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WITH A Ge(HP) DETECTOR**

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A Bone Density Scanner Using Gamma Ray Attenuation
with a Ge(HP) Detector*

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Introduction

The measurement of linear bone density by gamma-ray absorption has been championed by John R. Cameron for many years.^(e.g.1) A collimated beam of γ -rays is passed across and through the bone of interest and counted. The bone being heavier than the surrounding tissue, scatters photons out of the beam, attenuating the beam according to the transmission, I/I_0 :

$$I/I_0 = e^{-\left(\frac{\mu}{\rho}\right) (\rho \cdot x)}$$

where $\frac{\mu}{\rho}$ is the mass absorption coefficient of the object (bone)
(cm^2/gm)

ρ is the object density

x is the thickness.

Figure 1 is a schematic representation of the method, but contains details of this system that will be mentioned later. The bone - generally the arm - is immersed in water to achieve uniform tissue absorption across the scan. As the scan proceeds across

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(1) J. R. Cameron and J. Sorenson, Science 142, 230 (1963)

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the bone, a reduced counting rate compared with the region of water-tissue is observed due to the heavier denser bone. Figure 2 illustrates the general shape of bone absorption.

The ratio of the counting rates through bone to that through water (at a particular scan speed) or the ratio of counts for a specific linear resolution increment ($\frac{\text{count rate}}{\text{scan speed}}$) is

$$\frac{N_{\text{bone}}}{N_{\text{water}}} = e^{-\left[\left(\frac{\mu}{\rho}\right)_b - \left(\frac{\mu}{\rho}\right)_w \cdot \frac{\rho_w}{\rho_b}\right] \rho_b t}$$

and the $\log \frac{N_{\text{bone}}}{N_{\text{water}}}$ relates directly to bone thickness at a given position:

$$\ln \frac{N_{\text{water}}}{N_{\text{bone}}} = \left[\left(\frac{\mu}{\rho}\right)_b - \left(\frac{\mu}{\rho}\right)_w \cdot \frac{\rho_w}{\rho_b}\right] \rho_b \cdot t$$

if $\left(\frac{\mu}{\rho}\right)_b > \left(\frac{\mu}{\rho}\right)_w \cdot \frac{\rho_w}{\rho_b}$, then

$$\ln \frac{N_{\text{water}}}{N_{\text{bone}}} = \left(\frac{\mu}{\rho}\right)_b \cdot \rho_b \cdot t$$

The above approximation is not arithmetically valid, but often used to show the direct relationship of counting rates to bone mass. The previous expression of the "effective" attenuation coefficient can be used with an "averaged" ρ_b and is strictly true.

The integral over the limits of the bone absorption, 0 to x_0 if just the cross-sectional area of the bone A

$$\int_0^{x_0} \ln \frac{N_w}{N_b} dx = \left(\frac{\mu}{\rho} \right)_b \rho_b \int_0^{x_0} t(x) dx$$

$$= \left(\frac{\mu}{\rho} \right)_b \rho_b A$$

Realizing that the counts are recorded per unit of source width, a factor of bone width, w , should appear on the right hand side so that we have a direct relationship to bone mass M .

$$\int_0^{x_0} \ln \frac{N_w}{N_b} = \left(\frac{\mu}{\rho} \right)_b \rho_b A \cdot w = \left(\frac{\mu}{\rho} \right)_b M$$

Variations of density in the center portion of the bone may also be evident in this technique, c.f. Fig. 2., as the cortex at the edges can be clearly distinguished from the central bone.

Equipment

Figure 1 is a schematic of the physical layout of the detector and arm or bone positioning device. A collimated, 150 mCi, ^{241}Am source is used to provide a beam of 59.54 keV γ -rays. Counting rates of approximately 2×10^4 cps through 3" of water are observed. The source-to-detector distance is variable to allow the possibility of measuring very small (animal) bones in vitro; improved collimation would also be required. The dose rate was measured in the water container with thermoluminescent dosimeters, and was found to be less than 10 mR/hr.

The synchronous motor used is an Apco Series 2302-2, 1 rpm, which has built-in reduction gears ranging by factors of two from 1:1 to 1:32. The gears are set manually by a thumbwheel on the side of the drive assembly. The 1" diameter gear-on-rack drive thus allows a 3" scan to be made in about one minute. Geared reductions of 4 or 8 of this scan speed were found most useful. Roller bearings on machined rails allow smooth, non-binding linear transport.

A germanium detector was chosen partly because of its relative availability, but also to achieve the scatter rejection available through its excellent energy resolution. Figure 3 shows the pulse height spectrum obtained from ^{241}Am with this detector, and indicates the "window" of acceptable γ -rays used in the attenuation measurement. A resolution of 530 eV is achieved, and a window width of about 2 keV is used. This width rejects ^{241}Am gamma rays which have been Compton-scattered through as little as 12° , and should improve the multiple scattering contribution to this "good" geometry experiment. The germanium detector is a "high purity" detector (Ge(HP)) which may be warmed up and recooled without deleterious effect. It is a grooved detector, 3 mm deep, about 4 mm in active diameter. The 3.5L LN_2 dewar has a holding time of about one week.

The electronic signal processing is standard "NIM" module equipment; a block diagram is shown in Fig. 4. The preamplifier

is dc-coupled to the detector and bias up to 900 V is provided by a battery box. The single channel pulse height analyzer with its window set as shown in Fig. 3 drives a ratemeter and strip-chart recorder to produce a linear display of attenuation as in Fig. 2. It also is connected to a pulse height analyzer operating in multi-scaling mode. This unit stores the data of Fig. 2 and permits easy integration of the area and a paper tape readout.

Experimental Tests

Scans were made of the aluminum block phantom shown in Fig. 5 to establish the sensitivity and precision of the method. The phantom approximates bone thickness (in mg/cm^2) and was measured immersed in 3" of water with scanning times of the order of several minutes, approximating operating, normal conditions. To determine sensitivity to material variations, 0.25" wide slots were milled in the length of the block. The depths of the slots are as shown, and correspond to aluminum voids of 1, 3, 5, 10, 20 and 30% of the total aluminum thickness.

Figure 6 shows a scan taken of this phantom in normal scanning time. The count rate indicated by h_0 is the rate in the 0.975" full thickness. Noting that the rate α_5 is clearly discernible over h_0 in the scan width of 0.25", we estimate that voids of about 3% are visible. Lateral spatial resolution of about 1/16" at this scan speed can also be estimated. This result is consistent with collimator geometry and statistics. The counting statistics are below 1% (fractional standard deviation) in this linear resolution interval.

Counting rates α , α_2 , α_3 , α_4 , α_5 and h_0 may be extracted from this plot and compared with that predicted by the attenuation of the known slot thickness. The difference in counting rate α_i and the full aluminum value h_0 is

$$\alpha_i - h_0 + I_0 (e^{-\mu x_i} - e^{-\mu x_0})$$

where the normalization constant I_0 is obtained from the counting rate at any thickness, x_1 , for example.

Using the counting rate values from Fig. 6, we get (in divisions of Fig. 6 scale):

<u>Thickness Number</u>	<u>Calculated Rate</u>	<u>Observed Rate</u>
2 (20%)	63.0	63.5
3 (10%)	34.8	34.9
4 (5%)	21.8	20.3
5 (3%)	16.1	15.0

Considering the precisions of the method, agreement is believed to be satisfactory, and the contention that a 3% density variation is observable may be substantiated.

Several sets of runs were made over both the aluminum phantom and several positions on a human mandible to check the reproducibility of the method. Total counts in the absorption area of the

scan were integrated and are presented along with observed standard deviations:

Aluminum Phantom

<u>Run No.</u>	<u>Counts</u>
3	337,100
4	336,880
5	339,090

$$\bar{x} = 337,690 \pm 860 (0.25\%)$$

Mandible

<u>Area 1</u>	<u>Counts</u>
1	296,720
2	311,610
3	272,730
4	357,280

$$\bar{x} = 309,580 \pm 20550 (6\%)$$

(Note this scan was taken over a tooth, which suggests a gross non-uniformity in area)

Area 2

5	245,600
6	260,040
7	263,810
8	252,680

$$\bar{x} = 255,530 \pm 4660 (1.8\%)$$

<u>Area 3</u>	<u>Counts</u>
11	243,390
12	233,840
13	227,600
14	239,890
$\bar{x} = 236,180 \pm 4010 \text{ (1.7\%)}$	

<u>Area 4</u>	
15	244,190
16	239,170
17	245,190
$\bar{x} = 242,850 \pm 2280 \text{ (0.9\%)}$	

Summary

A scanning source and detector has been developed and evaluated which measures bone density by the attenuation of ^{241}Am gamma rays. It uses a high resolution Ge(HP) detector which will improve scatter rejection and is conveniently stored and operated. Standard electronic equipment is used. Density variations on the order of 3% are visible in scans at scanning rates of about 5 min per 3-inch scan. The precision or reproducibility derived from several representative scans is about 1% and should improve with use as possible systematic errors are found and eliminated. The

statistical error of attenuated counts can be somewhat less than this value.

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Figure Captions

- Figure 1. Schematic representation of bone scanning system.
- Figure 2. Scan of cow bone as an illustration of typical bone attenuation.
- Figure 3. Pulse-height spectrum of ^{241}Am taken with Ge(HP) detector. Gamma-rays accepted by the discriminator are noted.
- Figure 4. Block diagram of electronic components.
- Figure 5. Aluminum block phantom used for sensitivity determinations.
- Figure 6. Scan of aluminum block phantom showing sensitivity to the various density levels.

0 3 6 9 12
APPROXIMATE SCALE IN INCHES

CROSS SECTION OF ALUMINUM BLOCK BONE PHANTOM (all dimensions in inches)