Determination of the Electronic Density and the Average Atomic Number of Tissues in Man by γ-Ray Attenuation[1]

Note of the Editor. The publication of the results of a series of painstaking measurements may serve, we hope, the community of Radiologists and Radiobiologists. The sudden decease of the senior author (G.J.) during the preparation of the manuscript prevented a full discussion of the implications (e.g. comparison with theoretical values derived from standard compositions, sensitivity to deviations hereof, etc.).

In spite of the increasing use of the radiations in medicine, we have few experimental data at our disposal about their attenuation in the tissues. The attenuations or the absorptions are generally calculated with the help of conventional atomic compositions for the soft tissues and the bones, given by the International Commission on Radiological Units and Measurements (ICRU). For this reason, we thought it would be useful to determine the number of electrons per g and the average atomic number of some human tissues, fresh from dissection.

At 661.6 keV, for the soft tissues, the attenuation only depends on the Compton effect, and the number $Ne = NZ/A$ of electrons per g is determined by the measure of the mass attenuation coefficient μ_o at this energy[2]. We have

$$\mu_o = Ne\,{}_e\sigma^{KN} \text{ and } Ne = \frac{\mu_o}{{}_e\sigma^{KN}}$$

where ${}_e\sigma$ (Compton cross section per electron) is calculated by the Klein-Nishina formula. For the bones, a correction of $-2.2\,^0/_{00}$ of the measured attenuation coefficient μ_o takes into account the increase of the cross section due to the presence of P and Ca.

At low energies of 60 and 28.5 keV, the attenuation depends on the Compton effect with electronic binding σ^{BD}, Rayleigh scattering σ^{R} and photoelectric effect τ and is a function of Z, and we have

$$\mu_o = Ne\,({}_e\sigma^{BD} + {}_e\sigma^{R} + {}_e\tau)$$

$$\frac{\mu_o}{Ne} = \frac{1}{Z}\,({}_a\sigma^{BD} + {}_a\sigma^{R} + {}_a\tau) = \frac{1}{Z}\,({}_a\sigma + {}_a\tau) \qquad (1)$$

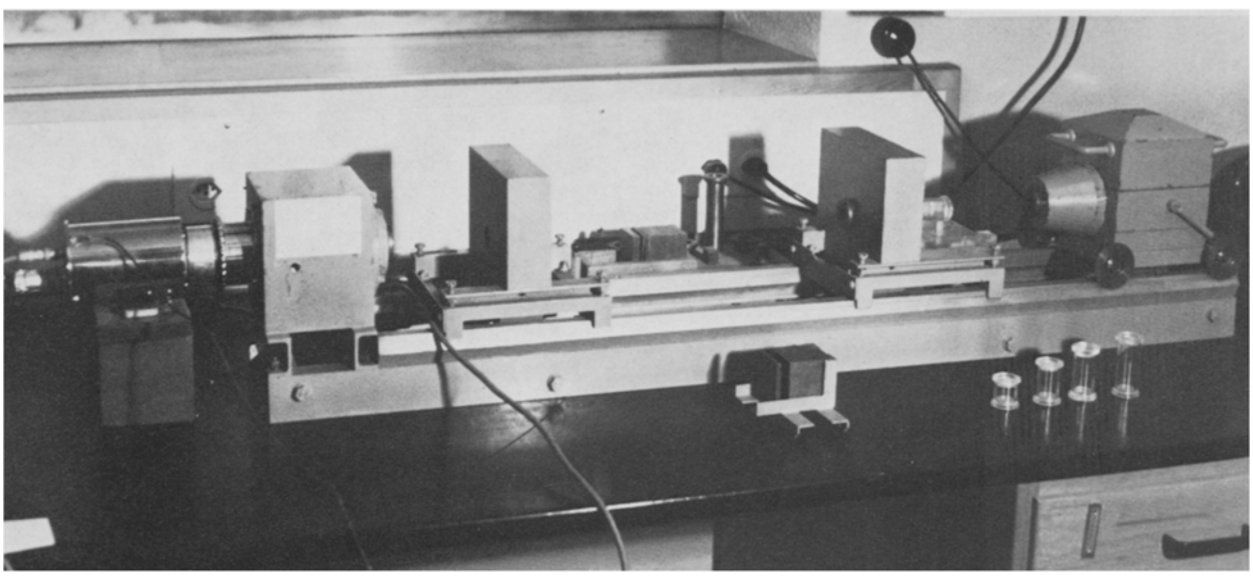

Fig. 1. Absorption apparatus for γ-rays with narrow beam collimating system. The sample was placed between the first and the second collimator as shown on the right side of the photograph: note the disposition of the plexiglas cylinder for measuring water and tissues. In order to average out variations from the average thickness, the sample was given a quarter of a turn after each sample count. Each count series of 1 sample was preceded and followed by one or several counts without sample (with empty container for water and tissues) and by one or several background counts, so that the total of counting statistics errors of one measured value of μ_o did not exceed 0.4%.

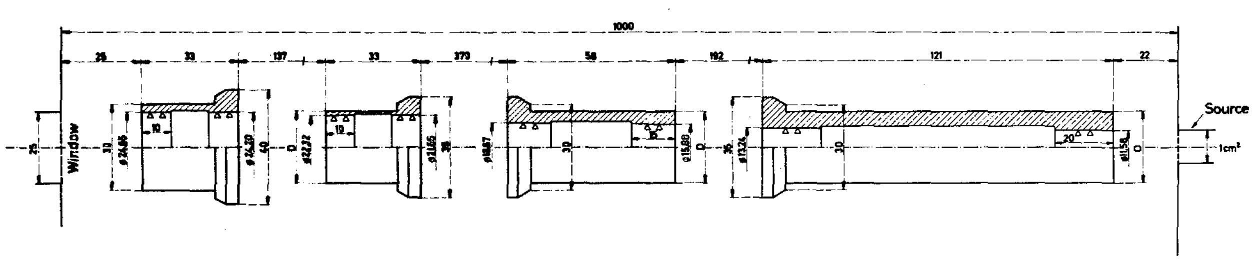

Fig. 2. Schematic diagram of the narrow beam geometry (dimensions in mm). The scheme shows the longitudinal section of the inner part of the lead collimators.

where the photo and Compton sections per atom have lately been worked out anew by HUBBEL[3]. If we introduce on the left hand side of (1) the measured values, we determine by interpolation, on the right hand side, an average Z.

The *mass attenuation coefficients of human tissues* for 661.6 keV, 59.6 keV and 28.5 keV were measured in a narrow beam geometry with a device described by DAVISSON and EVANS[4]. Our design was fitted with a NaI(Tl) detector of $^1/_4$ inch thick $\times$ 2 inch diameter and an electronic window (single channel analyzer) (Figures 1 and 2). The radioactive photon sources used were ^{137}Cs (5 mCi), ^{241}Am (1 mCi) and ^{125}I (2 mCi)[5].

In order to check the method, *the mass attenuation coefficients of carbon, aluminium and water* were measured in the same geometry. Carbon was in graphite form; a small correction had to be applied because of impurities. This correction in very pure aluminium was negligeable (0.035$^0/_{00}$ at 60 keV and 0.064$^0/_{00}$ at 30 keV). Both carbon and aluminium were machined to the shape of disks. The error on the superficial density was $\leqslant 0.5^0/_{00}$. Distilled water was put in a calibrated plexiglas cylinder as shown in Figure 1. Identical containers were used for measuring the attenuation of tissues.

The results of these measurements are given in Table I. There is a good correlation between the experimental data of Ne and the calculated ones of NZ/A. The experimental values of μ_o/Ne (calculated) for $Z = 6$ and $Z = 13$ agree well with these of HUBBEL[3] and GRODSTEIN[6] at 60 keV and 28.5 keV, as reported on the diagrams of Figures 3 and 4. From the data of HUBBEL, we have calculated for each energy the curves passing through the two experimental points. These curves have been used as a reference for the $\bar{Z}$ determinations. For water, we obtain $\bar{Z} = 7.35 \pm 0.06$ at 60 keV and $\bar{Z} = 7.40 \pm 0.01$ at

[1] This paper was presented to the Swiss Physical Society on May 5, 1973, in Neuchâtel, Switzerland, in the form of a short lecture. Prof. JOYET had begun, before his death in December 1973, to expand the contents of this lecture with the intention of publishing a comprehensive report. All work was conceived, directed, and its results mainly put together by him. But it was actually written only after his death, with the help of his notes. It has no other aim than to report the summarized results of this research.

[2] The total attenuation coefficient, μ_o with units of cm^2 g^{-1}, is defined by the equation $I = I_o e^{-\mu_o x}$ where I_o is the incident beam intensity, I is the transmitted beam intensity, and x is the sample thickness in g/cm^2.

[3] J. H. HUBBEL, Natn. Bur. Stand. Rep. NSRDS-NBS 29 (1969).

[4] C. M. DAVISSON and R. D. EVANS, Rev. modern Physics *24*, 101 (1952).

[5] 28.5 keV for ^{125}I is an average energy which takes into account the relative intensities of the different lines.

[6] G. WHITE GRODSTEIN, Natn. Bur. Stand. Circular 583 (1957).

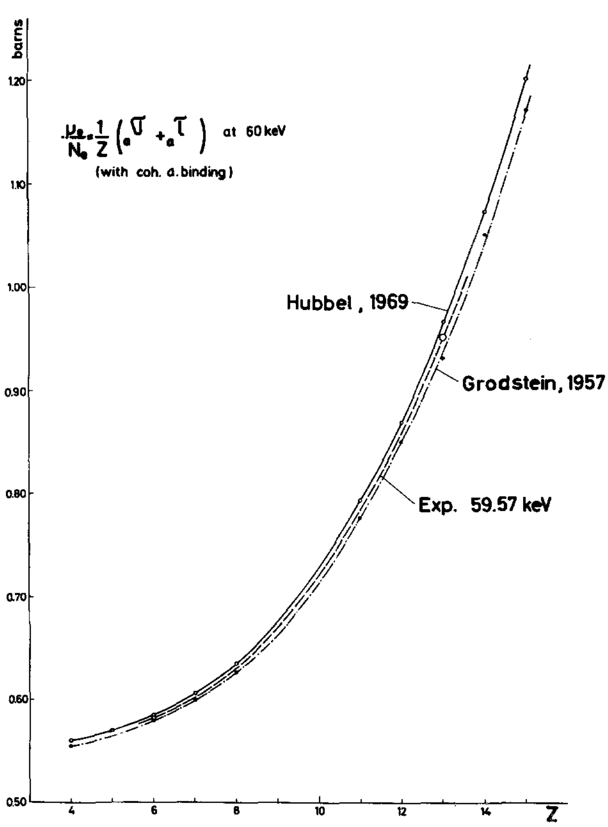

Fig. 3. Cross-sections (photoelectric + Compton) per electron (barns) versus atomic number Z at 60 keV according to HUBBEL[3] and WHITE GRODSTEIN[6], and experimental values for $Z = 6$ and $Z = 13$. The latter are within 0.3% for $Z = 6$ and 1.5% for $Z = 13$ of these of HUBBEL (who estimates the uncertainties on his values to be about 1% and 1 to 2% respectively).

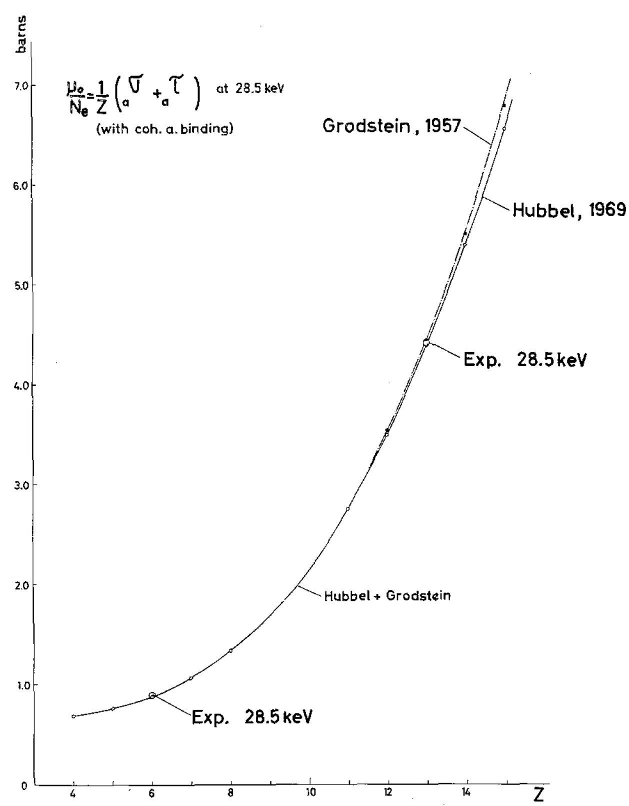

Fig. 4. Cross-sections (photoelectric + Compton) per electron (barns) versus atomic number Z at 28.5 keV according to HUBBEL and WHITE GRODSTEIN, and experimental values for $Z = 6$ and $Z = 13$. The latter are within 2.5% for $Z = 6$ and 0.5% for $Z = 13$ of these of HUBBEL (estimated uncertainties by HUBBEL on his values are about 5–10% and 1–2% respectively; there is also some uncertainty about 28.5 keV taken as an average energy for ^{125}I to which the values of HUBBEL were interpolated).

Table I. Attenuation data for C, Al and H_2O

	μ_o (cm^2 g^{-1})	Ne (el g^{-1})	NZ/A (calc)
Attenuation at 661.6 keV ($_e\sigma^{KN} = 0.25618 \times 10^{-24}$ cm^2)			
Carbon	0.07710	$3.009_8 \cdot \pm 1.5‰$	3.0085×10^{23}
Aluminium	0.07452	$2.908_8 \cdot \pm 1.6‰$	2.9017×10^{23}
Water	0.08552	$3.338_4 \cdot \pm 2.0‰$	3.3430×10^{23}
	μ_o (cm^2 g^{-1})	μ_o/Ne(calc)	Z
Attenuation at 59.57 keV			
Carbon (cor. imp. $-0.7‰$)	$0.1752 \pm 1.5‰$	0.5823×10^{-24}	6
Aluminium	$0.2758 \pm 1.6‰$	0.9506×10^{-24}	13
Water	$0.2044 \pm 1.9‰$	0.6114×10^{-24}	7.35
Attenuation at 28.5 keV			
Carbon (cor. imp. $-3.9‰$)	$0.2696 \pm 1.1‰$	0.8960×10^{-24}	6
Aluminium	$1.2852 \pm 1.2‰$	4.4291×10^{-24}	13
Water	$0.4013 \pm 1.8‰$	1.2004×10^{-24}	7.40

The indicated errors of the experimental data are the standard errors obtained from repeated experiments with various superficial densities.

Table II. Attenuation data of striated muscle in man

Person	Attenuation μ_o (cm^2 g^{-1})		
	661.6 keV	59.57 keV	28.5 keV
A	0.0850	0.2018	
B	0.0846	0.2026	
C	0.0846	0.2042	
D	0.0845	0.2017	0.3944
E	0.0848	0.2021	0.4044
F	0.0845	0.2024	0.4099
G	0.0843	0.2028	0.3975
Mean ± S.D.	$0.0846 \pm 0.0002_3$	$0.2025 \pm 0.0008_5$	0.4016 ± 0.0070
	$Ne = 3.303 \times 10^{23} \pm 2.7‰$;	$\bar{Z} = 7.4_2 \pm 0.1_2$;	$\bar{Z} = 7.4_6 \pm 0.0_7$.

Table III. Attenuation coefficients μ_o (cm^{2}g^{-1}), number of electrons per g Ne and average atomic number $\bar{Z}$ of soft tissues in man

Tissue	661.6 keV		59.57 keV		28.5 keV	
	$\bar{\mu}_o$	$\overline{Ne}$	$\bar{\mu}_o$	$\bar{Z}$	$\bar{\mu}_o$	$\bar{Z}$
		$\times 10^{23}$				
Muscle	0.0846	3.303	0.2025	$7.4_2 \pm 0.1_2$	0.4016	$7.4_6 \pm 0.0_7$
Fat	0.0850	3.317	0.1951	$6.3_2 \pm 0.2_8$	0.3090	$6.1_9 \pm 0.0_9$
Brain	0.0851	3.320	0.2041	$7.4_7 \pm 0.3_3$	0.4008	$7.4_1 \pm 0.0_1$
Liver	0.0845	3.300	0.2030	$7.5_0 \pm 0.1_4$	0.3999	$7.4_3 \pm 0.0_4$
Kidneys	0.0845	3.298	0.2037	$7.5_6 \pm 0.1_5$	0.4095	$7.5_5 \pm 0.0_7$
Lungs	0.0837	3.268	0.2028	$7.6_8 \pm 0.4_2$	0.4032	$7.5_2 \pm 0.1_5$
Thyroid	0.0836	3.265	0.2048	$7.9_0 \pm 0.3_2$	0.4044	$7.5_5 \pm 0.1_0$
Testes	0.0848	3.309	0.2032	$7.4_5 \pm 0.1_8$	0.4005	$7.4_2 \pm 0.0_1$
Skin	0.0840	3.280	0.2011	$7.4_2 \pm 0.2_0$	0.3861	$7.3_0 \pm 0.0_1$
Aorta	0.0853	3.328	0.2060	$7.6_2 \pm 0.0_4$	0.4054	$7.4_6 \pm 0.0_3$
Vena Cava	0.0857	3.343	0.2030	$7.2_0 \pm 0.1_5$	0.3884	$7.2_5 \pm 0.1_4$
Cartilage	0.0876	3.420	0.2121	$7.6_5 \pm 0.3_4$	—	—

Each value is the average of the measurements of samples taken from 5 to 7 persons at 661.6 keV and 59.6 keV, 3 to 4 persons at 28.5 keV, except for the 3 last ones: aorta and v. cava 2 persons, cartilage 2 persons (average of 4 measurements) at 661.6 keV and 1 person (average of 3 measurements) at 59.6 keV. The S.D. on these averages vary for μ_o at 661.6 keV and for Ne from 0.3 to 1.5%, for μ_o at 59.6 keV from 0.4 to 1.2%, for μ_o at 28.5 keV from 0.1 to 1.7%. The error on $\bar{Z}$ corresponds to the S.D. on the average of the quotients μ_o/Ne at each energy, read on the diagrams of Figures 3 and 4. The precision of one single determination of μ_o/Ne is $\leqslant 1.6\%$.

Table IV. Attenuation coefficients μ_o ($cm^2 g^{-1}$), number of electrons per g Ne and average atomic number $\bar{Z}$ of bones in man

Person	661.6 keV		59.57 keV		28.5 keV	
	μ_o	Ne	μ_o	$\bar{Z}$	μ_o	$\bar{Z}$
	Corpus femoris					
H	0.0899	3.509×10^{23}	0.3610	$13.7_4 \pm 0.05$	1.461	$12.7_3 \pm 0.03$
I	0.0884	3.451	0.3465	13.5_2	1.559	13.1_1
K	0.0827	3.228	0.3460	14.1_2	1.537	13.3_5
Mean				13.8		13.1
	Caput femoris					
H	0.0895	3.494	0.2771	11.1_5	1.052	11.3_2
I	0.0875	3.416	0.2665	10.9_5	1.007	11.2_4
K	0.0890	3.474	0.2865	11.5_7	1.027	11.2_5
Mean				11.2		11.3
	Trochanter major					
H	0.0904	3.529	0.3003	11.9_1	1.218	11.9_1
I	0.0888	3.466	0.3019	12.1_5	1.055	11.3_7
K	0.0873	3.408	0.2807	11.5_6	1.142	11.7_8
Mean				11.9		11.7
	Ribs					
I	0.0893	3.486	0.3246	12.7_8	1.355	12.4_3
K	0.0875	3.416	0.3031	12.3_2	1.351	12.4_9
Mean				12.6		12.5
	Squama frontalis					
I	0.0882	3.443	0.3290	13.0_6	1.474	12.8_5
K	0.0826	3.224	0.3313	13.7_1	1.535	13.3_5
Mean				13.4		13.1

The variation of 0.05 or 0.03 on $\bar{Z}$ corresponds to an average error of 0.7% on the attenuation coefficient per electron μ_o/Ne.

28.5 keV. (With the values of HUBBEL, $\bar{Z} = 7.38$ and 7.44 respectively.)

The measured tissues were taken immediately after the death of the subjects and put into the Plexiglas cylinders mentioned above. The bones were crushed. An example of the experimental data for one tissue (striated muscle) is given in Table II. The summarized results of Tables III and IV show that $\bar{Z}$ varies from 6 to 8 for the soft tissues and from 11 to 14 for the bones[7]. The high and variable values of $\bar{Z}$ for the bones suggest the possibility of an in-vivo determination of calcium and phosphorus[8].

Résumé. Le coefficient d'atténuation massique μ_o des tissus humains pour 662, 60 et 28,5 keV est mesuré dans une géométrie à faisceau étroit, avec un détecteur NaI(Tl) mince, pourvu d'une électronique à fenêtre. Le nombre Ne d'électrons par g est déterminé avec une précision de ≤1,5% (S.D.). A partir des valeurs de μ_o mesurées à 60 et 28,5 keV, avec une précision de ≤1,7% (S.D.), on détermine un $\bar{Z}$ moyen qui varie de 6 à 8 pour les tissus mous et de 11 à 14 pour les os. On montre que le $\bar{Z}$ moyen de l'eau est très voisin de celui des tissus mous, la graisse exceptée.

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[7] The radiation of ^{125}I not being monoenergetic, the measured attenuation coefficient slightly varies with the thickness of the absorber. The result may be, for the high Z, an error of about 2% on μ_o whose consequence will bring down the values of $\bar{Z}$ for the bones.

[8] Acknowledgments are due to the Fund for Scientific Research, University of Zürich, which financed the electronic equipment and the NaI(Tl)-Crystal, and to the Institute of Pathological Anatomy of the University Zürich (Prof. Dr. med. E. Uhlinger and Prof. Dr. med. C. Hedinger) for supplying us with tissues.

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Inability of Specific Antibodies to Discriminate Between Frog and Tadpole Haemoglobins in Mixture

Rana catesbeiana tadpole (larval) and frog (adult) haemoglobins have different electrophoretic mobility and amino acid composition[1,2]. Both are relatively potent immunogens, and sera of rabbits immunized against tadpole or frog haemoglobins have been shown to be specific and without any significant degree of cross reactivity[3,4]. The following results show that rabbit antisera against tadpole or frog haemoglobins cannot discriminate between these two antigens when *R. catesbeiana* larval and adult haemolysates are mixed

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[2] S. J. AGGARWAL and A. RIGGS, J. biol. Chem. *244*, 2372 (1969).
[3] G. MANIATIS and V. M. INGRAM, J. Cell Biol. *49*, 380 (1971).
[4] J. BENBASSAT, J. Cell Sci., in press.