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A Whole-Body Counter for Precision *In Vivo* Measurement of Radio-Iron

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ABSTRACT. The *in vivo* counting system described accurately measures the absolute level of total body ^{59}Fe, regardless of body size or isotope distribution. These results are accomplished by: (1) counting only the Compton scatter radiation emitted from the body rather than the full energy unscattered photons; (2) employing an optimum arrangement of multiple NaI crystal detectors; and (3) surrounding the subject with tissue equivalent plastic pellets. This counting system provides an accurate and efficient means for studying iron absorption or loss in man.

1. Introduction

During the past two decades, ^{59}Fe has been used extensively to measure body iron exchange in man. Its use requires a method that will accurately reflect the total body isotope content regardless of its distribution within the body. Whole-body counters can provide such a method provided the isotope reaches a constant distribution within the body and body size can be standardized or allowance made for differences. ^{40}K, ^{137}Cs and ^{24}Na are good examples of isotopes that can be measured reliably by most whole-body counters, regardless of the type of geometry or radiation detector used, because of their uniform body distribution. Other isotopes, such as ^{59}Fe and ^{65}Zn, do not reach a fixed distribution until one to several weeks after their administration. Thus, changes in counting efficiency may have occurred due to changes in self-absorption of γ-rays within the body. Warner and Oliver (1966) have described a whole-body counting method for ^{59}Fe in which errors due to absorption of γ-rays within the body were minimized by using two opposing collimated detectors and employing the combined count of the Compton scatter and photopeak region. Appreciable changes in detector responses still occurred, however, when comparing a localized with a distributed source of radio-activity.

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Our objective has been to develop a whole-body counter designed specifically for iron absorption measurements, using the principles of the Warner–Oliver counter but attempting to overcome the residual geometrical and self-absorption errors.

2. Preliminary studies

Several counter arrangements have been developed which give a constant count rate from a point source in air when placed in any position normally occupied by the body, but when the source is placed in various positions within a water-filled phantom, the count rates may vary by as much as a factor of two. However, studies with such a counter (Palmer and Langford 1967) show that if the Compton scatter region of the γ-ray spectrum is used, rather than the photopeak region which is normally used, the count rate becomes practically independent of the position of the source. Table 1 shows a comparison of counts in the Compton scatter region versus the photopeak region for a ^{137}Cs source (γ-ray energy = 0·662 Mev) placed in various positions from the centre to the outside of a 25·4 cm diameter phantom. All counts in the Compton scatter region were within $\pm$ 1·6%, whereas with photopeak energies, the count in the outside position was 83% higher than the centre.

Table 1. Comparison of count rate in Compton scatter region with that in photopeak region for a point source of ^{137}Cs in cylindrical water phantom

Source position	Compton scatter (counts/min)	Photopeak (counts/min)
Centre of phantom	67,662	30,919
Distance from centre: 2·5 cm	68,170	31,943
5·1 cm	68,357	34,343
7·6 cm	69,231	38,207
10·2 cm	69,453	44,572
12·7 cm	67,216	56,508
Average	68,348	39,398
Range	+1·6% −1·6%	+43% −22%

Since the body is more nearly elliptical in shape, an ellipsoidal water phantom was constructed from styrofoam plastic to provide phantom walls of low mass. The water-filled phantom had a minor axis of 22·9 cm, a major axis of 39·4 cm and was 30·5 cm high. Four 15·2 cm diameter by 10·2 cm thick NaI(Tl) detectors were placed around the phantom as shown in fig. 1; their optimum position was empirically determined such that a point source of ^{59}Fe placed anywhere in the phantom on a plane parallel to the centre of all four detectors

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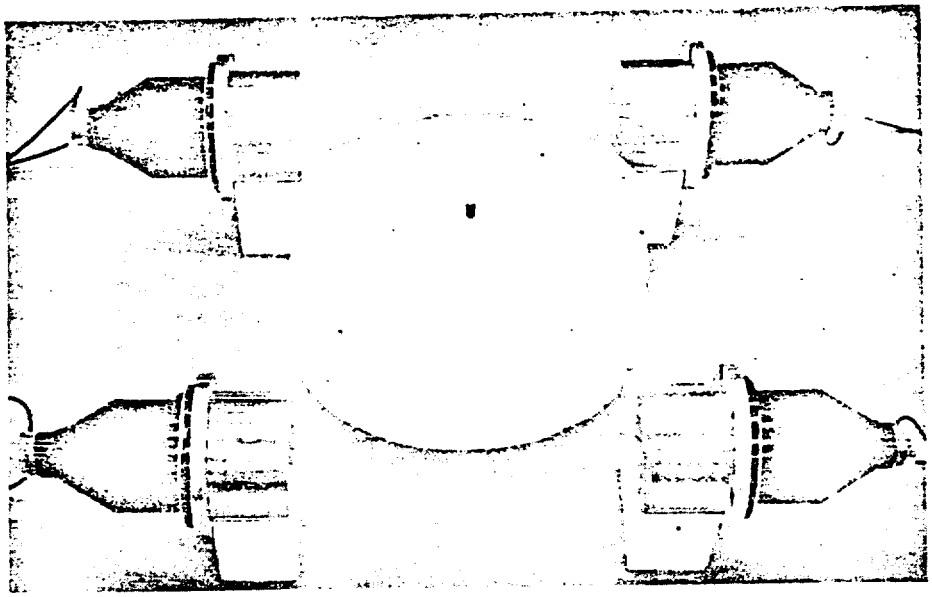

Fig. 1. Water phantom used to determine optimum crystal position.

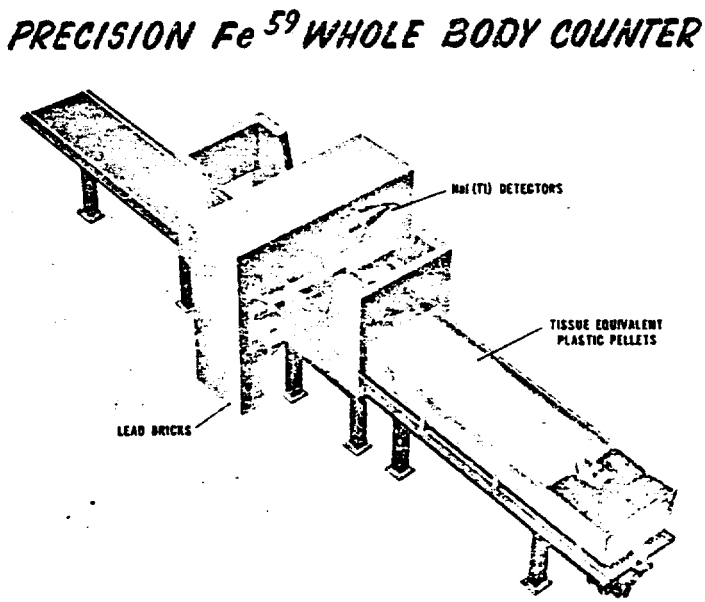

Fig. 2. ^{59}Fe whole-body counter demonstrating the use of Delrin plastic placed around the subject to obtain uniform thickness.

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gave the same count rate in the Compton scatter region. The optimum arrangement of the detectors for ^{59}Fe γ-rays is 43·2 cm between the faces of the two vertical sets of opposing detectors, and 38·1 cm between the sides of the detectors in the two horizontal sets.

3. Whole-body counter

The detectors in the arrangement described above were placed in a shadow shield type (Palmer and Roesch 1965) whole-body counter shown in fig. 2. Diagrammatic scale drawings of the detector and shielding configurations are shown in fig. 3. This counter was designed to minimize the required lead brick shielding. The subject is transported in a mobile carrier through and beyond the major viewing area of the detectors.

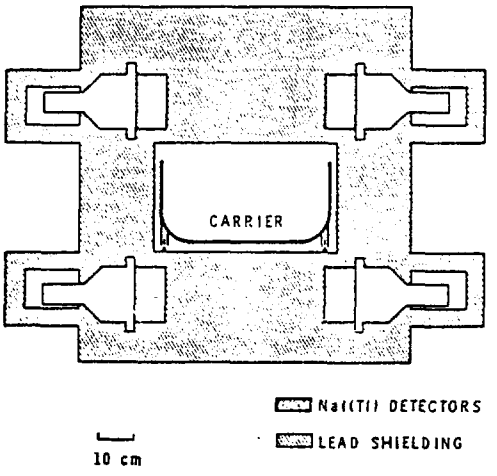

Fig. 3 (*a*). Scale drawing of detectors inside lead shielding (end view).

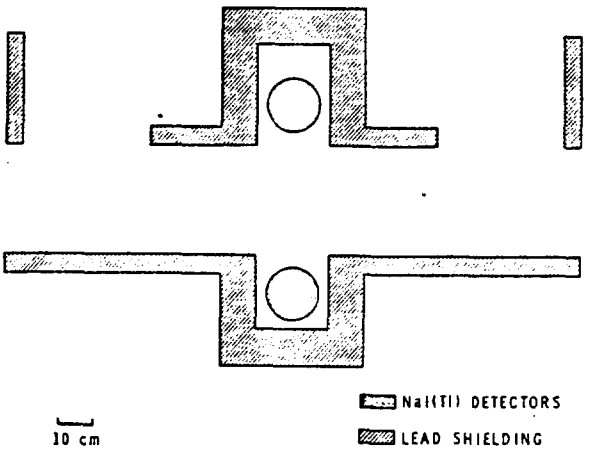

Fig. 3 (*b*). Scale drawing of a cross section of ^{55}Fe counter (side view).

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The shielding weighs about 5 tons. The centre section of 10·2 cm thick lead is 99·1 cm high, 40·6 cm wide and 91·4 cm long. The 5·1 cm thick shadow shielding extends out 61·0 cm from each side of the centre section and is constructed so that background γ-rays from the surrounding room cannot directly enter any of the detectors without going through at least 7·6 cm of lead. The opening through the lead bricks for the patient and carrier to pass through the counter is centred between the four detectors and is 50·8 cm wide and 30·5 cm high. The total length of the counter is 4·72 metres. The carrier is driven by a stepping motor and chain drive that is controlled by a constant speed pulser. When a multi-channel analyser is used, the speed can be controlled by pulses from the live time scaler of the analyser, so that errors caused by the dead time of the analyser are eliminated (Sheen, Palmer and Stringer 1967). The patient carrier is made of 0·32 cm thick aluminium, and the inside dimensions are 20·3 cm deep, 46·4 cm wide and 2·13 metres long. The radius of curvature of bottom corners of the carrier is 7·6 cm. The cost of the counter as shown in fig. 2 without the four detectors and counting instruments was about $3,000, and the cost of the detectors was approximately $10,000.

The rather small tunnel through which the patient travels during a traverse count has not presented any problems. However, the patients would feel less confined during the counting procedure if the tunnel dimensions were enlarged with the addition of more lead bricks to provide a proportional increase in shadow shielding.

4. Characteristics of the counter

The best results with patients would be expected if they were all of the same size and had the same general body contour. The same effect can be accomplished by layering small pellets of a heavy plastic called Delrin over the person until level with the top of the aluminium carrier. The small Delrin plastic has a density of 1·4 but the bulk density of the small 0·32 cm pellets is about the same as the human body. Delrin is a polymer of the molecule—OCH_2—and consists of 53% oxygen, 40% carbon, and 7% hydrogen. A point source of ^{59}Fe placed within a Delrin phantom provides a useful means of assessing the distributional effects of ^{59}Fe activity as they might occur *in vivo*. The Delrin can be easily poured in around the subject, and after counting it can be removed rapidly with a vacuum hose connected to a 40-gallon tank in which the Delrin is stored.

When a source of ^{59}Fe was placed anywhere in the Delrin-filled carrier, the accumulated count rate during a 10-minute traverse of the carrier was within $\pm 4\%$ for all positions in a Delrin thickness of 21·6 cm. This was similar to the results obtained earlier in the water phantom, even though the shape and width of the carrier were slightly different. Fig. 4 shows the relative count rate of the Compton scatter events as a point source is placed in various positions in a vertical cross section of Delrin pellets. This relatively constant counting rate occurs over the entire length of the Delrin-filled carrier, except at 10 cm

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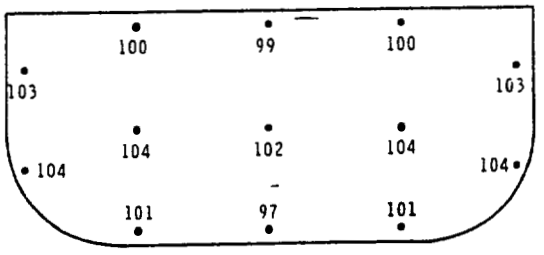

Fig. 4. Relative count rates obtained with different locations of a point source of ^{59}Fe in a vertical cross section of Delrin plastic pellets.

from each end where it begins to drop. 10 cm or more of Delrin on each end of the subject eliminates the end effect that would occur if ^{59}Fe in the top of the head or bottom of the feet did not have scattering material completely surrounding them.

Fig. 5 compares the γ-ray spectra of two measurements of a point source of ^{59}Fe placed at two extreme positions in Delrin. Curve A was obtained when the source was placed on top and near the side of the Delrin phantom, and curve B when it was in the centre. A large reduction in photopeak counts was obtained as the source was moved into the centre because of increased

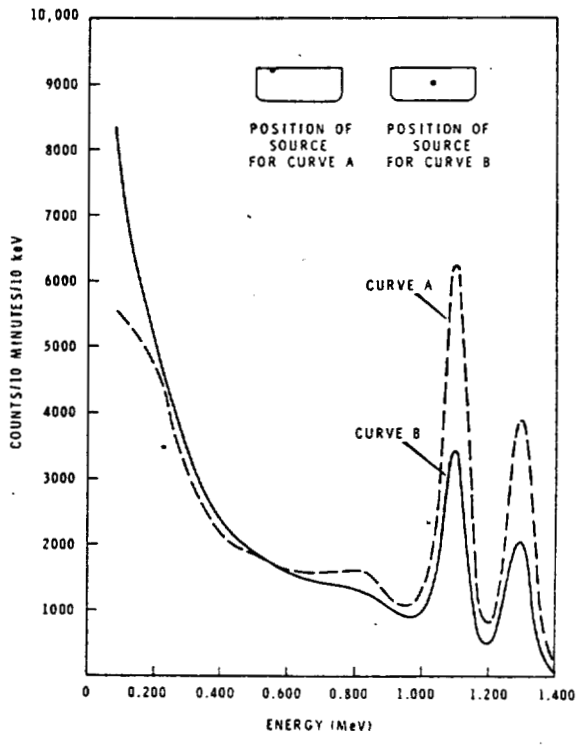

Fig. 5. Gamma-ray spectrum of ^{59}Fe from two different conditions of absorption by tissue equivalent material.

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absorption of the γ-rays, whereas the area under the Compton scatter region remained nearly the same. For the latter region, a slight reduction of counts in the region of 800 kev was offset by a comparable increase in counts below 500 kev, with the result that the integral count rate between 90 and 960 kev remained constant. This explains why the use of the Compton scatter photons provides a count rate that is independent of the location or distribution of the radioactivity.

Fig. 6 shows a spectrum from a 10-minute count of 1 μCi of ^{59}Fe in a human subject packed in Delrin after the background of the counter and the subject have been subtracted. The Compton scatter region of energy used in all studies includes all events between 90 and 960 kev and is shown by the shaded region of the spectrum. The 10-minute net count rate in the Compton scatter region was 144,000 with a background of 30,500, whereas the photopeak measurements gave values of 43,000 and 4,200 respectively. The standard

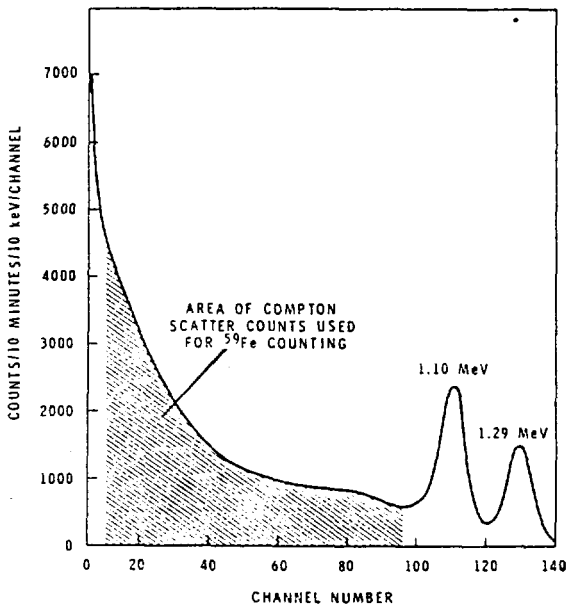

Fig. 6. Gamma-ray spectrum of a whole-body count in a subject containing 1 μCi of ^{59}Fe.

deviation of the net count, considering only counting statistics, is $\pm 0{\cdot}31\%$ and $\pm 0{\cdot}53\%$ for the Compton scatter counts and photopeak counts respectively. Therefore, the use of Compton scatter allows both greater absolute accuracy and precision for determining the total body content of ^{59}Fe. The background for Compton scatter count of a subject added from 1,500 to 2,000 counts to the counter Compton scatter background depending upon the body size. The counter background remained quite constant from day to day within a three-week period. Background counts measured during a 10-minute traverse on

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40 occasions over a one-month interval gave a standard deviation 2·2 times the value for a single background count as determined by the Poisson distribution for radioactive decay, indicating excellent day-to-day stability of counter background. To obtain count rates with low statistical error, a minimum ^{59}Fe whole-body activity of 0·20 μCi is required which gives a net whole-body count rate equal to the counter background and a standard deviation of $\pm 1\%$ for a standard 10-minute traverse.

5. Discussion

Several investigators have obtained improved whole-body counting results with different isotopes using the combined counts of the photopeak and scatter region or just the scatter region (Gibbs, Hodges and Lushbaugh 1966; Warner and Oliver 1966; Genna 1966; Dudley and ben Haim 1968; and Naversten, Lidén, Stahlberg and Norden 1969), and it has been suggested (Dudley and ben Haim 1968) that the majority of γ-rays emitted in the body with energies exceeding 1·0 Mev ultimately emerge from the surface although their energy may be reduced and their angular distribution altered by Compton collisions. Although this suggests that both photopeak and Compton events should be used, much more constant count rates can be obtained when only Compton scatter counts are used. Measurements on phantoms reported here indicate that the total body content of ^{59}Fe can be determined in any size person within a maximum error of $\pm 2\%$ when using the Compton scatter energy band. The application of this technique to γ-rays of other energies has not been investigated. The data shown in table 1 indicate that the method will work with γ-ray energies as low as 0·66 Mev, but a slightly different detector arrangement may be required.

The counter employed here is simple to use and requires rather unsophisticated instrumentation because of the broad band of photon energies used. We used a multi-channel analyser, but a single-channel analyser and scaler will adequately perform the counting. All whole-body counts can be compared directly with that of a standard with identical counting efficiency when placed in a Delrin phantom. Slight instrumental changes affect standard and subject comparably, so that the relationship between the two remains unchanged. Counter materials are relatively inexpensive and easily assembled. Like other types of shadow shield counters it can be disassembled and built up in a different location or can be mounted in a truck to service several locations.

Résumé

Compteur pour le corps entier, employé pour la mesure de précision du radio-fer *in vivo*

Le système pour le comptage *in vivo*, décrit dans ce mémoire, mesure avec précision le niveau absolu de ^{59}Fe contenu dans le corps entier, indépendamment de la grandeur du corps ou de la distribution de l'isotope. Ces résultats sont accomplis en: 1° comptant seulement la radiation diffusée de Compton, émise du corps plutôt que les photons non-diffusés avec énergie complète: 2° employant un arrangement optimum des détecteurs multiples au cristal de NaI; et 3° entourant le sujet de pastilles en matière plastique équivalente au tissu. Ce système de comptage fournit un moyen précis et effectif pour l'étude de l'absorption et de la perte de fer dans l'organisme humain.

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Zusammenfassung

Ein Ganzkörperzähler für genaue Messungen von Radio-Eisen *in vivo*

Das beschriebene System für Zählung *in vivo* misst genau das absolute Niveau des Gesamtkörper-^{59}Fe, unabhängig von der Körpergrösse oder der Isotopenverteilung. Diese Ergebnisse werden zustande gebracht, indem man: (1) nur die vom Körper ausgestrahlte Compton-Streustrahlung zählt, vielmehr als die ungestreuten Photonen mil voller Energie; (2) eine optimale Anordnung der vielfachen NaI-Kristalldetektoren anwendet; und (3) den Subjekt mit den gewebeäquivalenten Kunststoffpastillen umringt. Dieses Zählsystem beschafft ein genaues und effektives Mittel zum Studium der Eisenabsorption und -Verlust im Menschenkörper.

Резюме

Счетчик для измерения активности всего тела, применяемый для точного измерения радиоактивного железа *in vivo*

Описанная система для счета *in vivo* измеряет точно абсолютный уровень полного содержания ^{59}Fe в теле, независимо от величины тела или распределения изотопов. Эти результаты достигаются: (1) счетом одного только рассеянного комптоновского излучения, излучаемого телом, предпочтительно счету нерассеянных фотонов с полной энергией; (2) применением оптимального расположения большого числа детекторов с кристаллами NaI; (3) окружением субъекта тканеэквивалентными пластмассовыми шариками. Эта система счета предоставляет точное и эффективное средство для исследования поглощения или потери железа человеком.

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