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IN-VIVO MEASUREMENT OF THE GAMMA AND NEUTRON DOSE RATE ON PATIENTS WITH ^{238}Pu PACEMAKERS IMPLANTED

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Abstract:

In vivo measurements on Medtronic pacemaker were performed with a proportional counter for the measurement of neutrons and with thermoluminescence dosimeters and a scintillation dose rate meter for gamma measurements. The paper discusses the technique of phantom calibration, the in-vivo measurement of the neutron emission rate and the estimation of dose equivalent. Results are presented for phantom and in-vivo measurement at different positions from the ^{238}Pu source. The dose equivalent rate from neutrons and gamma rays were measured on seven patients with ^{238}Pu-pacemakers implanted and were found to be 5.6 ± 0.1 mrem/h and 2.54 ± 0.5 mrem/h, respectively at the surface of the pacemaker in 1.25 cm distance from the center of the source.

Zusammenfassung

Es wurden in vivo Messungen an Medtronic Herzschrittmachern durchgeführt, wozu ein Proportionalzähler zur Messung der Neutronen sowie Thermolumineszenzdosimeter und Szintillationsdosisleistungsmesser zur Messung der Gammastrahlung eingesetzt wurden. Der Bericht diskutiert die Technik der Phantomkalibrierung, die in vivo Messung der Neutronenemissionsrate sowie die Ermittlung der Äquivalentdosis. Es werden Ergebnisse von Phantom- und in vivo Messungen in verschiedenen Abständen von der ^{238}Pu-Quelle wiedergegeben. Die Äquivalentdosisleistung von Neutronen-und Gammastrahlung wurde an 7 Patienten mit implantierten ^{238}Pu-Herzschrittmachern gemessen und ergab sich zu 5,6 ± 0,1 mrem/h bzw. 2,54 ± 0,5 mrem/h an der Oberfläche des Herzschrittmachers in 1,25 cm Abstand von der Quellenmitte.

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1. Introduction

The radiation burden from gamma rays and neutrons was measured on seven patients with ^{238}Pu pacemakers implanted. For dose rate measurement on the very body surface high-sensitive, direct-reading dose rate meters were used. These are a special kind of a scintillation dose rate meter for the gamma measurement and a large-area proportional counter for the neutron measurement. Special care had to be devoted to the calibration of the detectors placed in this measuring position. Additional measurement runs were required including ^{238}Pu and ^{252}Cf neutron sources of a known emission rate installed at different distances (detector-sources) to determine the influence of the body as well as the attenuation in the tissue with respect to fission neutrons and gamma rays. The maximum radiation burden of the patients on the surface of the pacemaker was found to be a dose equivalent of 5.6 ± 0.1 mrem/h for neutrons and 2.54 ± 0.5 mrem/h for gamma rays which is in good agreement to the results of other authors based on free air and phantom measurements.

2. Measurement of Gamma rays

2.1 Dose Rate Measurement

For direct measurement of the gamma dose rate a high-sensitive scintillation dose rate meter Type H 7201 with an indication of lower than 1 µR/h was used [1] allowing to measure the exposure

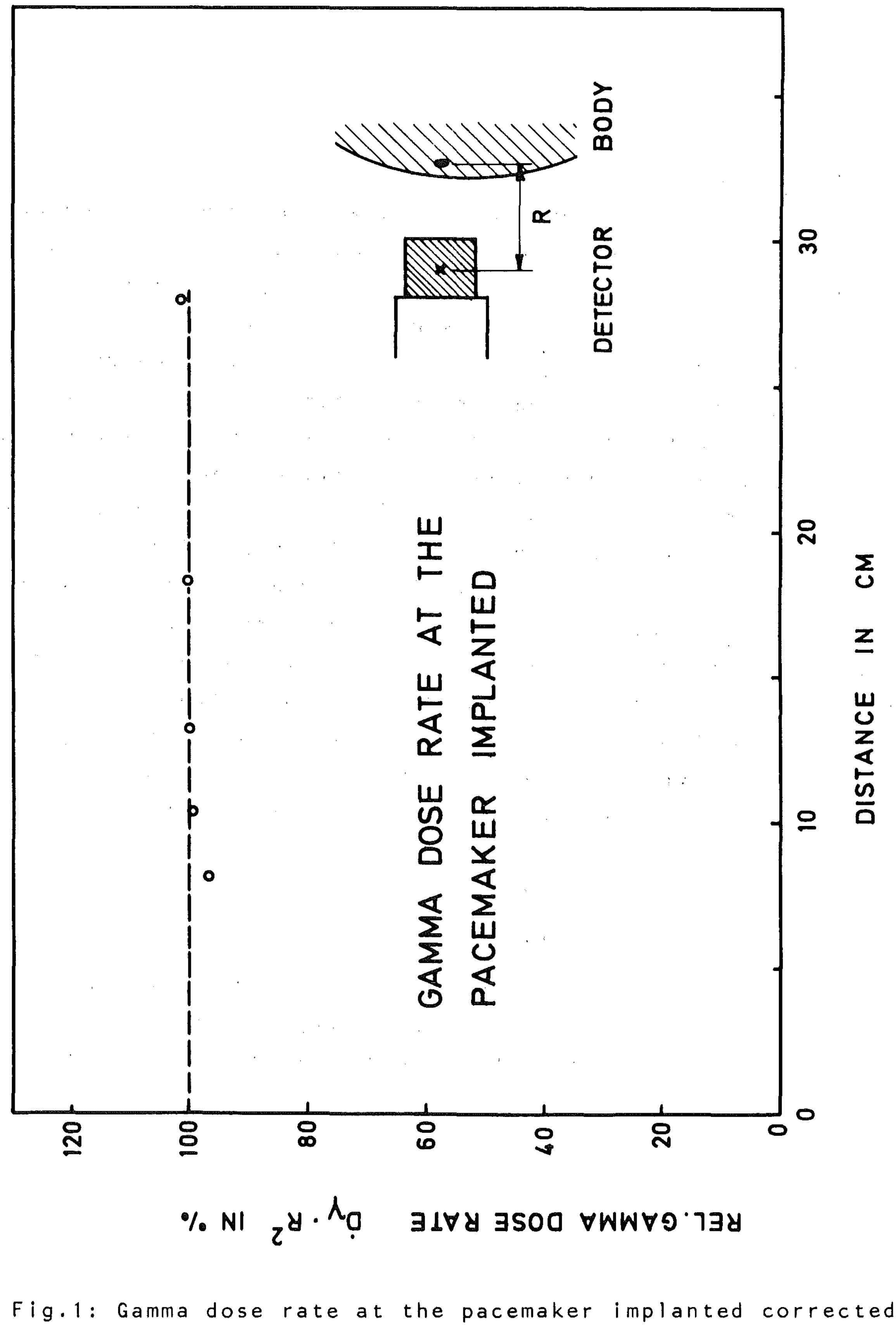

Fig.1: Gamma dose rate at the pacemaker implanted corrected for geometrical attenuation

rate practically energy independent in the range 25 keV to 1.2 MeV. To determine the gamma dose rate on the body surface a set of measurements were performed at distances of 0 to 50 cm from the surface of the patients. The measured dose rate was plotted as a function of the actual distance source-detector (see for example Fig.1), taking into account the thickness of tissue (direct measurement on one patient yielded 2 cm), the distance of the assumed ^{238}Pu point source from the surface of the pacemaker (1.25 cm), the distance of the detector surface from the detector central point (5 cm), and the natural background radiation level. Also in case of the relatively infavorable position on the body surface a square law could be found for all patients. The attenuation of gamma rays of 10 ± 1 % at 2 cm tissue depth was obtained by free air and phantom measurements with a non-implanted pacemaker. The dose on the surface of the pacemaker implanted was determined by graphic extrapolation to be 2.54 ± 0.5 mrem/h, taking into account the square law and the attenuation in the tissue.

2.2 Dose Measurement

For direct measurement of the gamma dose accumulated over a long time on the body surface of patient G, CaF_2:Dy dosimeters of the size 3 mm x 3 mm x 0.9 mm were exposed for two weeks at 14 positons immediately over the pacemaker. Additional ^{6}LiF and ^{7}LiF dosimeters served to measure thermal neutrons and gamma rays. The result of this series of measurements is represented in Fig.2. To record the maximum dose, the dosimeters had been exposed in an appropriate coordinate system parallel to the X and Y axes, respectively. The location of the ^{238}Pu source and, hence,of the dose maximum on the body surface could be determined in the positions 2.4 cm/2.3 cm. The dose rate of the pacemaker calculated for the body surface from the period of exposure was found to be 0.385 mrem/h with the LiF-dosimeter and 0.376 mrem/h with the CaF_2-dosimeter and was in good agreement with the measured result of the scintillation rate meter, which was 0.380 mrem/h.

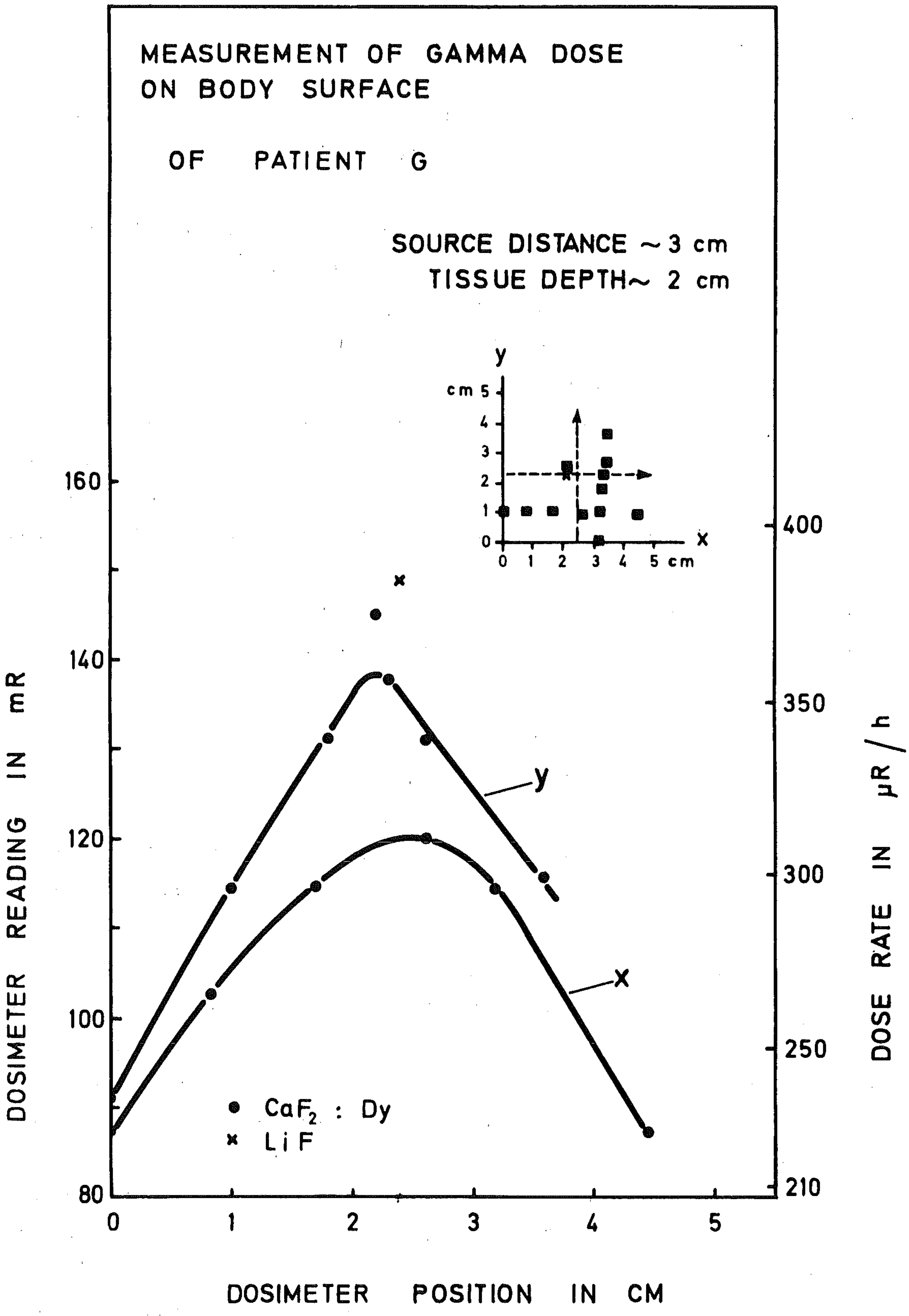

Fig. 2: TLD reading of gamma dose on the body surface of patient G

3. Measurement of Neutrons

3.1 Detector Characteristics

Fast neutrons were measured with a large-area proportional counter of the size 32 cm by 32 cm with butane gas flow in direct contact with the body surface of the patients. The counter used was a commercially available proportional counter employed in α/β activity and contamination measurements. Large-area proportional counters are able to detect fast neutrons via recoil nuclei generated in the hydrogenous counter gas as well as in the thin detector wall. The proportional counter consists of a narrow-meshed counting wire grid and is operated at high voltage of 2,100 V. In the absence of a plateau the increase in the counting rate-voltage characteristic is about 30 % per 100 Volt. The detection sensitivity of the proportional counter was found to be $7 \cdot 10^{-4}$ counts per neutron for an Am-Be source approximatly in 2π geometry. The background rate was about 5 cpm. A gamma background level of 1 R/h from a ^{60}Co source did not change the background rate. The count rate of the proportional counter was first calibrated to a neutron emission rate for the given geometry and then converted into the neutron flux density, taking into account the square law and the attenuation of the radiation in the body.

3.2 Phantom calibrations

To examine the body influence and the detection characteristics of the proportional counter, phantom measurements were carried out at different distances from the source and for tissue-equivalent plastic layers placed in between. ^{252}Cf and RaD-Be neutrons sources with higher emission rate were used which in addition have different effective neutron energies of 2.3 MeV and 4 MeV, respectively. Under free air condition the proportional counter covered with a thin plastic foil of 0.9 mg/cm^2 shows similar proporties with respect to both neutron sources (see Fig.3). Contrary to free air measurement the proportional counter shows an increased counting rate for RaD-Be neutrons compared to ^{252}Cf neutrons when lower thicknesses are involved

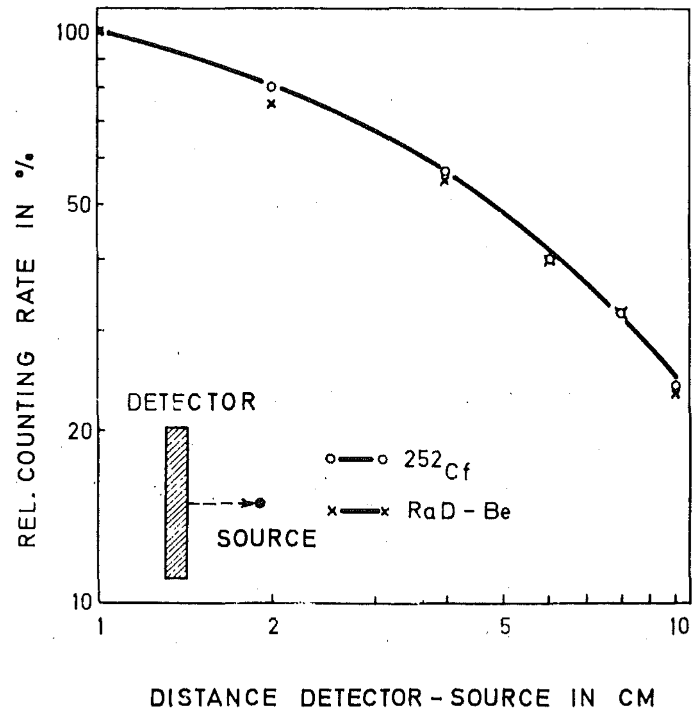

Fig.3: Counting rate-distance characteristic of the large-area proportional counter

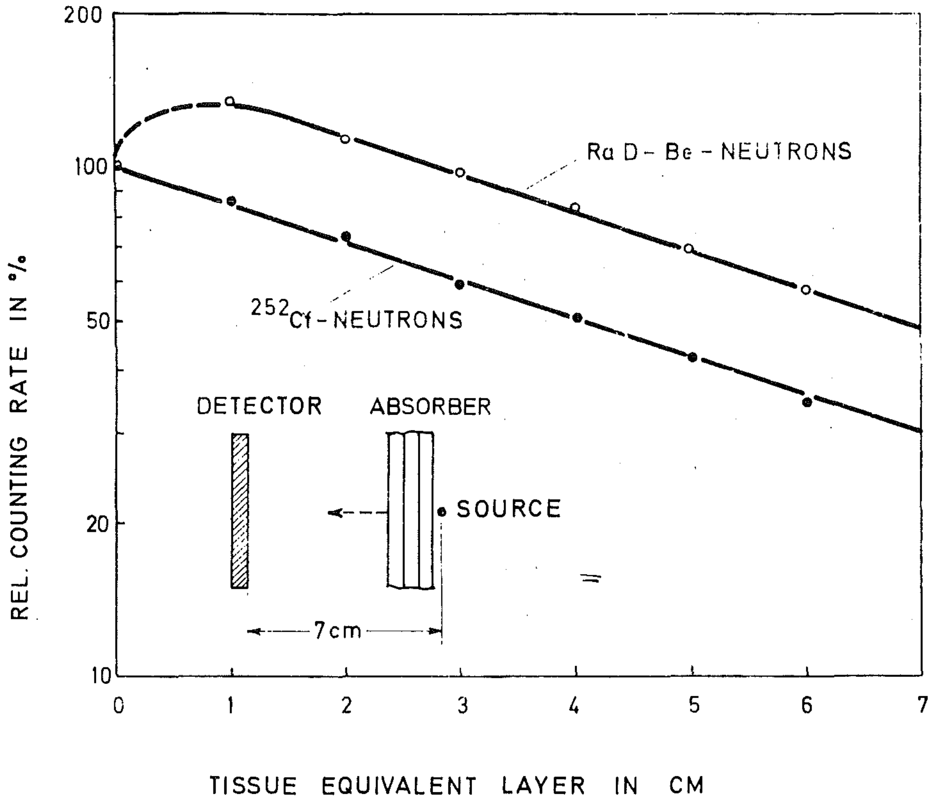

Fig.4: Attenuation in tissue of the neutron counting rate measured with the large-area proportional counter

(see Fig.4). Responsible for this buildup behaviour is a back-scattering of higher-energetic neutrons in the tissue-equivalent material.

Additional measurements performed with a ^{238}Pu capsule used for pacemakers showed that ^{238}Pu emits above all fission neutrons so that the fraction of higher-energetic (α,n) neutrons has not to be taken into account for the attenuation in tissue. Table 1 summarizes the counting rate of the proportional counter for different neutron sources placed at 1.25 cm from the proportional counter, both for free air measurement and a measurement behind a tissue layer of 3 cm thickness. The counting rate fractions resulting from ^{252}Cf and ^{238}Pu neutrons detected at 3 cm tissue depth differs by less than 10 %. Therefore, for in-vivo measurements of ^{238}Pu pacemakers calibration values were adopted which had been determined for ^{252}Cf neutrons in Figs.3 and 4.

Neutron detection with the proportional counter is practically independent of energy for the neutron energy distributions of interest here, both with respect to the measurement of the neutron emission rate and of the neutron flux density and the dose equivalent. The pertinent results of calibrations are presented in Table 2. The ^{244}Cm source is a plane source, the activity of which was not sufficiently known. The neutron flux density measured with the proportional counter differs from the value calculated from the known emission rate by less than 9 % for ^{238}Pu, ^{252}Cf and RaD-Be. Comparison measurements performed with a rem-counter of Anderson-Braun at 50 cm distance from the source yielded agreement within 5 % for ^{238}Pu and ^{252}Cf and within 14 % for RaD-Be for the dose equivalent reading of the rem-counter and the proportional counter.

3.3 Error Estimation

In the determination of the neutron dose rate via the counting rate of the proportional counter the statistical error must be considered above all which is about 10 % for 10 min of measuring

Table 1: Counting Rate of the Proportional Counter and Attenuation at 3 cm Tissue Depth

	Free Air		Phantom
Neutron Source	Counting Rate at 1.25 cm		+ 3 cm Tissue
	cpm	%	%
^{252}Cf	9550	100 ± 0,9	36.2
^{238}Pu	27.1	100 ± 3	33
3R0079N	15.3	100 ± 10	30
RaD-Be	280	100 ± 2	57

Table 2: Comparison of Nominal with Measured Neutron Flux Density

Neutron Flux Density at 1.25 cm					
Neutron	$n/cm^2\ s$			Relative Reading	
Source	Emission Rate	Prop. Count.[1]	Rem-Count.[2]	Prop.Count.	Rem-Count.
^{238}Pu	84	=84	79.5	100 %	100,5 %
^{252}Cf	2.75×10^4	2.96×10^4	2.98×10^4	107.5 %	114 %
^{244}Cm	1.4×10^4	1.74×10^4	1.66×10^4	124 %	124,5 %
RaD-Be	799	870	754	109 %	100,5 %

[1]) reading at 1.25 distance from the source

[2]) calibration with Am-Be-neutrons; measured at 53 cm distance

time. Other erroneous effects are produced by the assumption of an identical 2 cm tissue depth for all patients. For example, an increase of 0.5 cm in the tissue thickness and the detector-source distance, respectively, entails a reduction of the neutron dose by 7 % and 9 %, respectively. Individuel values of the effective detector-source distance can be directly derived from the results of an in-vivo gamma measurement. Referred to the actual source distance, the gamma values measured at different distances from the body surface follow a square law. However, because of the different attenuation of gamma rays and neutrons in tissue, the source distance evaluated on patients can not be transferred directly to the neutron measurement.

3.4 Measurement of the Neutron Emission Rate

The neutron emission rate is determined by comparison with a ^{238}Pu standard source S, using the same irradiation geometry as in the in-vivo measurement (see Fig.5). $N_F(c)$ is the counting rate in the free air at a distance c = 1.25 cm and $N_p(d)$ is the counting rate obtained on a phantom with the source placed at 2 cm tissue depth (d-c) and at a distance d = 3.25 from the source. In an in-vivo measurement the neutron emission rate is found to be

$$Q_S = a_P\, N_P(d) = a_F\, N_F(c) \qquad (1) \qquad \text{(calibration with standard source)}$$

$$Q = a_F \left(\frac{N_F(c)}{N_P(d)}\right)_S N_P(d) \qquad \text{(in-vivo measurement)}$$

We obtain $a_F = \left(\frac{Q}{N_F(c)}\right)_S$ in $\frac{\text{neutrons}}{\text{count}}$ by free air calibration

and $\left(\frac{N_F(c)}{N_P(d)}\right)_S = 2.08$ found from the ratio of free air and phantom counting rates of the proportional counter. The counting rate of the proportional counter is determined by the geometrical decrease (k_a), the buildup and attenuation in tissue. Therefore the counting rate in an in-vivo measurement is expressed by the equation

$$N_p(d) = k_a \; b(g) \; e^{-\alpha g} \; N_F(c) \qquad (2)$$

3.5 Measurement of the Neutron Flux Density

Using formula (1) and (2) the neutron flux density at the distance x from the center of the neutron source under free air conditions is given by

$$\Phi_F(x) = \frac{Q}{4\pi x^2} = \frac{a_P \; N_P(d)}{4\pi x^2} = \frac{a_F \; N_p(d)}{4\pi x^2 \; k_a \; b(g) \; e^{-\alpha g}} \qquad (3)$$

It is of special interest to estimate the neutron flux density on the surface of the pacemaker as the maximum value in the body of the patient and the neutron flux density on the body surface. In an in-vivo measurement the neutron flux density for a given distance x from the source is determined from the counting rate $N_P(d)$ on the patient, taking into account the free air calibration of the proportional counter after formula (2) and (3)

$$\Phi_T(x) = b(x-c) \; e^{-\alpha(x-c)} \; \Phi_F(x) \qquad (4)$$

$$\Phi_T(x) = \frac{a_F \; N_p(d)}{4\pi x^2 \; k_a} \; \frac{b(x-c)}{b(g)} \; e^{-\alpha(x-c-g)} \quad \text{for } x \leq d \qquad (5a)$$

$$\Phi_T(x) = \frac{a_F \; N_P(d)}{4\pi x^2 \; k_a} \quad \text{for } x > d \qquad (5b)$$

This yields for the flux density on the body surface with x=d

$$\Phi_T(d) = \frac{a_F \; N_P(d)}{4\pi d^2 \; k_a} = \frac{1.52 \; a_F \; N_P(d)}{4\pi d^2} = 0.695 \; N_P(d)$$

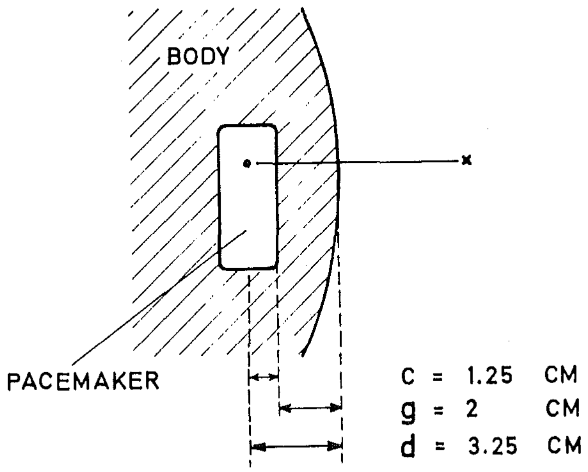

Fig.5: Measuring positions for the in-vivo measurement

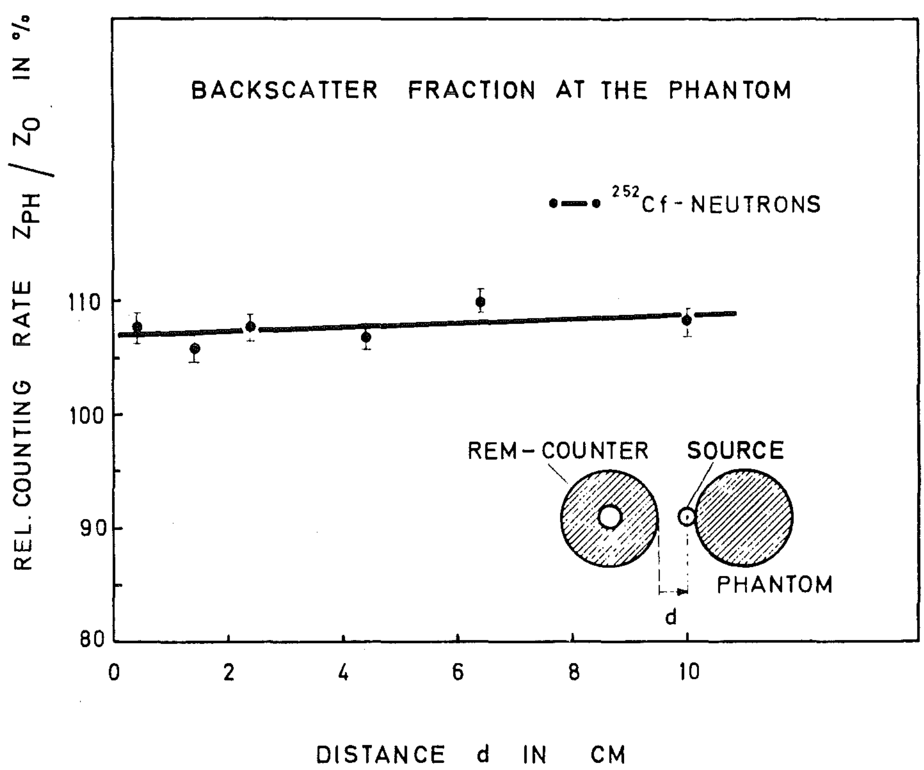

Fig.6: Backscatter fraction at the phantom measured with the rem-counter

and for the flux density on the surface of the pacemaker with x=c

$$\Phi_T(c) = \frac{a_F\ N_P(d)}{4\pi c^2\ k_a}\ \frac{b(0)}{b(g)\ e^{-\alpha g}} = \frac{2.08\ a_F\ N_P(d)\ b(0)}{4\pi c^2} = 7.1\ N_p(d)$$

where b(0) is practically the fraction of backscattering from the body on the very surface of the pacemaker, i.e., at a distance of 1.25 cm from the source center at 2 cm tissue depth. Additional measurements performed at the proportional counter with and without phantom, respectively, yielded b(0) = 1.1 ± 0.01. Similar results were obtained from measurements with the rem-counter (see Fig.6). These results agree well with the calculation of dose distribution in the immediate vicinity of a ^{252}Cf needle embedded in the tissue, which were performed by Auxier et al [2]. At a distance of 1 cm from the needle the neutron dose encountered differs by some 10 % from the corresponding kerma value found under free air conditions. However, at 0.5 cm in the tissue the dose has built up by 40 %. The pacemaker however is not surrounded by body tissue at these distances from the relatively thin disk source.

3.6 Estimation of the Dose Equivalent Rate

In a first approximation a fission neutron spectrum can be assumed for a ^{238}Pu source. Measurements of the neutron energy distribution of $^{238}PuO_2$ sources reveal a peak at 2.3 MeV which is caused by additional ^{18}O (α,n) reactions [3, 4]. The corresponding fluence-dose conversion factors for fission neutrons, for 2.5 MeV neutrons and for Am-Be-neutrons are listed in Table 3. Following computations were made for the determination of the dose equivalent rate:

1. Fluence-kerma conversion factor for 2.5 MeV neutrons with respect to the fluence assayed in the body on the surface of the pacemaker as well as a quality factor Q = 9.

2. Fluence-dose equivalent conversion factor for 2.5 MeV neutrons according to the NCRP recommendation with respect to the fluence encountered in free air.

Table 3: Fluence-Dose Conversion Factors

	For Kerma d_K rad cm^2	For Absorbed Dose* d_H / Q rad cm^2	Q	For Dose Equivalent d_H rem cm^2	
2 MeV	3.0×10^{-9}	3.63×10^{-9}	8.8	3.19×10^{-8}	ANSI (1970) [6]
		4.27×10^{-9}	9.3	3.96×10^{-8}	ICRP (1973) [5]
2,5 MeV	3.3×10^{-9}	3.85×10^{-9}	9	3.47×10^{-8}	NCRP (1971) [7]
		4.35×10^{-9}	8	3.48×10^{-8}	ICRP (1964) [8]
^{238}Pu	3.04×10^{-9}	4.06×10^{-9}	9.1	3.7×10^{-8}	Kluge et.al [9]
Am-Be	3.66×10^{-9}	4.66×10^{-9}	7.6	3.54×10^{-8}	Kluge et.al [4]
$^{235}U(n,f)$	2.69×10^{-9}	3.77×10^{-9}	9.52	3.59×10^{-8}	Kluge et.al [4]
^{252}Cf	2.81×10^{-9}	3.9×10^{-9}			Kluge et.al [9]
	3.0×10^{-9}				Stone et.al [13]

*) Absorbed dose at a tissue depth characterized by the maximum dose equivalent

Table 4: Calibration Factors for the Proportional Counter used for In-vivo Measurements of Neutrons

Counting rate of the proportional counter		
	Np cpm at 3.25 cm depth	
Probability of detection		
	$\alpha_F = 3.67 \times 10^3$ neutrons per count	
Emission rate		
	$Q = 1.27 \times 10^2 \times Np$	s^{-1}
Body surface		
	$\Phi_T = 0.695$ Np	$n/cm^2\ s$
	$\dot{D} = 0.0745 \times Np$	mrem/h
Surface of pacemaker		
	$\Phi_T = 7.10 \times Np$	$n/cm^2\ s$
	$\dot{D} = 0.76 \times Np$	mrem/h

3. Fluence-dose equivalent conversion factor for the ^{238}Pu spectrum measured according to Kluge and Zille with respect to the fluence encountered in the free air.

The conservative calculation according to [2] and [3] is based on the maximum absorbed dose or dose equivalent found in a 30 cm thick slab of soft tissue with parallelly incident neutrons. This means overestimation of the dose equivalent, since with a implanted neutron point source the comparable dose attenuation curve in the tissue decreases more rapidly at small distances from the source than with a broad beam of parallelly incident neutrons.

This is also confirmed by neutron isodose curves in tissue calculated by Auxier et al [2] for a ^{252}Cf needle. The assumption Q = 9 is equally conservative, since according to the ICRP-recommendations the definition of Q is also based on the maximum dose equivalent in a 30 cm thick slab of tissue [5], whereas, the dose equivalent close to the pacemaker is smaller.

Calculation according to 1. yields a value of 5.6 mrem/h for the dose equivalent rate on the surface of the pacemaker. In comparison, a value higher by 6.5 % and 13 %, respectively, is obtained using calculations 2. and 3.

Due to the low detection sensitivity for neutrons, direct measurements of the dose equivalent rate by means of the rem-counter was possible only with the reference source. Considering the buildup and attenuation of neutrons in 2 cm of tissue (see Fig.7) and the backscattered fraction of neutrons from the phantom (see Fig.6) 0.89 times the free air value is found for the dose equivalent on the surface of the body. In the case of the proportional counter no buildup appears in the first tissue layers which gives only 0.8 times the free air value. The dose equivalent rate measured with the rem-counter is therefore

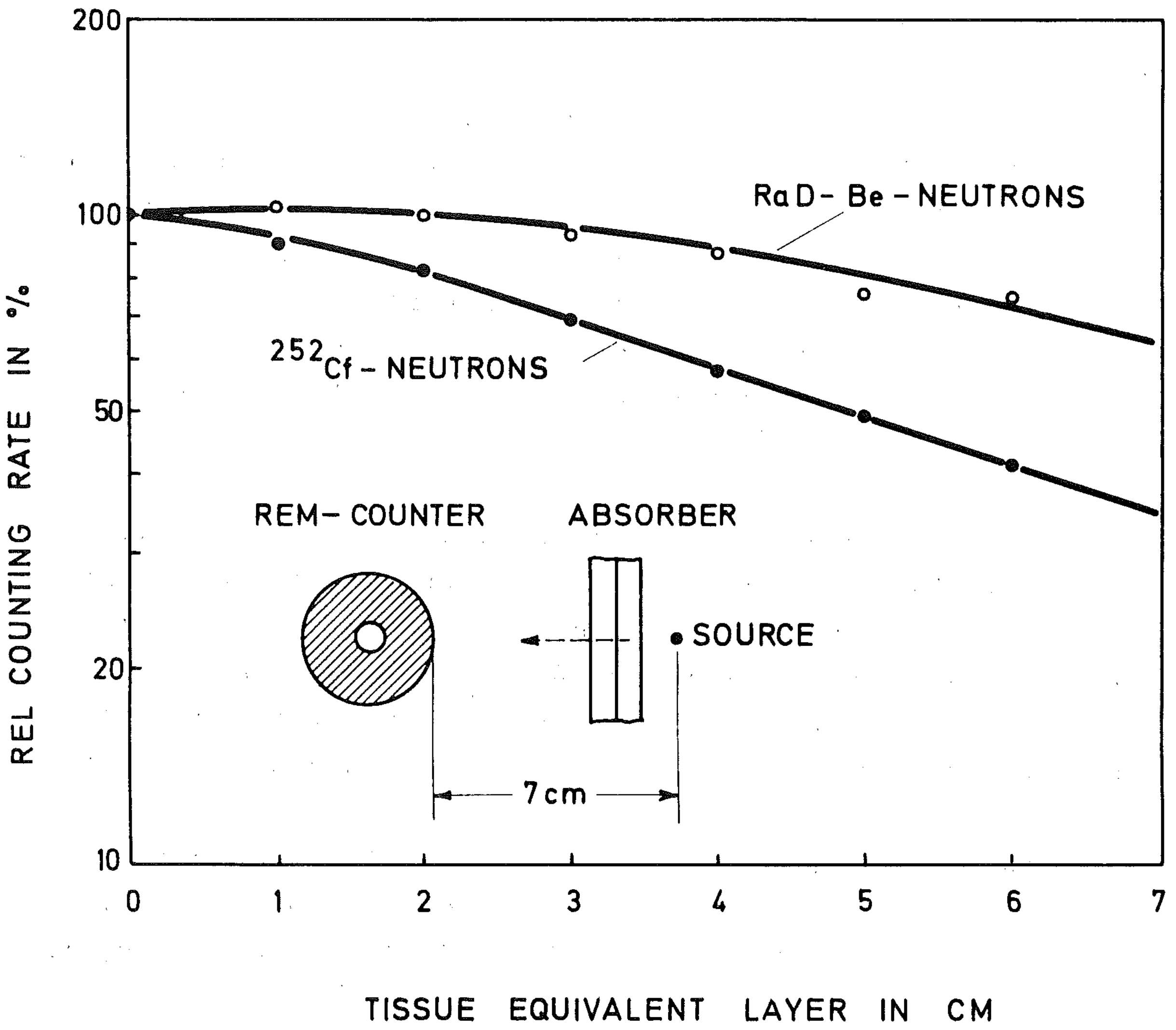

Fig. 7: Attenuation in tissue of the neutron counting rate measured with the rem-counter

Table 5: Measured Result of In-vivo Measurements

	Neutron Measurement		Surface of Pacemaker			
	$N_p(d)$ cpm	Q $10^3\ \frac{n}{s}$	Φ $\frac{n}{cm^2 s}$	$\dot{D}_n$ mrem/h	$\dot{D}_\gamma$ mrem/h	$\dot{D}_n/\dot{D}_\gamma$
Patient A	8.4	1.07	60	6.4	2.45	2.5
B	6.0	0.76	43	4.55	2.38	1.91
C	6.5	0.83	46.5	4.95	2.31	2.14
D	6.4	0.81	46	4.9	2.23	2.2
E	8.7	1.10	62	6.6	3.19	2.07
F	6.3	0.80	45	4.8	2.38	2.02
G	9.2	1.16	66	7.0	2.83	2.38
Phantom with 3R 0079N	6.7	0.85	48	5.1	2.48	2.11
Phantom with ^{238}Pu capsule	13	1.65	93	9.9	2.83	3.5
A - G	7.4	0.93	53±10	5.6±1	2.54±0.5	2.18±0.3

Table 6: Comparison of Measured and Nominal Neutron Emission Rates

	Neutron Emission Rate s^{-1}		
	Q_M [1]	Q_o [2]	Q_M/Q_o
A	1070		
B	762	750	1.015
C	825	750	1.1
D	812	750	1,08
E	1100		
F	800	750	1.075
G	1170		
Phantom 3R0079 N	850	864.7	0.98
Phantom ^{238}Pu-capsule	1650		
A - G	940		

[1] in-vivo measurement using proportional counter

[2] as specified by supplier

higher by 11 % compared to the flux measurement according to 1. This result is in good agreement with a higher value of 13 % obtained in calculation 3., since in both cases approximatly the same conversion factors are taken into consideration.

4. Total Exposure of the Patient

4.1 Results of In-vivo Measurements

The results of in-vivo measurements carried out with the proportional counter are represented in Table 5 for seven patients. Additional phantom measurements were also performed with a complete pacemaker and the reference source (^{238}Pu capsule). To convert the neutron flux density into the dose equivalent rate the fluence-kerma conversion factor of calculation 1 was used for 2.5 MeV neutrons with Q = 9 giving a factor of 0.107 mrem/h per n/cm s. Consequently, the average neutron doseequivalent rate on the surface of the implanted pacemaker was 5.6 ± 1 mrem/h, the respective value of gamma radiation 2.54 ± 0.5 mrem/h. The neutron gamma dose ratio is 2.18 which is higher by about 60 % for the ^{238}Pu reference capsule due to the higher neutron dose fraction.

Besides errors of measurement (see 3.3) systematic errors must be taken into account, above all with respect to the emission rate of the ^{238}Pu reference source used, which was determined spectroscopically to be 1.65×10^3 s^{-1} [3]. Using the Anderson-Braun rem-counter, the calibration of which is based on an Am-Be standard yield a value of $1.66 \times 10^3 s^{-1}$. Thus, a calibration of the proportional counter with the Am-Be standard instead of the ^{238}Pu reference source gives a dose equivalent rate which is lower by 5 % (cf. also Table 2).

4.2 Comparison with Other Measurements

The results of the in-vivo measurement show good agreement with the results of phantom measurements and with the information of the supplier about the neutron emission rate of the individual nuclide batteries. Deviations are within the error of measurement of 10 % (see Table 6).

Table 7: Comparison of Measured Results of Dose Equivalent Rate on the Surface of the Pacemaker

	Emission Rate n/s	Distance cm	$\dot{D}n$ mrem/h	$\dot{D}\gamma$ mrem/h	$\dot{D}n$ [1] mrem/h	$\dot{D}\gamma$ [1] mrem/h	$\dot{D}_{tot}$ [1] mrem/h
Mean of in-vivo measurement	940	1.25	5.6	2.54	5.6	2.54	8.14
3 R0079 N in Phantom	850	1.25	5.1	2.42	5.6	2.68	8.28
2 R00185 in Phantom [11]	716	1.3(n)	3.6	1.5	5.15	2.3	7.45
Battelle-Northwest [11]		1.35(γ)	max.	1.77		2.7	7.85
^{252}Cf in Phantom [10]	1400	2	3	-	5.7	-	
Gibson et.al [12]	700±70	2	2	-	5.15 [2]	2.7	7.85
					5.6 [2]	2.7	8.3

[1]) dose equivalent for 940 n/s on the surface of the pacemaker implanted at 1.25 cm distance of the source

[2]) recalculated from emission rate using the same fluence-dose equivalent conversion factor as for the other sources; phantom value higher than free air value

The total burden of the patient by gamma rays and neutrons is presented in Table 7 for the surface of the pacemaker. The table includes the results of respective phantom measurements with a ^{252}Cf source [10] as well as results measured by Battelle-Northwest [1] on a Medtronic pacemaker and results measured by Gibson et al [12] on an English pacemaker. The results were related to a source strength of $940 s^{-1}$ and 1.25 cm distance from the center of the ^{238}Pu source. So, the maximum burden on the surface of the pacemaker implanted is 8.14 mrem/h and 71.5 rem/a, respectively. Considering the random and systematic errors of measurement, the agreement ±4 %is very good which was found for the results of in-vivo measurement and those proposed by other authors. Differences in the amount of 0.6 ppm ^{236}Pu found with the Medtronic pacemaker by in-vivo measurement and of 0.26 ppm with that of Battelle-Northwest do not produce an essentially different gamma dose rate, since these differences are compensated again by different separation ages of ^{238}Pu of one and two years, respectively.

Table 8 shows additional dose equivalent rates to be anticipated on the body surface and at 50 cm from it, respectively.

4.3 Long-term Radiation Burden

The ^{236}Pu-fraction, via the thalium-208 decay product implies an increase in the gamma dose rate following chemical separation of ^{238}Pu. Based on theoretical computations, an increase by a factor of 2.6 of the gamma dose rate is expected for a pacemaker containing 0.5 ppm ^{236}Pu after a period of ten years following chemical separation (see Fig.8) [11]. However, within the period 0 to 10 years, the mean dose rate for neutrons and gamma rays is increased by 20 % only for 0.5 ppm and by 7 % for 0.26 ppm ^{236}Pu, related to the dose rate measured one year after the chemical separation (see Table 9).

Table 8: Personal Burden through Medtronic Pacemaker

In-vivo Measurement[1]	Dose Equivalent Rate µrem/h $\bar{\dot{D}}_n$	$\bar{\dot{D}}_\gamma$	$\bar{\dot{D}}_{tot}$	rem/a $\bar{\dot{D}}_{tot}$
Surface of Pacemaker 1.25 cm from the source	5600	2540	8140	71.5
Body surface 3.25 cm from the source	550	340	890	7.8
Free air at 50 cm distance	2.3	1.4	3.7	0.032

[1]) mean value, related to 940 n/s^{-1} neutron emission rate 1-2 years after chemical separation

Table 9: Increase in the Mean Dose Equivalent Rate with Different Periods of Implantation of the Pacemaker

	Mean Dose Rate	
Period in years	$\bar{\dot{D}}_{tot}$ mrem /h 0.26 ppm ^{236}Pu	0.5 ppm ^{236}Pu
after one year[1]	8.3	8.3
0 - 5	8.42	8.63
0 - 10	8.91	10.0
0 - 15	9.11	10.55
0 - 20	9.20	10.8

[1]) related to the value measured on pacemaker 3R0079N

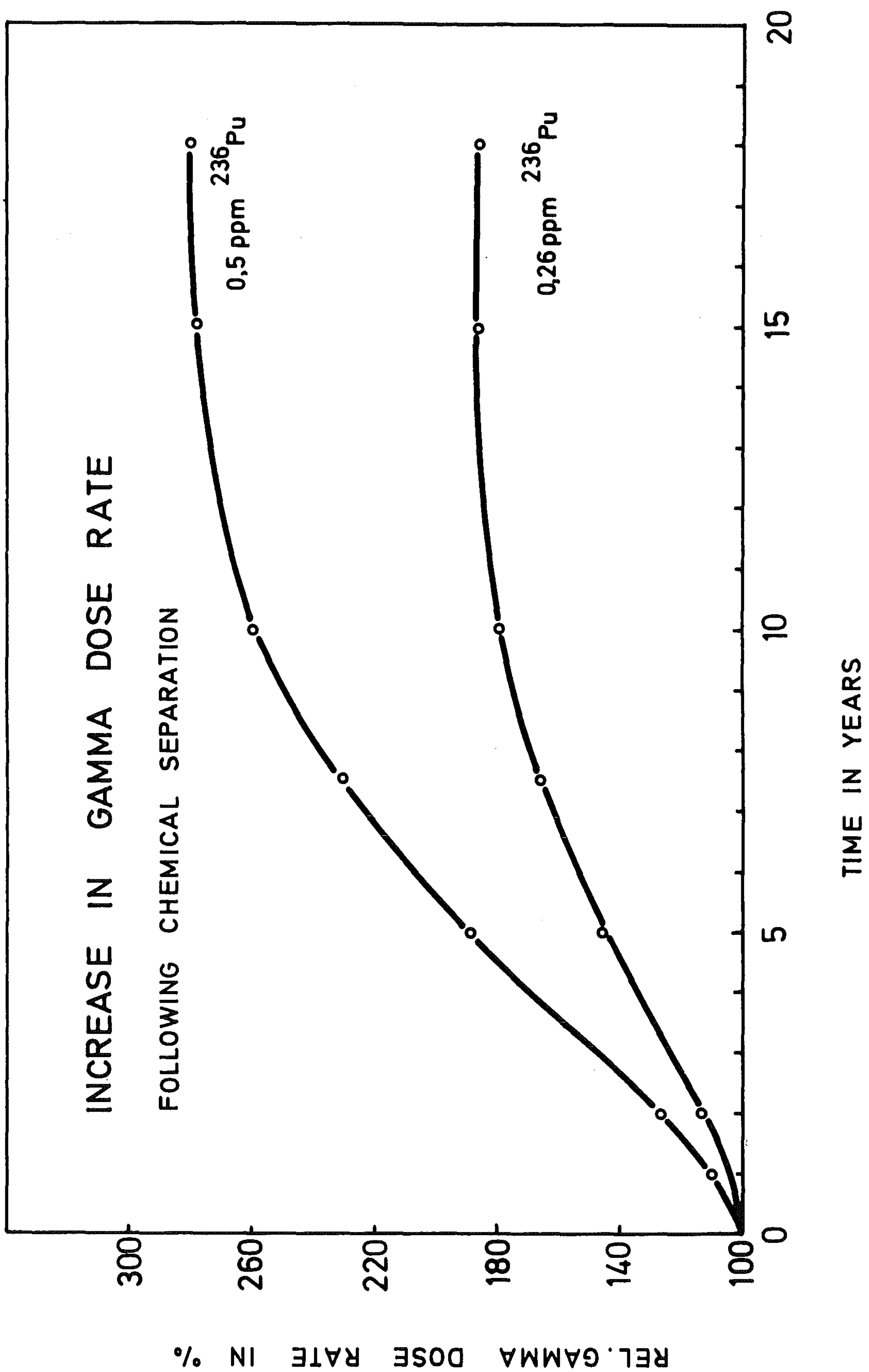

Fig.8: Increase in the gamma dose rate following chemical separation for a ^{238}Pu pacemaker with 0.26 ppm and 0.5 ppm ^{236}Pu

A ^{236}Pu content of 0.6 ppm for the Medtronic pacemaker was specified by the supplier. In-vivo measurements were carried out approximately 1 - 2 years after chemical separation. This implies that for the Medtronic pacemakers and ten years of implantation an increase in the mean gamma dose rate from 8.3 to about 11 mrem/h is anticipated. This represents the maximum tissue burden on the surface of the pacemaker. By using the direct measurement of the gamma dose rate on the patient the long-term 20 % increase per annum can be verified.

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