f i c i e n c y (%)			
		chair	scanning	scanning-end-stop	arc
100	$1.68 \cdot 10^{-1}$	$2.37 \cdot 10^{-1}$	$1.46 \cdot 10^{-1}$	$1.36 \cdot 10^{-1}$	$4.00 \cdot 10^{-2}$
150	$1.49 \cdot 10^{-1}$	$2.47 \cdot 10^{-1}$	$1.52 \cdot 10^{-1}$	$1.42 \cdot 10^{-1}$	$4.13 \cdot 10^{-2}$
200	$1.36 \cdot 10^{-1}$	$2.51 \cdot 10^{-1}$	$1.55 \cdot 10^{-1}$	$1.44 \cdot 10^{-1}$	$4.18 \cdot 10^{-2}$
300	$1.18 \cdot 10^{-1}$	$2.52 \cdot 10^{-1}$	$1.55 \cdot 10^{-1}$	$1.45 \cdot 10^{-1}$	$4.15 \cdot 10^{-2}$
400	$1.06 \cdot 10^{-1}$	$2.46 \cdot 10^{-1}$	$1.52 \cdot 10^{-1}$	$1.42 \cdot 10^{-1}$	$4.05 \cdot 10^{-2}$
500	$9.67 \cdot 10^{-2}$	$2.39 \cdot 10^{-1}$	$1.47 \cdot 10^{-1}$	$1.37 \cdot 10^{-1}$	$3.91 \cdot 10^{-2}$
600	$8.95 \cdot 10^{-2}$	$2.29 \cdot 10^{-1}$	$1.42 \cdot 10^{-1}$	$1.32 \cdot 10^{-1}$	$3.75 \cdot 10^{-2}$
800	$7.86 \cdot 10^{-2}$	$2.10 \cdot 10^{-1}$	$1.30 \cdot 10^{-1}$	$1.21 \cdot 10^{-1}$	$3.44 \cdot 10^{-2}$
1000	$7.07 \cdot 10^{-2}$	$1.92 \cdot 10^{-1}$	$1.19 \cdot 10^{-1}$	$1.11 \cdot 10^{-1}$	$3.14 \cdot 10^{-2}$
1500	$5.75 \cdot 10^{-2}$	$1.57 \cdot 10^{-1}$	$9.78 \cdot 10^{-2}$	$9.11 \cdot 10^{-2}$	$2.58 \cdot 10^{-2}$
2000	$4.94 \cdot 10^{-2}$	$1.37 \cdot 10^{-1}$	$8.58 \cdot 10^{-2}$	$8.00 \cdot 10^{-2}$	$2.24 \cdot 10^{-2}$

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