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Determination of Vertebral Bone Mineral In Vivo

by

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I. Introduction

Osteoporosis is a disease of the bone in which there is a simultaneous reduction of cortical and spongy bone. McLean and Urist (1) have indicated that the loss of the spongy bone is more rapid than the cortical bone. The vertebral bodies contain a higher percentage of spongy bone than other bones of the body (2). It is therefore believed that skeletal changes might be detected earlier by measuring the bone mineral content of the vertebral bodies rather than other bones. In addition, overt clinical symptoms of osteoporosis usually appear first in the spine through collapsed vertebrae ("dowagers hump") and through decreased height. It is the area that is usually examined by a radiologist to make a diagnosis of osteoporosis.

A method of in vivo determination of bone mineral content in the lumbar vertebrae by a linear dichromatic transmission scan has been described by Roos (3). In an effort to reproduce and extend his techniques, we have constructed a vertebral bone mineral measuring system. A crucial problem is the accurate localization of the vertebra to be scanned. In our system a fluoroscope and image intensifier are used to locate the vertebra of interest with the subject in a supine position. We are using Gadolinium-153 (Gd-153) with photon energies of approximately 43 and 100 keV as a dichromatic gamma ray source.* The beam is collimated by an adjustable rectangular collimator at the source and at the 2 inch diameter NaI (Tl) scintillation crystal. During this past year equipment for these measurements was designed and constructed. Only preliminary results will be presented in this report.

II. Theory

Figures 1 and 2 show the location and structure of the spinal column. Figure 3 depicts a typical third lumbar (L-3) vertebra of an adult male. The L-3 vertebra is an irregular body of about 3 by 9 cm as viewed by the source-detector system. The source and detector collimators were designed to produce a beam 3 cm by 1 cm at the level of L-3 and the vertebra is scanned laterally a distance of about 20 cm. The results of the transmission measurements of both energies are then processed to give the bone mineral content of the vertebra.

The equations for the determination of the amount of bone mineral and/or soft tissue in the path of a dichromatic beam have been previously described by Judy (4) and Roos (3). These equations are:

* This source is further described in USAEC Report COO-1422-71 (1970).

DISCLAIMER

$$M_{BM} = K_1 \log_e (I_o/I) + K_2 \log_e (I_o'/I)$$

$$M_{ST} = K_3 \log_e (I_o/I) + K_4 \log_e (I_o'/I)$$

where

M = mass in gm/cm^2

BM = subscript reierring to bone mineral component

ST = subscript referring to soft tissue component

I_o = unattenuated intensity for one energy

I = transmitted intensity for one energy

The primes indicate the second energy quantities,

and $$K_1 = \frac{\mu_{ST}'}{\mu_{ST}'\mu_{BM} - \mu_{ST}\mu_{BM}'}$$

$$K_2 = \frac{\mu_{ST}}{\mu_{ST}'\mu_{BM} - \mu_{ST}\mu_{BM}'}$$

$$K_3 = \frac{\mu_{BM}'}{\mu_{ST}'\mu_{BM} - \mu_{ST}\mu_{BM}'}$$

$$K_4 = \frac{\mu_{BM}}{\mu_{ST}'\mu_{BM} - \mu_{ST}\mu_{BM}'}$$

where the μ and μ' are the mass attenuation coefficients. While Roos's equations may appear to be different from Judy's because of the use of different symbols and scaling factors, fundamentally their equations are the same.

Because the above equations for determining the bone mineral mass assume exponential absorption, it is necessary to determine to what extent the relatively broad beam is attenuated by bone and soft tissue exponentially as a function of thickness. These equations also assume there is no interference between the measurements of the two photon beams. However, with a dichromatic source two photon energies are transmitted simultaneously; one must therefore correct for "spill over" due to scatter of the higher energy photons into the lower energy photon channel. Some of our absorption measurements show this effect.

III. Equipment

A small animal fluoroscope* was modified for vertebral bone mineral determinations (see figure 4). Thirty-eight centimeters below the tabletop of the fluoroscope a Gd-153 source holder is mounted on top of the x-ray tube. The source and holder are removed during the localization of L-3 and then are put back for the bone mineral determination. The holder is reproducibly positioned by four pins. Thirty-four centimeters above the tabletop both an image intensifier (with a T.V. camera) and a two inch diameter NaI(Tl) crystal (with photomultiplier tube and collimator) are mounted (see figure 5). They are fixed at right angles and are supported by the same vertical column which supports the x-ray head below the table. The image intensifier and NaI detector can swing in a horizontal plane above the tabletop so that the image intensifier is positioned for localization, after which the detector is moved into the same position for the bone mineral measurements. Accurate repositioning is made possible by the use of a tapered pin. The whole system can be moved in either direction in the horizontal plane. In normal operation the apparatus is moved in the lateral direction by a screwdrive.

The dichromatic source, a 60 mCi Gd-153 source** with principal energy peaks at approximately 43 and 100 keV, is initially collimated by its 6 mm diameter casing and is further collimated by a 1/16 inch thick lead sheet. This collimator is adjusted so that the beam is 3 cm by 1 cm at the L-3 height. The photons emerging from the body are then collimated at the detector by a similar rectangular aperture to minimize the scatter.

Proper setting and alignment of the source and collimators is essential. A light source (which can be substituted for the Gd-153 source) was constructed using a prefocused #222 miniature lamp mounted behind a 6 mm diameter plastic translucent window. This light source is inserted into the source holder such that its position and diameter is the same as the Gd-153 source. We compared the light source field with an x-ray picture of the Gd-153 beam profile at the L-3 level. The agreement was excellent; therefore we use the light source for adjusting and aligning the collimators.

The electronic components needed to process the transmission information of the Gd-153 source are shown in a block diagram in figure 6. A dual channel analyzer is needed to separate the two photoelectric peaks. The number of counts in each channel is counted for a fixed time at each measuring point. The information is then fed into a buffer from which it can be either printed, punched out on paper tape, or recorded on magnetic tape.

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* Continental X-ray Corp., Model 20-80 Horizontal Fluoroscope

** On loan from Oak Ridge National Laboratory

The initial measurements were made with the equipment shown in figure 7. Two Baird Atomic (Model #530) units, each with a preamplifier, single channel analyzer and timer-scaler, were used. The units were started simultaneously and the number of counts was recorded manually. In an effort to facilitate the handling of a larger quantity of data, some method of transferring the data to punched tape or magnetic tape was necessary.

The heart of this new instrumentation is a multi-channel analyzer* (see figure 8) that can perform multi-channel scaling and has a memory capable of 256 six digit numbers. We use the memory as a buffer. This unit also has a single channel analyzer which we modified to automatically alternate between two different single channel analyzer settings each time the memory location is advanced. It is therefore possible to alternately count and store the 43 and 100 keV channels. An entire scan can be stored in the analyzer's 256 memory channels. The numbers in the memory are then read out into a Teletype model 33ASR using the interface which is a part of the multi-channel analyzer. This produces simultaneously a listing and a punched paper tape. The paper tape is then fed into a computer for analysis.

The disadvantage of this system is that only the 43 keV or the 100 keV channel can be counted at one time. But this is not a serious limitation if there are sufficiently high count rates and if the settings of the single channel analyzer are alternated relatively fast with respect to the scanning speed.

IV. Results

The results of absorption studies made for water, pressed board and aluminum for the two energy peaks of Gd-153 are plotted in figure 9. The higher energy absorption curves are clearly exponential over at least a full decade for these materials. The slight departure from exponential absorption with increasing absorber thickness in the lower energy channel appears to be primarily due to spillover and perhaps partly due to the increased significance of imperfect resolution of the two peaks. Further experiments are planned to attempt to quantify the spillover and resolution effects.

Figure 10 is an x-ray photograph illustrating a phantom of a human trunk we used for a lateral scan of L-3. The top vertebral body in this x-ray is L-3.

The count rates for the lower and upper energy channels and the calculated bone mineral are shown in Figure 11. We counted for one minute at each 1 cm interval. The maximum change in count rate for either channel is less than a factor of 2. Over this limited range it appears that exponential absorption in both energy channels is a reasonable assumption.

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* Northern Scientific model NS600

V. Future Plans

We plan to continue our work in evaluating sources of error and performing calibration studies. Because the small fluoroscope we were using is not intense enough we plan to use a more intense patient fluoroscope for localization. In an effort to decrease the errors due to repositioning we are planning to build a new scanner capable of area scans in addition to linear scans. We will also scan other bones containing a high percentage of spongeosa, such as the cervical spine and the neck of the femur.

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REFERENCES

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2. Gong, J.K., Arnold, J.S., and Cohn, S.H., Composition of Trabecular and Cortical Bone, Anatomical Record 149: 325-332 (1964).

3. Roos, B., Rosengren, B., and Sköldborn, H., Determination of Bone Mineral Content in Lumbar Vertebrae by a Double Gamma-Ray Technique, in Proc. of Bone Measurement Conference, Cameron, J.R., ed. pp. 243-254, USAEC CONF-700515 (1970). In press.

4. Judy, P.F. and Cameron, J.R., A Dichromatic Absorption Method for the Measurement of Bone Mineral Content, USAEC Report COO-1422-60, (1969).

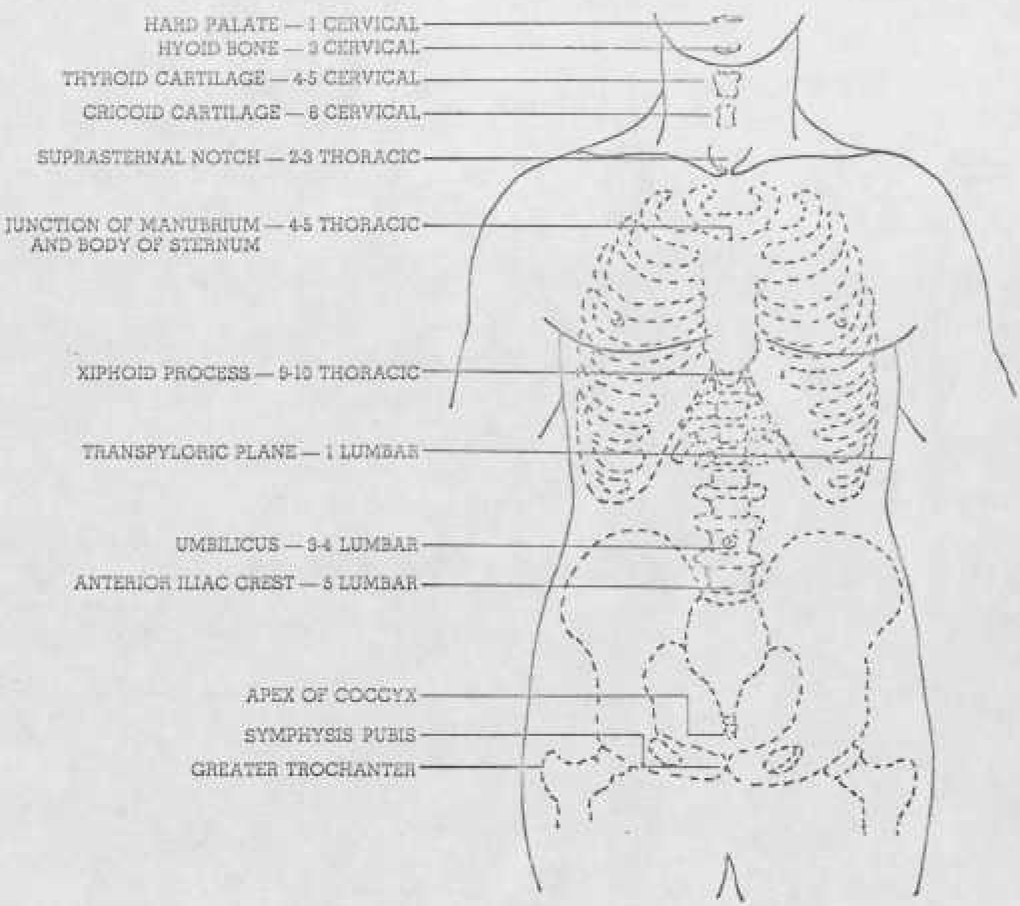

Figure 1: Human anatomical landmarks.

(from A Guide to Radiological Anatomy, Pub. No. 69-3416C. Published by General Electric, Medical Systems Dept., Milwaukee, Wis.)

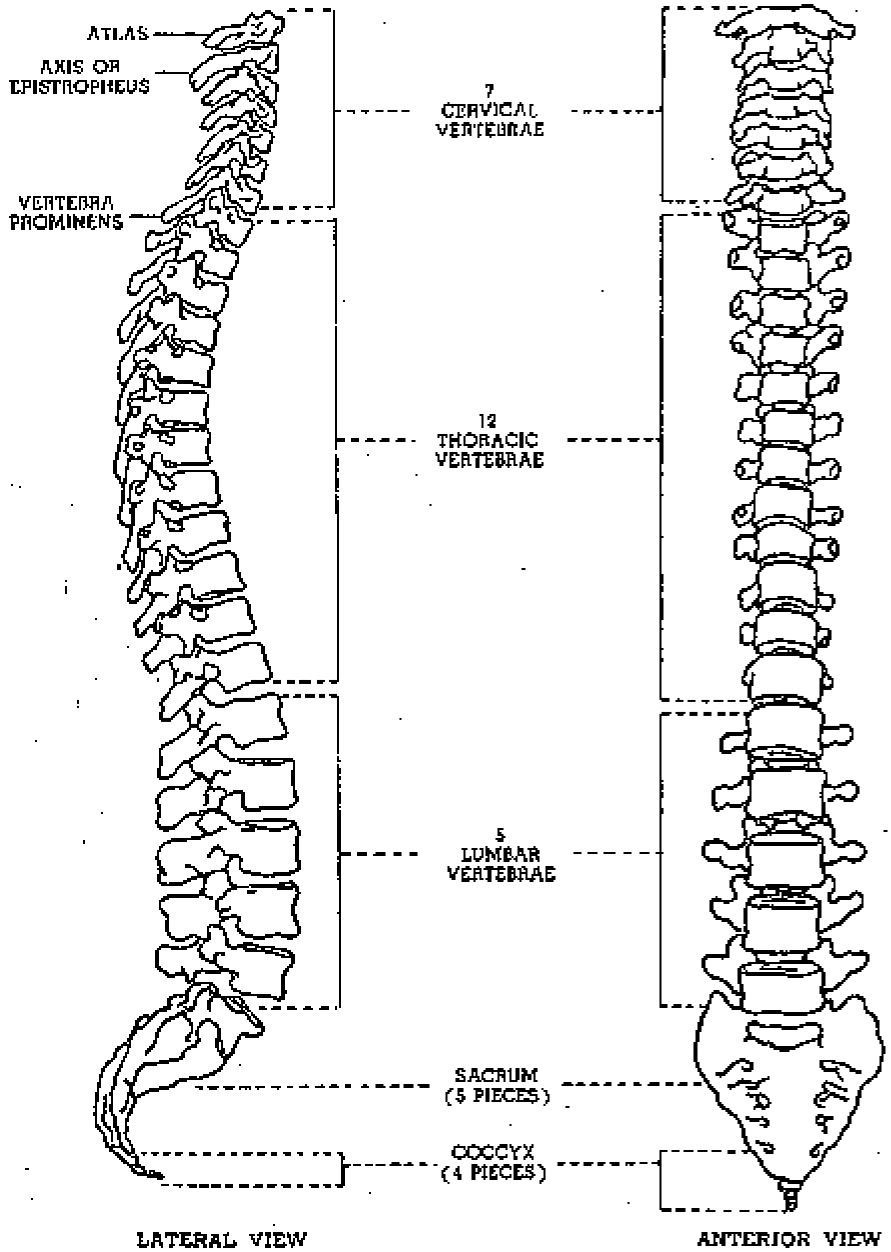

Figure 2: The vertebral column.

(from A Guide to Radiological Anatomy, Pub. No. 69-3416C. Published by General Electric, Medical Systems Dept., Milwaukee, Wis.)

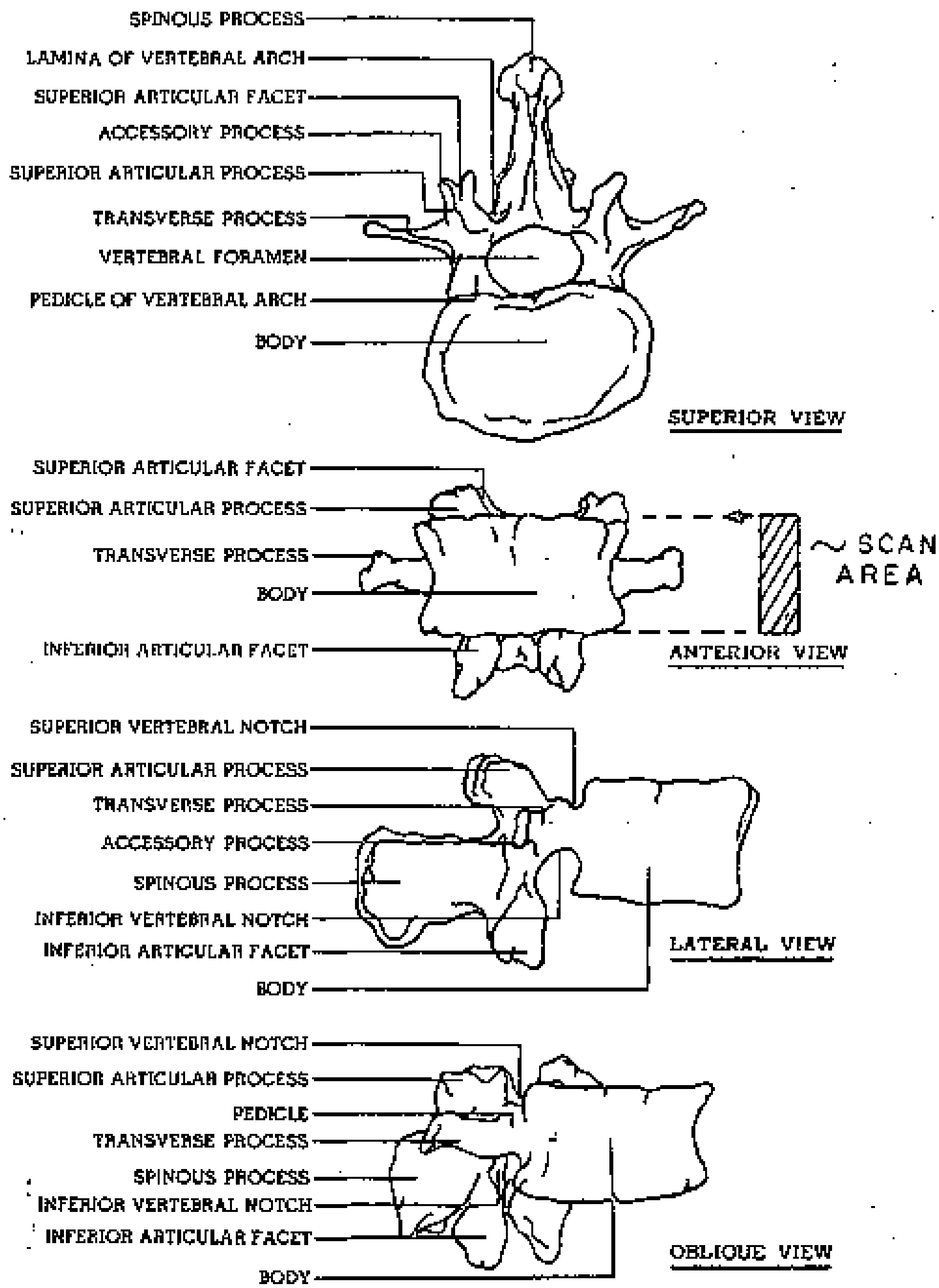

Figure 3: A lumbar vertebra with the approximate scan area sketched to the right of the anterior view.

(from A Guide to Radiological Anatomy, Pub. No. 69-3416C. Published by General Electric, Medical Systems Dept., Milwaukee, Wis.)

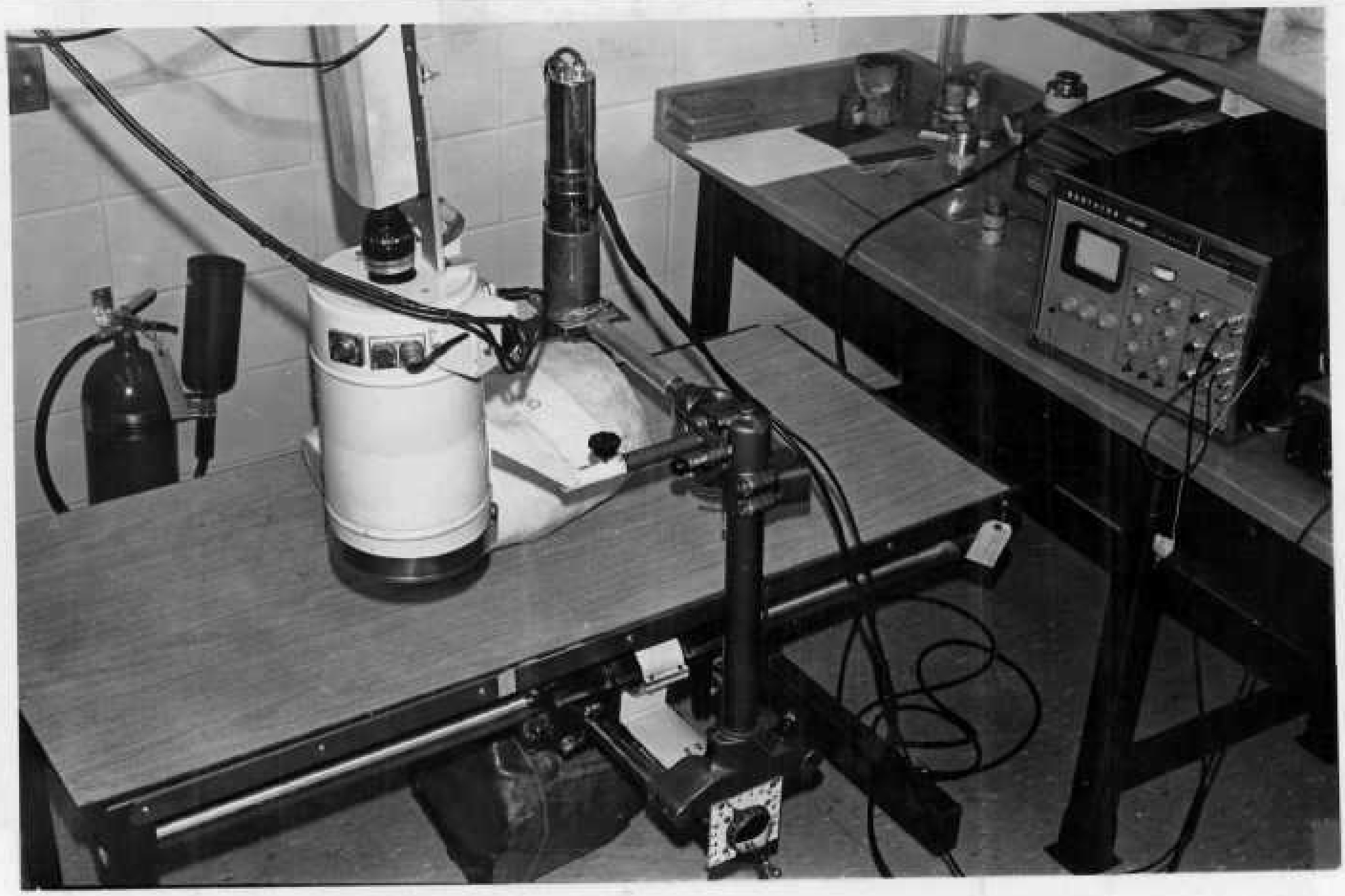

Figure 4: A photograph of the vertebral bone mineral measuring apparatus with the NaI(Tl) crystal and photomultiplier tube in position over a torso phantom. The white cylinder to the left is the image intensifier.

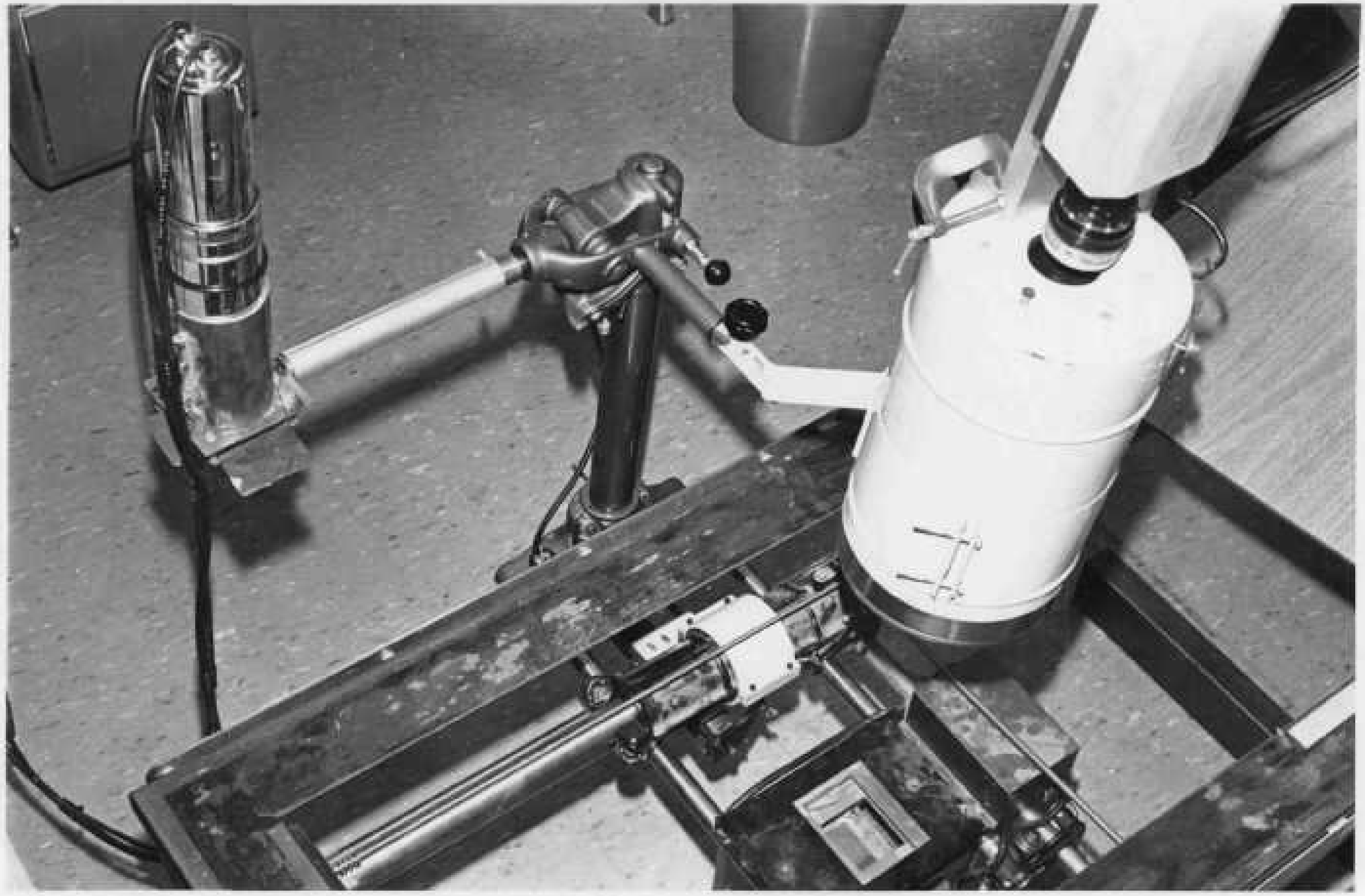

Figure 5: A photograph of the apparatus with the table top partially removed and with the image intensifier in position above the x-ray tube.

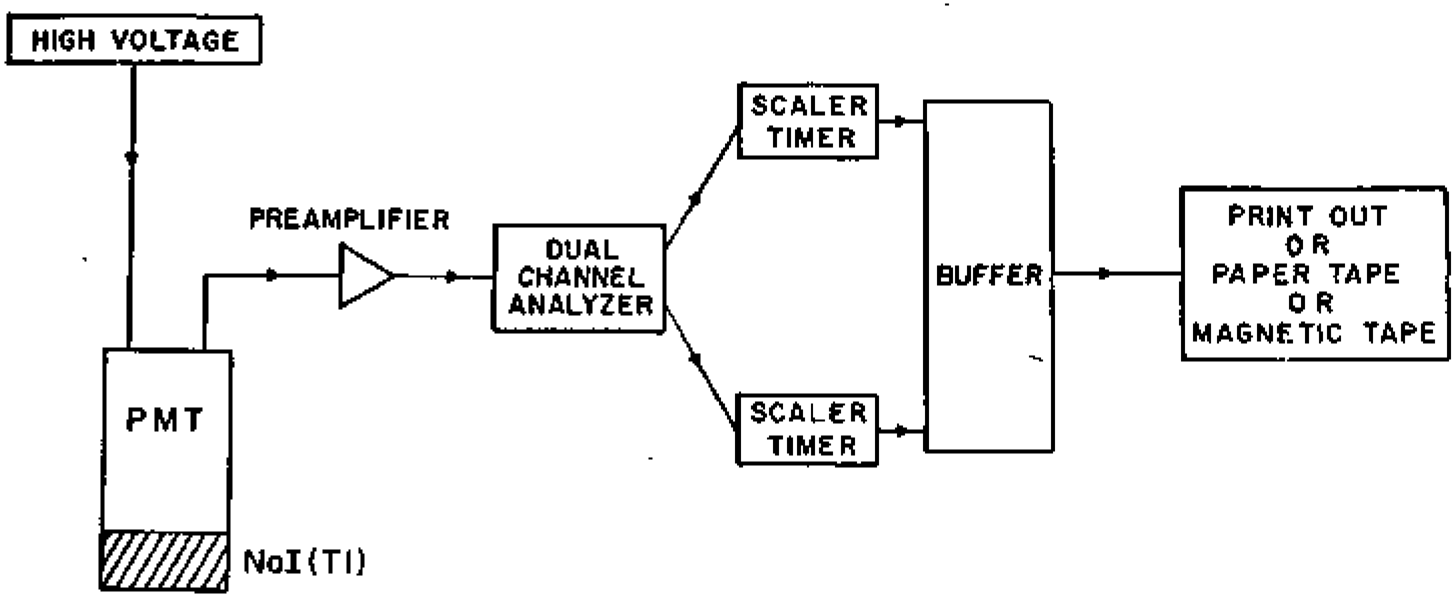

Figure 6: The basic electronic components needed to analyze a dichromatic transmission scan.

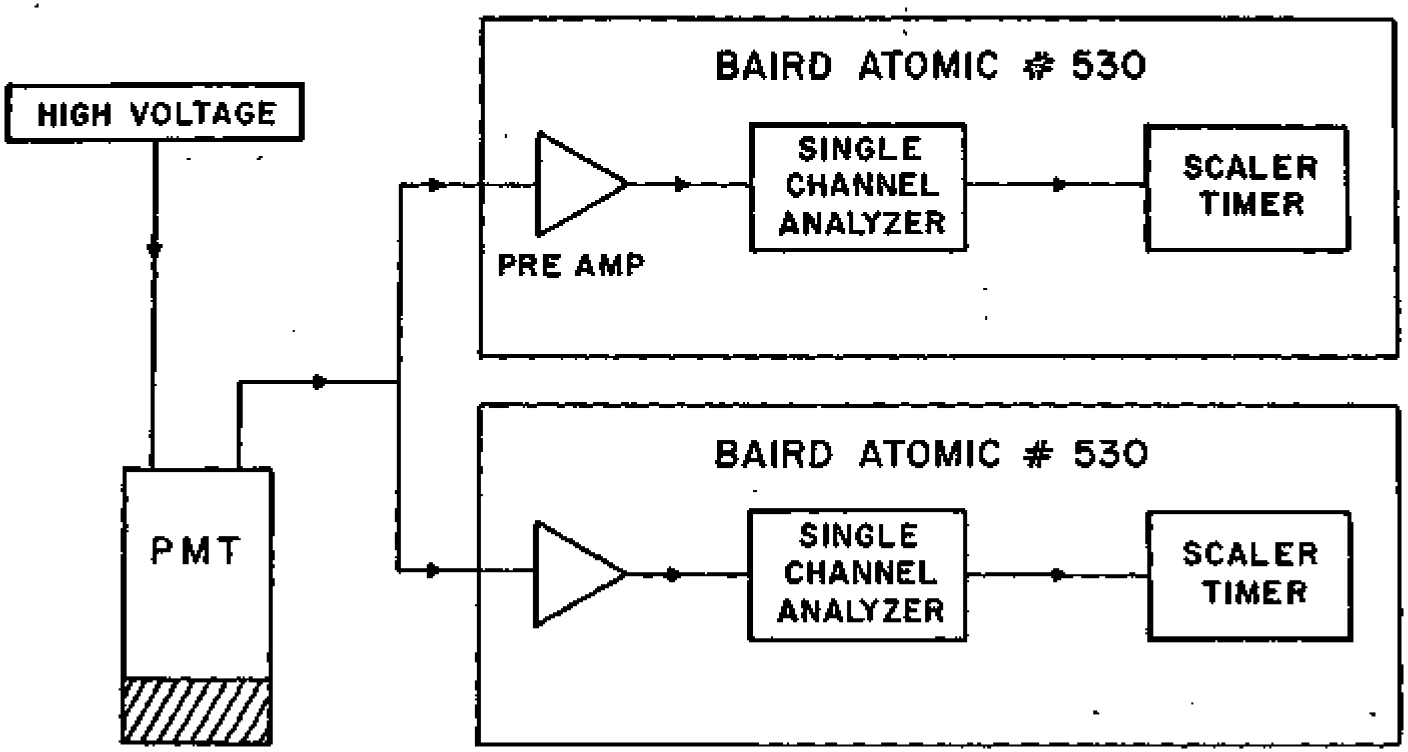

Figure 7: The electrical components used in preliminary measurements.

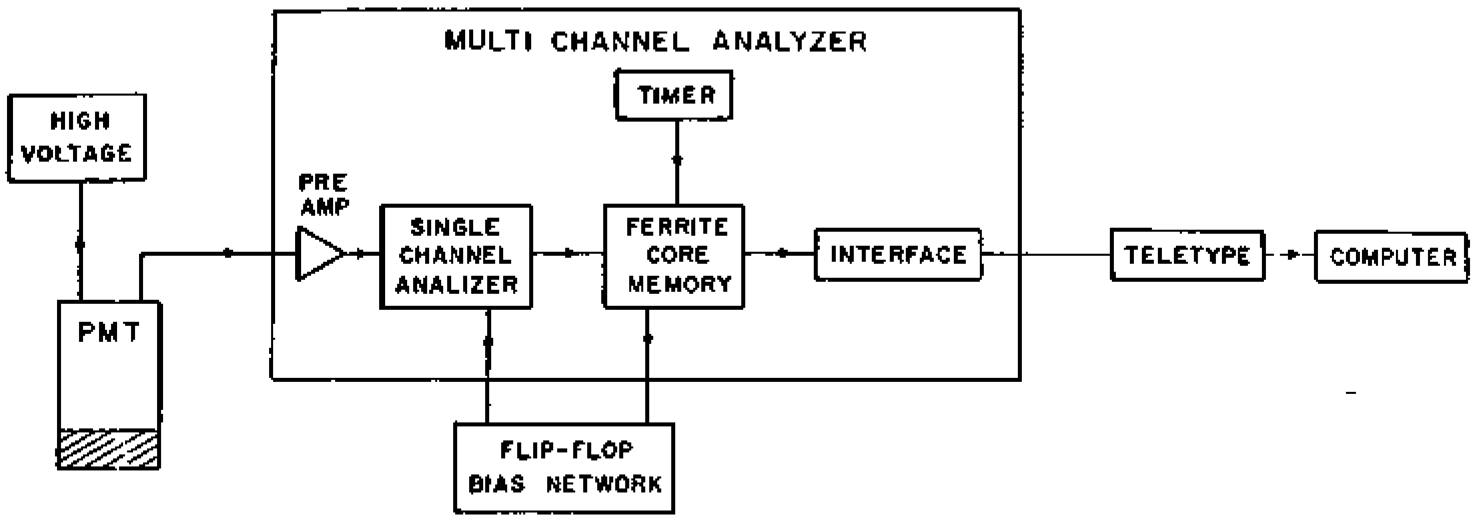

Figure 8: The electronic components currently being used.

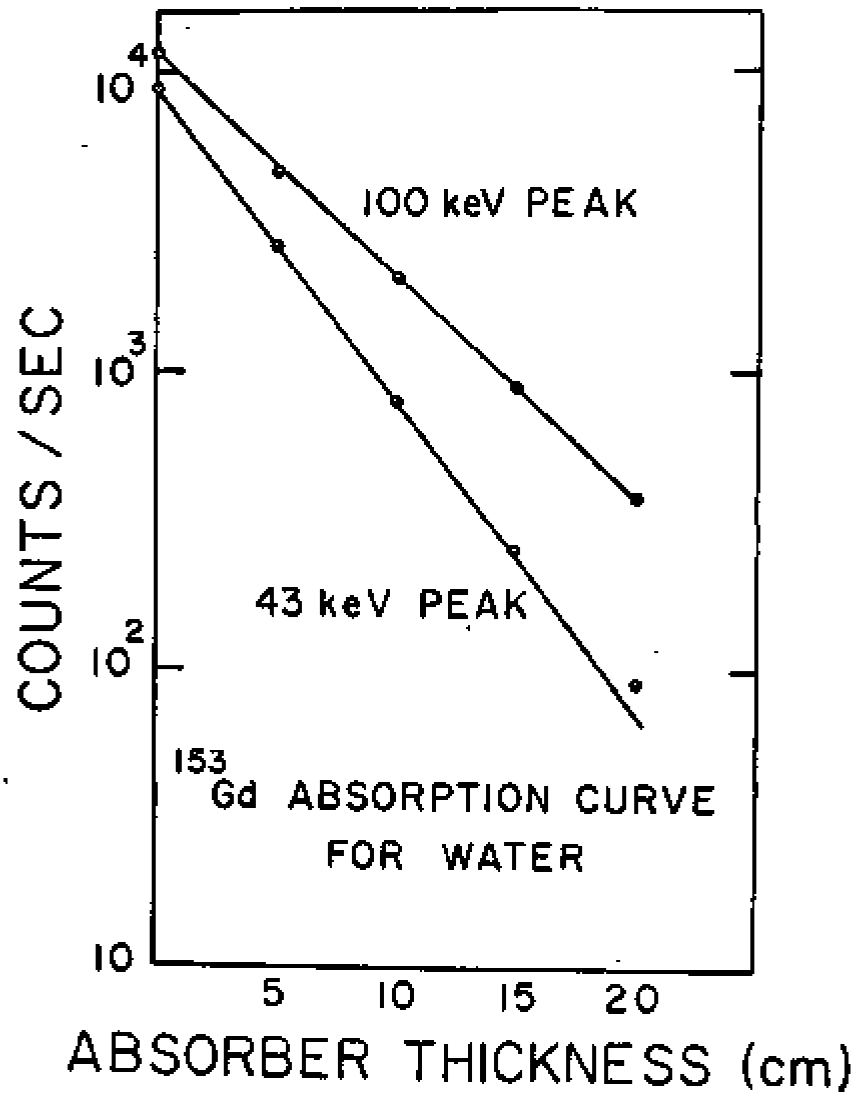

Figure 9a: The photon absorption for the two principal energy peaks of Gd-153 in water.

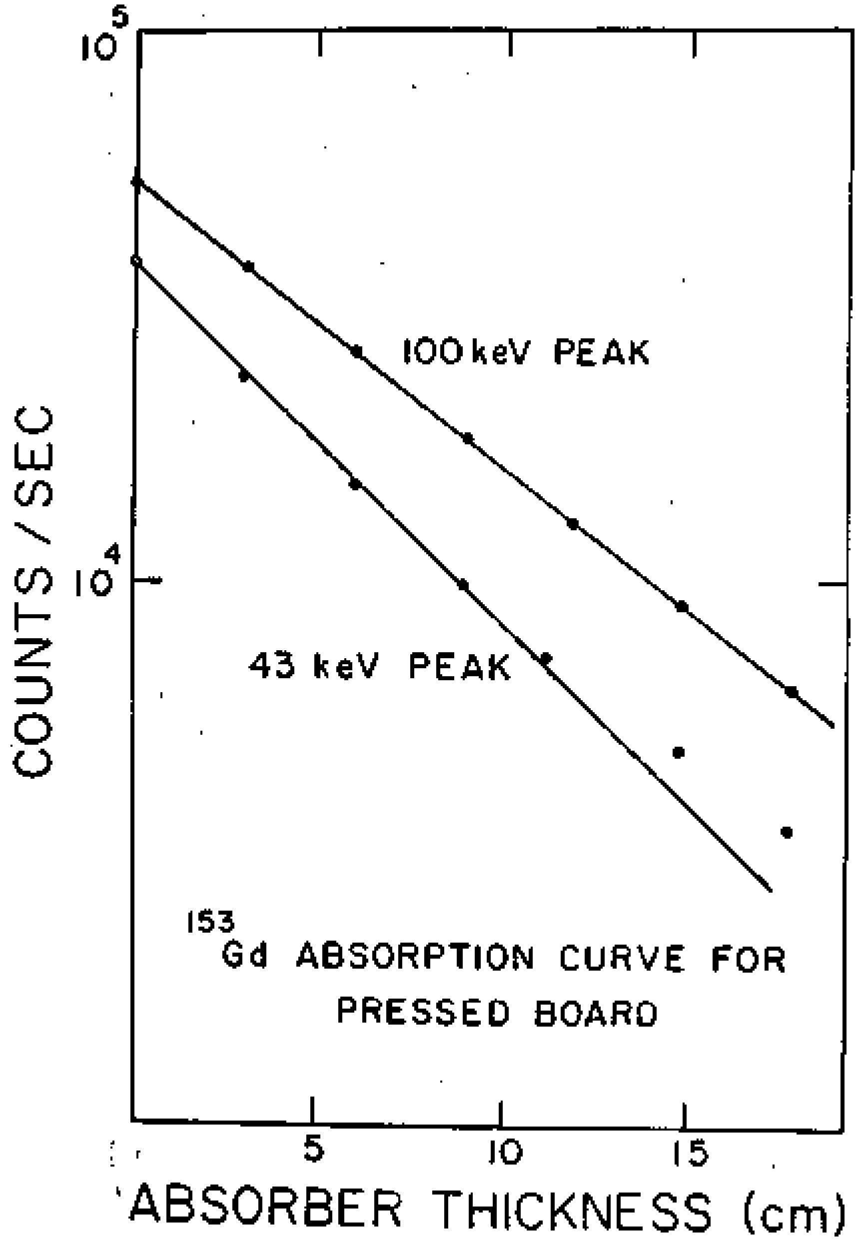

Figure 9b: The photon absorption for the two principal energy peaks of Gd-153 in pressed board.

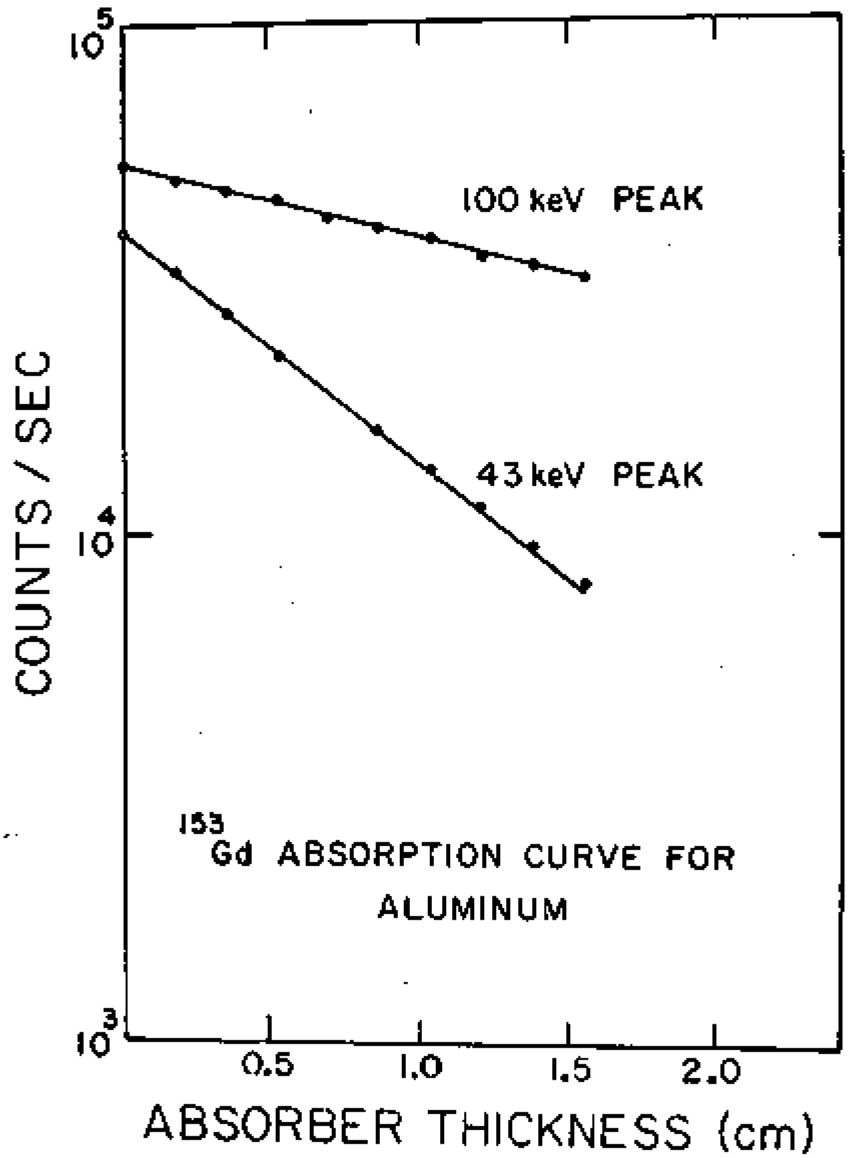

Figure 9c: The photon absorption for the two principal energy peaks of Gd-153 in aluminum.

Figure 10: An x-ray of the torso phantom we used for preliminary scans. The top vertebral body in this photograph is L-3.

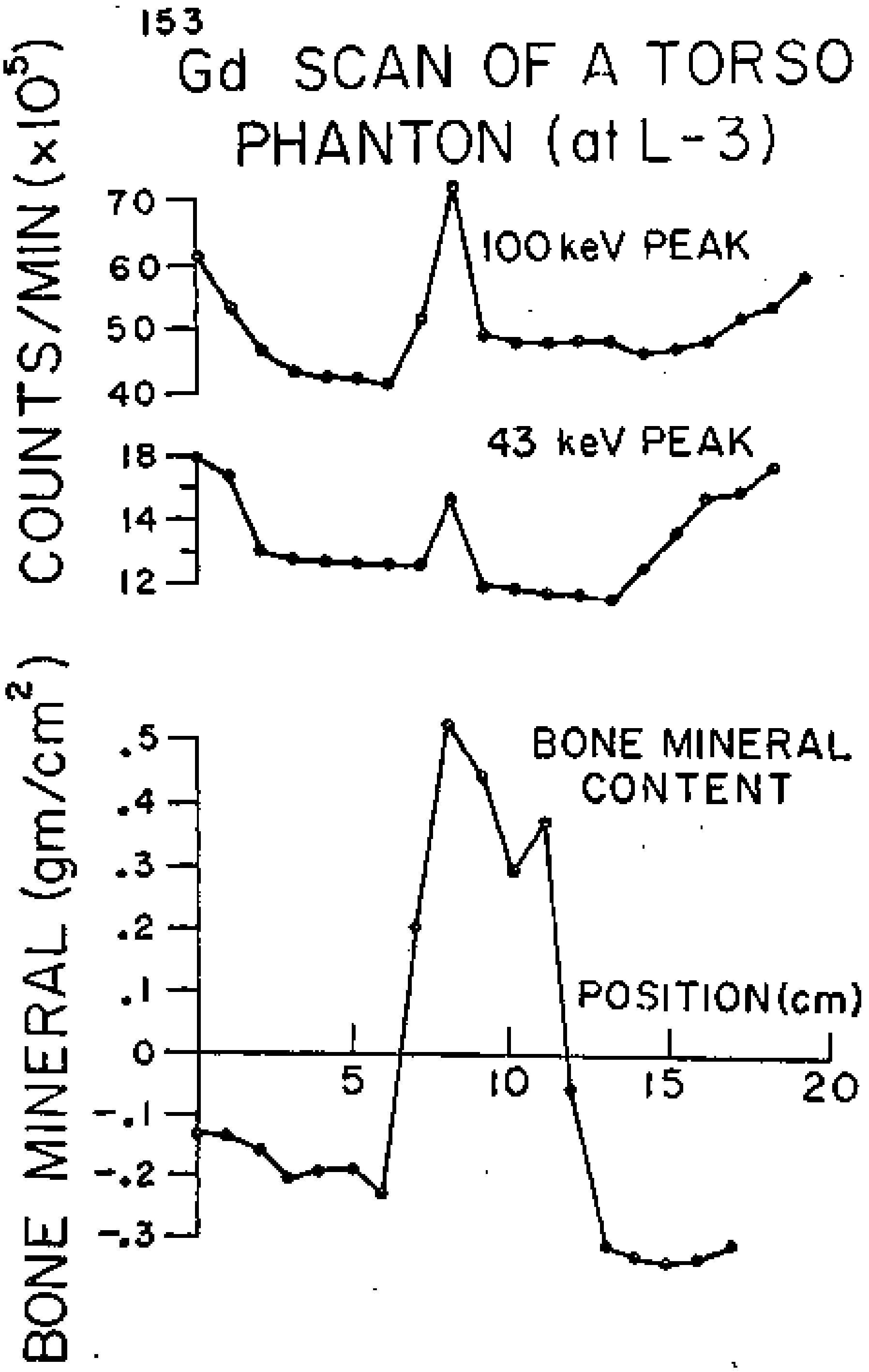

Figure 11: The data and calculated bone mineral for the phantom scan.