# RECTILINEAR TRANSMISSION SCANNING OF IRREGULAR BONES FOR QUANTIFICATION OF MINERAL CONTENT

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A recent modification of gamma-ray densitometric equipment has provided a significant advantage over older methods of evaluating bone-mineral content of irregular bones.

Heretofore, the two methods primarily employed to quantify bone-mineral content of osteoporosis (*1–2*), fracture healing (*3*), and the effect of weightlessness (*4*) have been based upon, first, x-ray analyses with subsequent densitometry of the radiograph and, more recently, a photon-absorption technique introduced by Cameron and Sorenson (*5*). The x-ray technique is subject to a large number of variables which hamper standardization. The monoenergetic photon-source technique has been primarily limited to the study of regularly shaped bones such as the radius and ulna and single row scans of the os calcis (*6*).

The study reported here required the development of new instrumentation which would permit successive reproducible measurements through the adaptation of gamma densitometry to gage the degree of demineralization of the os calcis, an irregular bone.

## METHODS AND MATERIALS

Three normal volunteers were placed on 6–9 months of absolute bed rest. Analysis of the os calcis was chosen because during short periods of bed rest and weightlessness demineralization has been demonstrated in this bone (*7*). Furthermore, the os calcis is a weight-bearing bone which, during the period of study, can most easily be removed from gravitational stresses. This condition is not shared by the upper extremities and only partially so by lower extremity long bones upon which stress is placed during movement in bed, especially during rotation to a new position.

**Instrumentation.** The scanning system consists of a custom-designed rectilinear scanner interfaced with control and data acquisition electronics. The basic elements of the scanner consist of (A) scanning head with source and detector, (B) scanner drive mechanism, and (C) control electronics (Fig. 1).

The source and detector are spaced 6 in. apart and move synchronously. The object to be scanned is placed on a fixed platform between these units, thereby allowing the radiation beam to pass through to the detector (Fig. 2).

Whereas both $^{241}Am$ (59.4 keV) and $^{125}I$ (27.5 keV) sources have been used, $^{125}I$ was chosen as the preferred source since the available $^{241}Am$ source had a limited photon yield. Iodine-125 from 100 to 400 mCi activity can easily be stored and shielded and has an excellent photon yield. Initially, sources were

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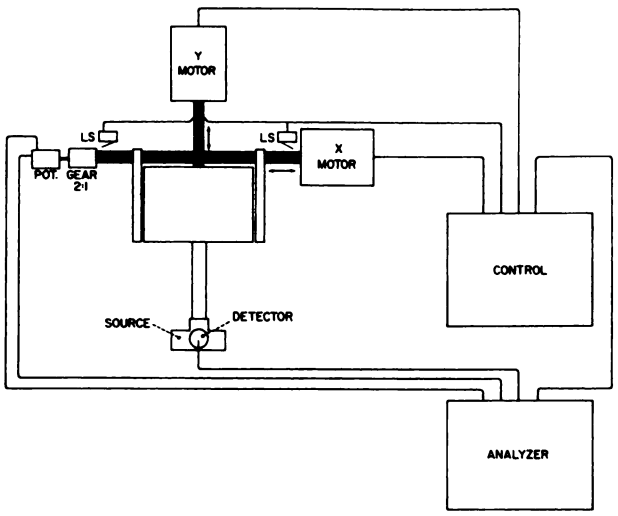


**FIG. 1.** Block diagram of rectilinear scanning system. Control unit drives x- and y-axis motors which move block containing source and detector in apposition at 6-in. distance. Limit switches control x travel distance. 2:1 gear reduces number of turns of potentiometer which relates x-axis location to voltage address of analyzer. Detector pulses are then stored in analyzer memory. When y motor is activated, control unit also signals analyzer of next y row.

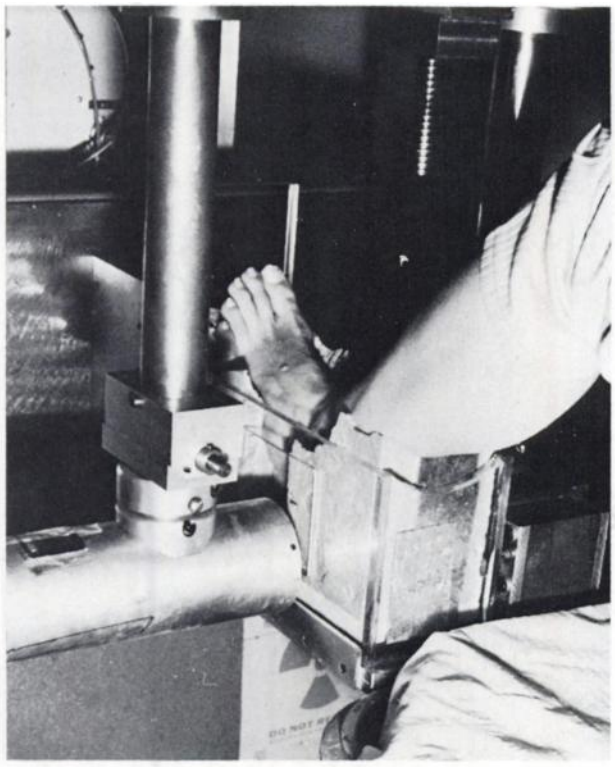

**FIG. 2.** Scanning position of foot between the source and detector. Custom-made mold placed in Plexiglas housing which is filled with water repositions foot accurately on platform. Water provides uniform tissue equivalent. Detector is on left, source is on right. Y-axis is vertical and x-axis is parallel to platform.

made by adsorbing carrier-free $^{125}I$ onto Dowex 1 × 8 resin beads (*5*). Recent sources were obtained from Atomic Energy of Canada, Ltd. They are prepared by electroplating $^{125}I$ onto charcoal beads, sealing in a metal capsule, and placing in a brass holder. This source is held in an aluminum housing which has a $\frac{3}{32}$-in. straight-bore collimator ½ in. in length mounted in direct apposition to the detector collimator and housing. A 2-mil tin filter is used to filter out the small number of 31- and 35-keV photons with a resulting beam energy of 27.5 keV.

To minimize background and to accommodate a low-energy gamma output, a Harshaw detector with a 1.5-cm diameter × 3-mm-thick NaI(Tl) crystal covered with a thin beryllium window is employed. The detector housing is fitted with a $\frac{3}{32}$-in. collimator consisting of two lead disks ¼ in. thick and spaced 1 in. apart.

Data obtained from the detector are fed through a single-channel analyzer adjusted to accept the photopeak pulses from the source within a 16-keV window and are subsequently stored in a Nuclear Data Model 3300 multichannel-analyzer system operating in a multiparameter mode. Count data are stored in the 4,096-channel analyzer memory in a 256 × 16 matrix. Storage address of the data is determined by the voltage obtained from a position-indicating potentiometer on the x-axis screw.

Accumulated data are transferred to digital magnetic tape for storage. Readout on punched paper tape and a high-speed parallel printer is used for data calculation. Two display formats are available. The contour display is a planar representation of the 16 × 256 data matrix. Intensity modulation governed by count data provides a display analogous to a radiograph (Fig. 3). This visual display is used to verify position reproducibility of a scan, each row line representing a ⅛-in. interval. The isometric display mode (Fig. 4) provides a spatial representation of the scan, giving a three-dimensional effect to the viewer. Analog counting-rate information is apparent in the display.

Data calculation utilizes the formula illustrated in Fig 5. Each row is calculated separately. The average counting rate at each side of the bone (through tissue and water only) represents 100% transmission value ($I_0$*). The counting rates represented by I and $I_0$* are accumulated during each $\frac{1}{64}$ movement of the scanner since data addressing relates to the

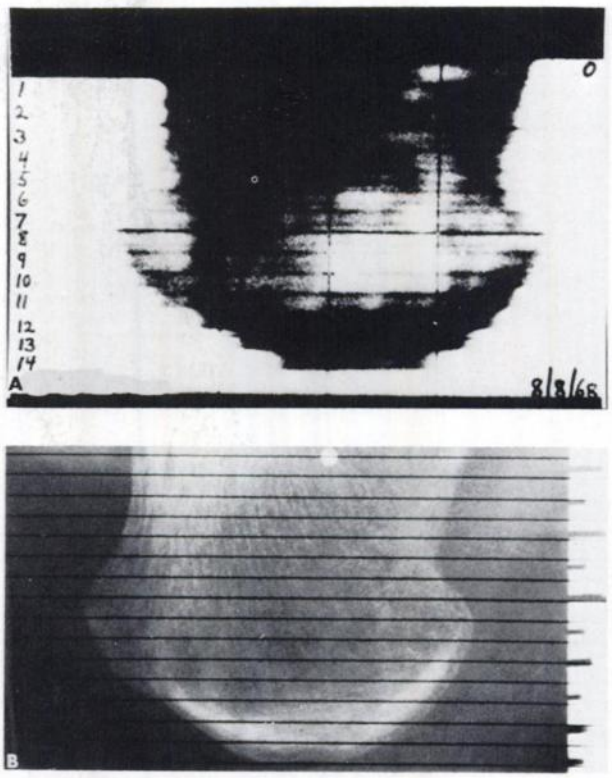


**FIG. 3.** Contour display and radiograph of os calcis. A: Contour display relates degree of radiation transmissibility to intensity of dot on oscilloscope. High transmission (tissue) is white, and low transmission (bone) appears in varying degrees of grey to black, depending upon mineral content. Photograph is obtained from defocused oscilloscope screen. B: Radiograph of same area of os calcis. Superimposed lines depict sequential scan lines, spaced ⅛ in. apart and relate to scan rows in contour display.

position of the potentiometer on the x-axis screw. Changes in speed alter sampling time but not the distance scanned. During a scan the speed is maintained constant by the use of precision stepping motors, thereby assuring a constant sampling time. The speed chosen is that which gives an $I_0$* counting rate greater than 500. The transmission value through bone for each data point, I, is ratioed to $I_0$*. The natural logarithm of these ratios is determined and summed for the row. The sum is then expressed in computer units as a positive value and is related to the absorption due to the bone interposed in that slice (*6*), increased computer unit values representing increased bone mineral (*8*).

Radiation dose to the heel is less than 3 mR/scan at these speeds and counting rate.

Data are normally calculated using a time-share computer terminal, with data entered automatically from the punched tape. Manual calculations also may be done using a programmed Olivetti 101 computing calculator.

**Systems check.** Prior to patient measurements, a daily systems check is performed. A spectrum analysis of the source is taken to identify the location of the photopeak. Coincidence circuitry can be used to identify the channels in which the photopeak resides, and the gain and window settings of the single-channel analyzer can be adjusted until a 16-keV window is centered at 27.5 keV.

Scanning of a plastic-embedded bone provides a day-to-day standard for overall systems operation. Analysis of these check values yielded a 1.8% variation (95% confidence) over a 2-month period.

Weekly calibration checks of the system are performed by scanning a step wedge containing varying concentrations of calcium hydroxyapatite uniformly suspended in a dental material.† The wedge has three different concentration zones, each containing six steps giving a total of 18 data points. Plotting the known hydroxyapatite in mg/cm² against the computer-derived absorption values gives a linear relationship of $y = 0.00240\ x + 0.05$ where y is the computer unit absorption value per data location and x is the hydroxyapatite content expressed as mg/cm².

**Patient positioning.** A mold of dental rock which permits optimum repositioning during subsequent scans is made for each patient. The mold is housed in a Plexiglass box and is placed on the platform between the source and detector (Fig. 2). The patient's foot is then positioned in the mold, and water is added. The addition of water compensates for variations in tissue thickness and thus provides a uniform tissue-equivalent thickness. Prior to the initial scan, x-rays are taken of the subject's foot in the mold. The x-ray, with scan lines superimposed, is used for future reference (Fig. 3). Scanning is begun 2 in. from the bottom of the os calcis.

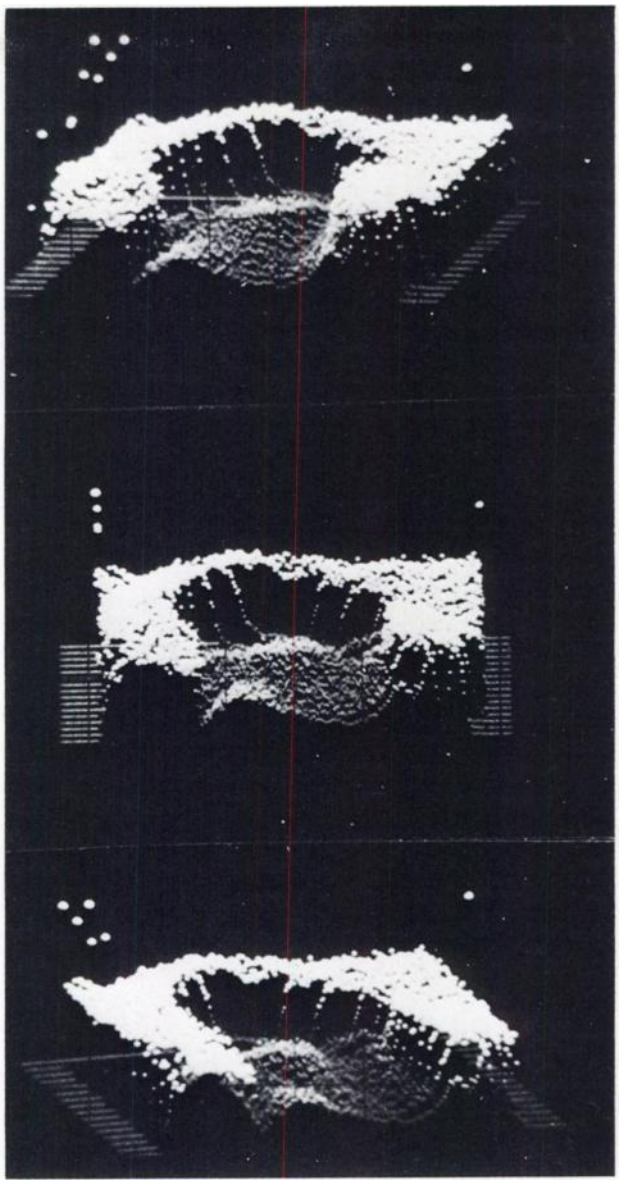

**FIG. 4.** Isometric display—os calcis. Three representations of same image viewed from different angles. High counting rate (white) represents tissue, and lower counting rate (dark) shows varying degrees of radiation adsorption as beam passes through bone. Sixteen rows of scan data are represented, one behind the other, with last row located below os calcis.

Any study involving multiple scans over a prolonged period of time demands accuracy of repositioning which is dependent upon the adequacy of the mold. Reproducibility scans were determined for each subject. Repetitive single scans were performed on an arbitrary line. After each pass, the subject

† Wedge manufactured by Zahntechn Laboratorium, Herdenstrasse 58, Stuttgart, W. Germany, according to specifications of Professors Heuck & Schmidt (*9*).

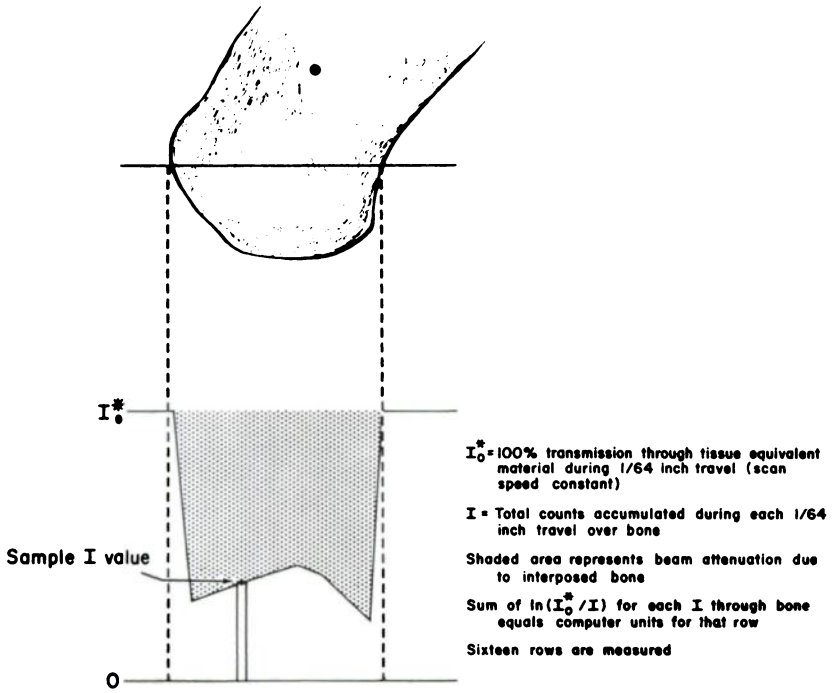


**FIG. 5.** Method of data calculation.

removed his foot, walked for 2 min, and then replaced his foot in the mold. Five passes were made in that manner. The 2 s.d. from the mean was 1.3%. Reproducibility of scans was found to be within 3.5% at 95% confidence level when an ambulatory subject was repetitively scanned over a 6-month period.

**Application of the scanning technique.** The scanning technique was applied to a study of the mineral content of the os calcis in three subjects who participated in a detailed mineral-balance study during 30–36 weeks of absolute bed rest (*10*). Twelve weeks of bed rest preceded the complete testing of the scanning system. Periodic measurements of 14–16 scan rows of the left os calcis of each subject were performed both during his ensuing bed rest period and subsequent reambulation. One subject (RR) was studied for a year after reambulation.

The absorption values for each scan row expressed as computer units were plotted against scan-row location. The data for GB is shown in Fig. 6. The values obtained during bed rest appear on one graph

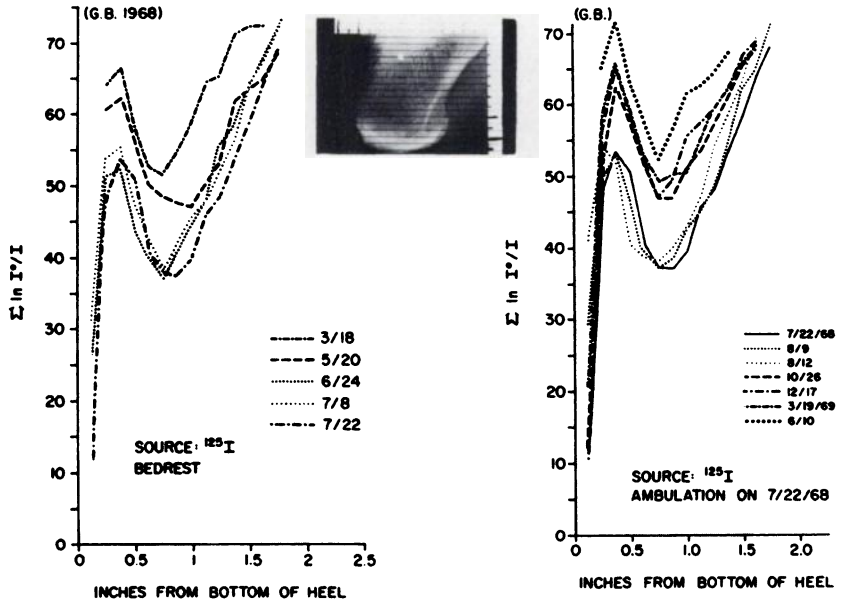


**FIG. 6.** Mineral content expressed in computer units for subject GB before and after bed rest. Relative mineral content for each scan row as identified in x-ray is plotted as location from bottom of heel for each of indicated dates. Last bed rest values are reproduced on ambulation graph as solid line. Increased rate of loss and regain of central os calcis, in contrast to higher areas is shown.

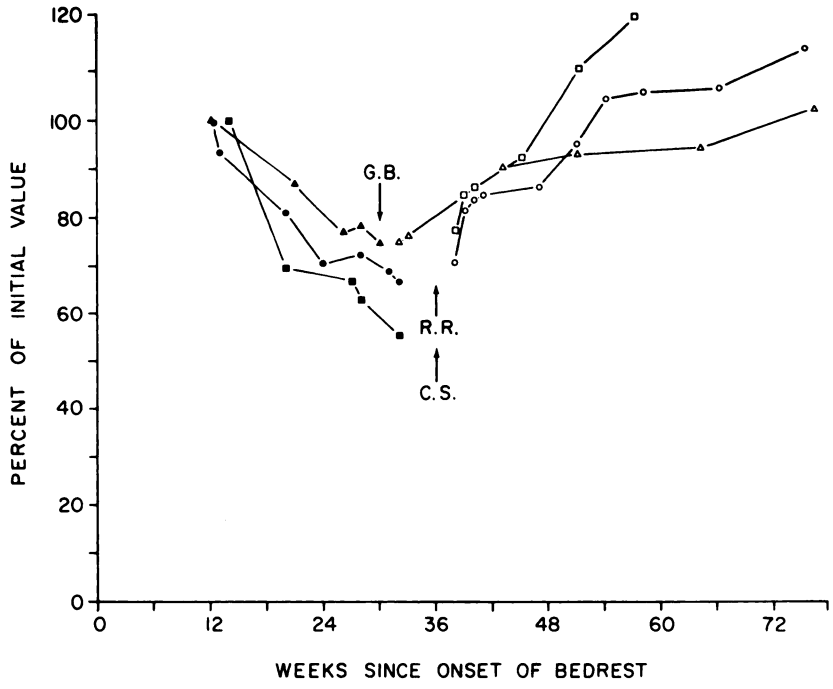


**FIG. 7.** Percent of mineral loss as function of weeks from onset of bed rest. First studies obtained 12 weeks after initiation of bed rest. Time of reambulation is indicated by arrows.

and those of reambulation on the other. The location of each scan row is easily identified on the accompanying x-ray.

## RESULTS

The variation of mineral content in different portions of the os calcis is evident in Fig. 6. Areas in the central os calcis, rows 3–11, lose mineral more rapidly and, conversely, regain it more rapidly when reambulation occurs. Areas higher on the bone are less affected and therefore regain mineral slowly.

Over 30–36 weeks of recumbency, when the sum of 9 rows in the areas of the central os calcis is plotted (as percent of the initial value vs. weeks since the beginning of bed rest) rather large mineral losses are demonstrated (Fig. 7). The degree of disuse osteopenia appears to relate to the initial mineral content. Initial mineral values expressed in mg/cm$^2$ were 694.3, 587.0, and 518.5 for GB, RR, and CS, respectively. The subject with the greatest initial mineral content, GB, lost the least mineral, 174.3 mg/cm$^2$, and conversely CS, who had the least, lost 230.7 mg/cm$^2$. The rate of mineral regain appears to follow a similar pattern. Lack of uniformity in loss as well as regain of mineral suggests a remodeling activity within the os calcis when gravitational forces are again brought into action.

The percent losses during the 12th through 36th week of bed rest for CS and RR were 44.5 and 33.3%, respectively, and for GB, during the period of 12 to 30 weeks, 25.1%. In contrast, a 3% 2 s.d. value was observed on a normal ambulatory volunteer who was studied over a period of 30 weeks. After reambulation, GB, CS, and RR returned to the initial 12-week value in 70, 47, and 52 weeks, respectively. The rates of loss during successive 12-week periods are shown in Table 1. Losses during the 12–24-week bedrest period were greater than for the 24–36-week period.

## DISCUSSION

A single cross section of the os calcis can be repetitively scanned within 2% provided the scans are performed on the same day. Over a period of time, changes in the soft tissue resulting from inactivity of the foot and not wearing shoes alter the overall external anatomy of the foot. Under such circumstances, the foot may slip a little lower into the mold so that the individual scan lines may not be precisely reproducible and may vary by approximately $\frac{1}{32}$ in. The contour display mode of data presentation makes it possible to superimpose row data with this limit of variation on successive scans.

**TABLE 1. PERCENTAGE MINERAL LOSS**

| | 12–24 weeks | 24–36 weeks |
|---|---|---|
| RR | 28.9 | 4.4 |
| CS | 33.7 | 10.8 |
| GB | 22.3 | 2.8* |

* 24–30 weeks.

Since there is a rapid change in cross-sectional diameter of the os calcis, significant errors in localization can occur in the two lowest rows. The trabecular pattern is not uniform in a medullary bone such as the os calcis; thus the values may vary when the rows do not precisely match.

To overcome these problems in data presentation, bone mineral content for 9 rows in the central os calcis was summed to minimize small positional changes. These 9 rows comprise a total of 1⅛ in. of bone in the vertical axis and the total bone in the horizontal axis. When the bone mineral for this large segment of the os calcis is compared from scan to scan in a normal subject over a 6-month period, a very small variation between scans is present (s.d. ±2%).

The presentation of data in this study differs from that in studies of the radius or ulna, where slight longitudinal variations in the selection of a scan row make less difference in results. The variation of the mineral content as one scans higher on the os calcis has been graphically represented (Fig. 6).

Although no previous study has attempted to assess the mineral content change of the os calcis for a period of bed rest longer than 30 days, it has been clinically suspected that the os calcis exhibits large losses during disuse. This study demonstrated rather large losses of mineral in the os calcis in three subjects. This is in contrast to the loss of approximately 3% of the total-body calcium as demonstrated by balance techniques (*10*). It is reasonable to assume that the losses from the os calcis were not representative of losses in other parts of the skeletal system. Because the upper extremities were being used almost to a normal extent, they probably were not involved in mineral loss. Current studies of the radius and ulna support this assumption.

The os calcis, by virtue of its unique weight-bearing role and its primarily trabecular quality, appears to respond more quickly to factors involved in disuse osteopenia resulting from bed rest as demonstrated in this study. Whereas muscular forces are applied to other bones during rotational movement in bed, the os calcis is, for the most part, spared. During weightlessness of space flight, the same phenomenon can be expected; therefore the os calcis can be an early monitor of potential demineralization and calcium loss.

## SUMMARY

A system which permits accurate and reproducible evaluation of bone mineral content has been described. By utilizing the gamma absorption principle, various uncertainties of the radiographic approach are eliminated. The use of automated multi-row scanning and data handling techniques permits study of irregular bones as well as the more regularly-shaped bones of extremities which can be studied by single-line scans. The system's usefulness has been confirmed through its successful use in long-term studies of bed-rest subjects.

Further studies aimed at the evaluation of remedial measures in the prevention and treatment of disuse osteopenia are in progress.

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