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PATENT SPECIFICATION

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(71) We, PHILIPS MEDICAL SYSTEMS INC., residing at 710 Bridgeport Avenue, Shelton, Connecticut 06484, United States of America, a Corporation existing under the laws of the State of Connecticut, United States of America, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The invention relates to tomography, which in general terms relates to obtaining by radiographic means an image of internal body parts in a plane through the body. Specifically, the field of this invention, sometimes called transverse axial tomography, relates to the method and apparatus for applying a plurality of X- or gamma ray beams through a plane of a body, measuring the absorption of each beam as it passes through one segment of the body and using the multiple measurement information obtained to reconstruct individual absorption coefficients for each element of a defined element matrix in the body plane.

A prior art method and apparatus for transverse axial tomography is described in U.S. Patent 3,778,614 issued December 1, 1973. That patent describes a technique to reconstruct a cross-sectional view of a body from a series of transmission measurements obtained by translating a radiation source and detector across the body section and repeating this translation motion at a number of angular orientations in the plane of the section.

The objective of these measurements is to obtain, after computer analysis of thousands of pieces of raw information about beam attenuation through the body plane, the attenuation coefficient associated with each element of a matrix defined in the body plane. The method is useful for internal description of any body, but is primarily useful for identification of internal human body abnormalities. The attenuation coefficients are different for normal body tissue, tumors, fat, etc. and consequently provide identifying information about soft tissues in a human body. Especially useful for identification of brain disease and abnormalities, tomography by computer reconstruction can reduce or remove obvious disadvantages of patient discomfort and morbidity normally associated with brain investigations using pneumography, angiography and radio-active isotope scanning.

In the prior art method an X-ray tube X and detector D, fixed in positions opposite from one another, are linearly translated so that the X-ray beam traverses a body B. A narrow beam is defined by means of collimators at the output of the X-ray tube X and at the detector D so that the readings of the X-ray detector D at each translational and rotational position is a measure of the total attenuation along the particular beam path. Each detector measurement is stored for subsequent computer processing. After each linear scan, the X-ray tube/detector combination is rotated about an axis perpendicular to the body plane. This is more or less shown in figures 1a and 1b.

In the prior art method, the scan signals are processed to yield visual information and local values of the beam attentuation coefficients over the body section. Detector scan signals are applied to an analog/digital converter AD to convert the analog scan signals which are proportional to each beam attenuation to digital form and subsequently are recorded in a storage unit S. Computer analysis of the entire matrix of scan signals, typically about 28,000 points yields attenuation coefficients associated with a element matrix defined for the body B. These attenuation coefficients are related to the local physical properties in the body plane. After they are computed, by a computer K, the attenuation coefficients are recorded in a storage unit S, and subsequently converted to analog signals by means of a digital/analog converter DA. These signals drive a viewing unit V, typically a CRT, with the information content to pictorially display the attenuation coefficient for each matrix element. A permanent record of the display is achieved by means of a camera C. Foregoing is more or less shown in fig. 2.

A disadvantage of the prior art method and apparatus is that the entire body section must be scanned before the local value of the attenuation coefficients can be extracted. This is due to the fact that the readings at each position of the X-ray beam affect the computation of the attenuation coefficient at every point in the section. Thus the body section must be scanned in its entirety; the scanning cannot be confined to some particular region of interest. Furthermore, severe restriction is placed on the stability of the X-ray tube and detector systems and upon the mechanical precision of the devices since consistent data must be obtained over the entire scan time in order to compute the local attenuation coefficient values. Problems of reconstruction may similarly arise in regions of the body subject to motion. A scanning motion consisting of translation followed by rotation is clumsy and subject to mechanical vibration and wear. Because of the mechanical problems involved, it is also difficult to speed the sequence of translation and rotation movement to reduce the scanning time. Further problems are related to the complexity of the computer program necessary for restoration and the sophistication of the programs that are required.

It is an object of the invention to provide an improved computed tomography method and apparatus which can reduce or overcome at least some of the disadvantages of the prior art.

According to the invention there is provided a method of examining by X- or gamma rays a thin cross-section or plane through a body, said plane depicted for examination purposes as a two-dimensional matrix of elements, having a plurality of concentric circles forming a plurality of concentric rings, the outermost ring being denoted as the R ring, the next inner ring to said outermost ring being denoted as the R-1 ring and so on, each of said rings being divided into N_r elements, the notation N_R representing a plurality of equally angularly spaced elements of said R concentric ring, the R-1 ring being divided into N_{R-1} elements, and so on, the method comprising the steps of:

rotating X- or gamma ray beams, 360 degrees around the outside of said body, each beam being transmitted from outside of said body in a tangential direction through one of said concentric rings, and being continuously tangential with respect to said concentric ring, that is a constant distance from the centre of said ring,

recording for each of said beams emerging from said body, at N_r discrete angular intervals during the beams' 360 degree rotation, a discrete output signal representing the total attenuation of the X- or gamma ray beams through the elements in each respective concentric ring intersected by the respective beam,

generating in response to said N_R discrete output signals from the beam tangent to the R ring, signals proportional to the individual attenuation coefficients associated with each of the N_R elements in said R ring,

generating in response to said N_{R-1} discrete output signals from the beam tangent to the R-1 ring and in response to said signals proportional to the individual attentuation coefficients associated with the elements in said R ring, through which the beam tangent to the R-1 ring passes at each of the N_{R-1} discrete angular intervals, signals proportional to the individual attenuation coefficient associated with each of the N_{R-1} elements in said R-1 ring,

repeating the preceding step for each succeeding concentric ring in turn from ring R-2 toward the center of said concentric circles, to generate for each concentric ring, signals proportional to the individual attenuation coefficients associated with each of the N_r elements in the ring, in response to the N_r discrete output signals from the beam tangent to that ring and the previously derived signals proportional to the individual attenuation coefficients associated with the elements in all outer rings through which the beam passes at each of the N_r discrete angular intervals, and

producing in response to said signals proportional to the individual attenuation coefficients associated with each of the N_r elements in each ring a representation of the attenuation of the elements of the plane through the body.

Novel apparatus is disclosed for performing the method. A rotating frame is provided supported with respect to a fixed frame by means of a ball bearing and rotated by means of a motor. A source of X- or gamma rays is mounted on a first arm rigidly attached to the rotating frame. The source generates one or more beams in a plane perpendicular to the axis of rotation. The beams are intercepted by a system of detectors mounted on a second arm rigidly attached to the rotatory frame. The beams are defined by collimators associated with both the X- or gamma ray source and the detection system and directed so as to be tangent to concentric rings defined about the axis of rotation of the rotating frame in a plane of a body placed in or near the axis of rotation between the source and detector system.

In a preferred embodiment of the detector system a reference crystal detector and a plurality of measurement crystal detectors are provided in groups, which may be moved in position on a track so as to intercept different beams passing through the body on different rotations of the rotating frame. Photomultiplier tubes are provided, one for each measurement crystal detector, to generate electrical signals proportional to the corresponding beam intensity. Means are provided to magnetically store the beam attenuation signals in digital form. A stored program digital computer is provided for deriving signals proportional to attenuation or transmission coefficients for the defined element matrix in the body plane. These signals are stored, and are then useful to provide a representation of the absorption characteristics of the body plane.

In order that the invention may be clearly understood and readily carried into effect an embodiment thereof will now be described by way of example, with reference to the accompanying drawings in which:

Figs. 1(a) and 1(b) show a prior art method and apparatus for performing transverse axial beam measurements;

Fig. 2 shows a prior art system for calculating absorption or transmission coefficients of a prior art defined element matrix from a set of transverse axial beam measurements;

Fig. 3 shows an X- or gamma ray source detector orientation, constructed in accordance with the invention, for rotation of a beam pattern about a body in which an element matrix is defined by concentric circles and equally spaced radii;

Fig. 4 shows in more detail the defined element matrix, constructed to apply the method in accordance with the invention, for determination of absorption coefficients in a body plane;

Fig. 5 shows another defined element matrix, for determination of the absorption coefficient at a particular point;

Fig. 6 shows a perspective of physical apparatus, constructed in accordance with the invention, for rotating a beam pattern through a plane of a body and the measurement of beam attenuations after the beams pass through it;

Fig. 7 shows an X-ray tube beam spread, constructed in accordance with the invention, as it rotates about the body under investigation;

Fig. 8 shows a schematic diagram of beam generation and detection in accordance with the invention;

Fig. 9 shows a schematic diagram of an alternative embodiment of beam generation and detection in accordance with the invention; and

Fig. 10 shows a schematic diagram of measurement data collection, recording and processing in accordance with the invention.

Fig. 11 shows a flow chart for the construction of a computer program for the method using localized reconstruction in accordance with Fig. 5.

Description of the Invention

Concentric Ring Scanning

a) Uniform body scanning

Fig. 3 shows a sketch of a body plane 101 to be examined by transverse axial tomography by a method in accordance with the invention. The body 111 is assumed to be placed between a source 300 of X- or gamma rays and a detector 301, which may be a scintillator and a photomultiplier and which preferably also includes a collimator. For illustrative purposes, detector 301 is assumed to be movable on a track 302 such that beams 310, 311, 312, 313 may be detected which pass at various angles from the source through body 111. Multiple detectors, each with an associated collimator can of course be provided as detectors 301, 301′, 301″, etc., or multiple detectors may be movable on track 302. The X-ray source 300 and detectors 301, are attached to a rotating ring 303 which is rotatable about an axis O perpendicular to the body plane 101. Body 111 is shown in Fig. 3 coexistent with axis O, but it may be placed anywhere within the beam range of source 300 and detector 301.

As shown in Fig. 3 a series of concentric circles is defined about axis of rotation O. As C ring 303 rotates about the axis of rotation O, the X-ray beam or beams is continuously directed (as shown at one orientation angle of rotation) perpendicular to subsequent radii from axis O at point P at all times as C ring 303 rotates about axis O. As a result a beam such as 310 is at all times tangent to the outer ring about center O as the source-detector system rotates.

Fig. 4 shows in more detail the concentric system defined about axis of rotation O. Beam 310 is shown at a particular orientation during its rotation about body 111 and is perpendicular to a particular radius vector r at point P. By appropriate collimation, the beam width W can be made to approximate the concentric ring width Δr. The example depicted in Fig. 4 shows beam 310 passing through the outermost concentric ring i. Perpendicular to radius vector r, beam 310 is depicted as passing through elements labeled $j=n_i-1$ n_i, 1, 2 and 3. These elements are among those elements in the ring i, totaling n_i elements.

In order to describe the interior of body 111 according to the matrix of elements throughout the concentric ring-radius vector system shown in Fig. 4, each small element is assigned an unknown value of attenuation coefficient. For example, the attenuation coefficient for element j=1 in the ring i is designated $\mu_{i,1}$: for example j=2, $\mu_{i,2}$; for the jth element, $\mu_{i,j}$. The measured beam attenuation for beam 310 shown will be given by the sum of the average value of the linear attenuation constants μ for each element through which the beam passes.

During rotation about axis O, the beam attenuation between source 300 and detector 301 is obtained at n_i different positions, only one of which is shown in Fig. 4. Beam attenuation for each measurement designated $\beta_{i,k}$ is simply the sum of the linear attenuation constants for each element through which the beam passes multiplied by an individual geometrical factor determined by the interception of the beams with each cell. The rotation-measurements steps of the beam 310 as source 300 and detector 301 rotate about O are identified by an index k. This index k runs from 1 in steps of 1 until $k=n_i$, equal to the number of elements in ring i. Thus, the measurement of the beam attenuation at each position of the first intercepting ring leads to the equations

$$\sum_{j=1}^{n_i} (\alpha_{i,j-k})(\mu_{i,j})=\beta_{i,k} \qquad (1)$$

where $k=1, 2, \ldots n_i$.

The term $\alpha_{i,j-k}$ represents the geometrical factor determined by the interception of the beam 310 with each element j as it rotates in k steps about ring i.

Since j is taken equal to k, that is, the number of elements in ring i is j, and the number of measurements around ring i is equal to k, equation (1) represents a system of equations $k=n_i$ in number, having $j=n_i$ unknown parameters $\mu_{i,j}$. The solution of the system of equations (1) yields the values of μ associated with each element on the ring i.

In the next scanning ring, the ring i-1, the measurement of the beam attenuation leads to the new system of equations

$$\sum_{j=1}^{n_{i-1}} (\alpha_{i-1,j-k})(\mu_{i-1,j})=\beta_{i-1,k}-\sum_{j=1}^{n_i} (\alpha_{1,j-k})(\mu_{i,j}) \qquad (2)$$

for, $k=1, 2, \ldots n_{i-1}$, wherein $\alpha_{1,j-k}$ is the geometrical factor determined by the interception of the beam (e.g. beam 311, Fig. 3) in the new ring, i-1 with the elements of the outer ring i.

The values $\mu_{i,j}$ have been determined by the solution of equations (1); the solution of the system of equations (2) provides the values of $\mu_{i-1,j}$ in the ring i-1. The measurement in each scanning ring with decreasing radii provides a system of equations similar to (2) with terms on the right hand side containing known values of μ in the elements pertaining to the outer rings. It is apparent that the number of elements of each outer ring which contributes to the attenuation along an inner ring decreases rapidly as the scanning radius approaches zero, i.e. as the scanning beam approaches the center of rotation.

Thus, the local properties can be fully determined upon completion of each scanning ring without having to wait for the total scanning of the body section.

The number of equations in each set, similar to equation (2), is relatively small and can be arranged to decrease as the interior rings with smaller radii are measured. Assuming for example a scanning radius of the outer ring of the order of

150 mm and an element width of the order of 3 mm, each independent equation set for the outer rings consists of only several hundred equations. The solution for the unknown μ's for each ring sequentially from the outside ring toward the inside rings, requires far less computational time than prior art X-ray tomographic systems. As the inner rings are measured, it is possible to decrease the number of measurements taken around the ring (i.e. define n_i to be less for the inner rings than for the outer rings, thereby keeping the element size approximately constant) with the result that the equation set size is reduced. Computational time is correspondingly reduced for solution of inner ring μ's.

b) Localized Reconstruction

The method of determining the absorption coefficients for the elements defined as elements in concentric rings about the axis of rotation (Fig. 4) requires that all of the beam attenuation data be used in the successive ring equation solutions especially for a particular element near the axis O. It is often the case, however, that a diagnostician is primarily interested in investigating a particular point of the body plane 101. It is possible to use the beam attenuation data as described above to reconstruct an absorption coefficient matrix about a point P_o in the body section not centered at the axis O.

Fig. 5 which illustrates the method claimed in our copending application number 7927100, (Serial No. 1571490) shows body 111 which has been scanned by rotating beams, one of which, beam 310 is shown. About a particular point P_o are sketched a sequence of concentric circles having uniform spaced radii. These circles define a plurality of rings equally spaced by a radial distance r_1. Thus the radius for each circle from center P_o is

$$\rho = jr_1 \qquad (3)$$

where $j=0, 1, 2, \ldots$

Even if beam attenuation data is collected for a concentric ring system defined about center O, this data may, by coordinate transformation, be translated to the concentric ring system defined by a center at P_o and having radii defined by equation (3). The value of the attenuation of a beam tangent to a ring of radius ρ and center P_o coincides with the value of the attenuation measured with a beam tangent to the ring at center O, having a radius r according to the equation

$$r = \rho + r_p \cos(\theta - \theta_p) \qquad (4)$$

where θ is the angular coordinate of the point of tangency and r_p, θ_p are the polar coordinates of P_o. By means of equation (4), the measured beam attenuation values β in the concentric ring system about center O may be computationally translated to achieve a set of beam attenuation values tangent to the concentric rings about P_o. These values, β_j indexed with the subscript j, represent beam attenuation values measured completely around concentric circles $\rho = jr_1$, about P_o.

These beam attenuation values about the ring j, are equal to the sum of the inter-sections over all rings outside of ring j. This relationship is written

$$\int_0^{2\pi} \beta_j \, d\theta = 4\pi j r_1 \sum_{h=j}^{\infty} \theta_{j,h-j+1} \cdot \mu_h \qquad (5),$$

where $\theta_{j,h-j+1}$ is a geometrical parameter given by

$$\theta_{j,h-j+1} = \frac{1}{j}\left[\sqrt{(h+1)^2 - j^2} - \sqrt{h^2 - j^2}\right] \qquad (6)$$

The said geometrical parameter forms a measure of the length of that part of the path of the beam between the circle of radius h and the circle of radius h+1.

From equation (5), an expression for μ_o, the desired attenuation coefficient at P_o can be written as:

$$\mu_0 = \frac{1}{4\pi r_1}\int_0^{2\pi}\left(\beta_0 - \sum_{j=1}^{\infty}\frac{k_j}{j}\beta_j\right)d\theta \qquad (7)$$

where β_0 is the attenuation value of a beam passing through P_0 and the coefficients k_j are given by

$$k_1=\frac{1}{\theta_{1,1}}$$

$$k_2=\frac{1}{\theta_{2,1}}[1-\theta_{1,2}k_1] \qquad (8)$$

$$\vdots$$

$$k_j=\frac{1}{\theta_{j,1}}[1-\theta_{1,j}k_1-\theta_{2,j-1}k_2-\ldots-\theta_{j-1,2}k_{j-1}]$$

For large j,

$$\lim_{j\to\infty} k_j=\frac{2}{\pi}\frac{1}{j} \qquad (9)$$

The coefficients $k_{j/j}$ of β_j in equation (7) decrease asymptotically as j^{-2}. As a consequence, in a quasi-uniform distribution of values of j over the body section under scrutiny, the contribution to the computation of μ_0 of the corresponding values relating to P_j in areas surrounding P_0 decreases essentially as j^{-1}, which means that the scanning of an area located at a distance ρ from P_0 affects the computation of μ_0 as ρ^{-1}. This slow rate of decay of the effect of surrounding areas on the computation of μ at each point would make it necessary to use uniform scanning of the entire body section in order to proceed to the image reconstruction. Thus, the solution for μ_0 at point P_0 presented in equation (7) indicates that the confinement of the scanning to a limited area of the body section would lead to an error in the image reconstruction unless the area boundary partially coincides with the body section boundary.

On the other hand, if the difference of values of μ between two points is computed, the scanning in the surrounding areas affects the difference as

$$\frac{1}{r_1}-\frac{1}{r_2}$$

where r_1 and r_2 are the distances between an area of the body section and the respective points. Thus for large values of r_1 and r_2, the effect of the scanning in the surrounding areas decreases essentially as $r_{1,2}^{-2}$. This rapid rate of decay makes it possible to use a differential form of approach in the image reconstruction of a portion of the body section under scrutiny without the need of a complete uniform scan of the body section. To proceed with this approach the average value $\bar{\mu}$ within a circle of radius l_r, is first calculated by the equation:

$$\bar{\mu}=\frac{1}{l^2}\sum_{h=o}^{l-1}[(h+1)^2-h^2]\mu_h \qquad (10)$$

By virtue of Eq. (5), Eq. (10) transforms to

$$\bar{\mu} = \frac{1}{4\pi r_1}\frac{1}{l^2}\int_0^{2\pi}\left[\sum_{j=0}^{l-1}\frac{k_{i,j}}{j}\beta_j - \sum_{j=l}^{\infty}\frac{k_{e,j}}{j}\beta_j\right]d\theta \quad (11)$$

where

$$k_{i,j}=\frac{1}{\theta_{i,1}}[2j-\theta_{i,j}.\,k_{i,1}-\ldots-\theta_{j-1,2}.\,k_{i,j-1}] \quad (12)$$

$$k_{i,1}=\frac{2}{\theta_{1,1}} \quad (13)$$

$$k_{e,j}=\frac{1}{\theta_{j,1}}[\psi_j-\theta_{l,j}.\,k_{e,1}-\ldots-\theta_{j-1,2}.\,k_{e,j-1}] \quad (14)$$

$$\psi_j=1+\theta_{1,j}.\,k_{i,1}+\ldots+\theta_{l-1,j-l+1}.\,k_{i,l-1} \quad (15)$$

The coefficients k_j in Eq. (7) and $k_{e,j}$ in Eq. (11) satisfy the asymptotic condition.

$$\lim_{j\to\infty}[jk_{e,j}]=l^2\lim_{j\to\infty}[jk_j] \quad (16)$$

Thus from Eqs. (7) and (11) one obtains

$$\mu_o-\bar{\mu}=\frac{1}{4\pi r_1}\int_0^{2\pi}\left[\left(1-\frac{1}{l^2}\right)\beta_o-\sum_{j=1}^{l-1}\phi_{i,j}\beta_j+\sum_{j=l}^{\infty}\phi_{e,j}\beta_j\right]d\theta \quad (17)$$

where

$$\phi_{i,j}=\frac{1}{j}\left[\frac{1}{l^2}k_{i,j}+k_j\right]$$

$$\phi_{e,j}=\frac{1}{j}\left[\frac{1}{l^2}k_{e,j}-k_j\right] \quad (18)$$

Asymptotically the coefficient $\phi_{e,j}$ decreases as j^{-3} and this rapid rate of decay makes it possible to limit the number of terms in the second sum on the right hand side of Eq. (17) for the computation of $\mu_o-\bar{\mu}$. This means that it is possible to confine the scanning procedure to an area of the body section surrounding the region where the reconstruction of $\mu_o-\bar{\mu}$ has to be performed. Table I here below shows numerical values for k_j as a function of j=1 to j=95; $k_{i,j}$ as a function j from j=1 to j=10 (l=10) and $k_{e,j}$ as a function of j from j=11 to j=95; and $\phi_{i,j}$ as a function of j from j=1 to j=10 (l=10) and $\phi_{e,j}$ as a function of j from j=11 to j=95.

TABLE I

i	k_i	$k_{i,j}$ and $k_{e,j}$		$\phi_{i,j}$ and $\phi_{e,j}$	
1	.57735E+00	.11547E+01		.58689E+00	
2	.32826E+00	.24454E+01		.17424E+00	
3	.22153E+00	.37332E+01		.84126E–01	
4	.16542E+00	.50167E+01		.51720E–01	
5	.13153E+00	.62974E+01	$k_{i,j}$	.36715E–01	$\phi_{i,j}$
6	.10903E+00	.75764E+01		.28608E–01	
7	.73064E–01	.88542E+01		.23748E–01	
8	.81161E–01	.10131E+02		.20611E–01	
9	.71953E–01	.11407E+02		.18470E–01	
10	.64621E–01	.12683E+02		.16944E–01	
11	.58645E–01	.38795E+02		–.23816E–01	
12	.53681E–01	.20222E+02		–.94539E–01	
13	.4943E–01	.13914E+02	$k_{e,j}$	–.50385E–02	$\phi_{e,i}$
14	.45912E–01	.10779E+02		–.30383E–01	
15	.42814E–01	.88958E+01		–.20470E–02	
16	.40109E–01	.76298E+01		–.14342E–02	
17	.37735E–01	.76142E+02		–.10449E–02	
18	.35610E–01	.60172E+01		–.78441E–03	
19	.33719E–01	.54664E+01		–.60305E–03	
20	.32019E–01	.50184E+01		–.47279E–03	
21	.30482E–01	.46459E+01		–.37682E–03	
22	.29087E–01	.43303E+01		–.30460E–03	
23	.27813E–01	.40591E+01		–.24945E–03	
24	.26647E–01	.38230E+01		–.20616E–03	
25	.25575E–01	.36153E+01		–.17216E–03	
26	.24585E–01	.34310E+01		–.14500E–03	
27	.23670E–01	.32661E+01		–.12307E–03	
28	.22820E–01	.31176E+01		–.10519E–03	
29	.22029E–01	.29830E+01		–.90485E–04	
30	.21291E–01	.28604E+01		–.78291E–04	
31	.20601E–01	.27482E+01		–.68105E–04	
32	.19955E–01	.26451E+01		–.59541E–04	
33	.19348E–01	.25499E+01		–.52293E–04	
34	.18776E–01	.24617E+01		–.46126E–04	
35	.18238E–01	.23798E+01		–.40849E–04	
36	.17729E–01	.23034E+01		–.36311E–04	
37	.17248E–01	.22321E+01		–.32391E–04	
38	.16793E–01	.21652E+01		–.28990E–04	
39	.16361E–01	.21025E+01		–.26027E–04	
40	.15951E–01	.20434E+01		–.23435E–04	
41	.15560E–01	.19878E+01		–.21160E–04	
42	.15189E–01	.19352E+01		–.19155E–04	
43	.14834E–01	.18854E+01		–.17384E–04	
44	.14496E–01	.18383E+01		–.15814E–04	
45	.14193E–01	.17935E+01		–.14419E–04	
46	.13864E–01	.17509E+01		–.13174E–04	
47	.13569E–01	.17104E+01		–.12062E–04	
48	.13285E–01	.16718E+01		–.11065E–04	
49	.13014E–01	.16349E+01		–.10169E–04	
50	.12753E–01	.15997E+01		–.93627E–05	
51	.12502E–01	.15660E+01		–.86350E–05	
52	.12261E–01	.15338E+01		–.79768E–05	
53	.12029E–01	.15029E+01		–.73804E–05	
54	.11806E–01	.14732E+01		–.68389E–05	
55	.11591E–01	.14447E+01		–.63463E–05	
56	.11384E–01	.14174E+01		–.58975E–05	
57	.11183E–01	.13911E+01		–.54877E–05	
58	.10990E–01	.13657E+01		–.51130E–05	
59	.10804E–01	.13413E+01		–.47699E–05	
60	.10623E–01	.13178E+01		–.44551E–05	
61	.10449E–01	.12951E+01		–.41660E–05	
62	.10280E–01	.12731E+01		–.39000E–05	
63	.10117E–01	.12520E+01		–.36549E–05	

TABLE I

j	k_j	$k_{i,j}$ and $k_{e,j}$	$\phi_{i,j}$ and $\phi_{e,j}$
64	.99583E–02	.12315E+01	–.34288E–05
65	.98048E–02	.12117E+01	–.32200E–05
66	.96560E–02	.11926E+01	–.30269E–05
67	.85117E–02	.11740E+01	–.28481E–05
68	.93716E–02	.11560E+01	–.26823E–05
69	.92356E–02	.11386E+01	–.25284E–05
70	.91035E–02	.11217E+01	–.23855E–05
71	.89751E–02	.11053E+01	–.22525E–05
72	.88502E–02	.10984E+01	–.21286E–05
73	.87288E–02	.10740E+01	–.20132E–05
74	.86107E–02	.10590E+01	–.19055E–05
75	.84953E–02	.10444E+01	–.18050E–05
76	.83838E–02	.10302E+01	–.17110E–05
77	.82748E–02	.10164E+01	–.16230E–05
78	.81686E–02	.10029E+01	–.15406E–05
79	.80651E–02	.98986E+00	–.14634E–05
80	.79641E–02	.97713E+00	–.13910E–05
81	.78657E–02	.96472E+00	–.13230E–05
82	.77697E–02	.95262E+00	–.12591E–05
83	.76760E–02	.94083E+00	–.11991E–05
84	.75845E–02	.92933E+00	–.11426E–05
85	.74952E–02	.91812E+00	–.10893E–05
86	.74079E–02	.90717E+00	–.10392E–05
87	.73227E–02	.89648E+00	–.99189E–06
88	.72394E–02	.88605E+00	–.94736E–06
89	.71579E–02	.87586E+00	–.90511E–06
90	.70783E–02	.86590E+00	–.86528E–06
91	.70005E–02	.85617E+00	–.82762E–06
92	.69243E–02	.84666E+00	–.79200E–06
93	.68498E–02	.83736E+00	–.75827E–06
94	.67768E–02	.82826E+00	–.72631E–06
95	.67054E–02	.81936E+00	–.69603E–06

An important property of both Eqs. (7) and (17) is the uniform averaging of the attenuation measurements over each circle of the image reconstruction sequence, as a result of the integration over 2π. Thus the effect of the statistical fluctuations of the individual measurements of β is minimized uniformly over the entire reconstruction area.

Eqs. (7) and (17) provide the solution of the reconstruction problem and in particular Eq. (17) defines the approach for a localized measurement and reconstruction of μ. Obviously in Eq. (17) an independent measurement of $\bar{\mu}$ is required. However the measurement of $\bar{\mu}$ requires only a coarse scanning of the body section under scrutiny with less stringent requirements on the statistics of the corresponding attenuation measurements.

Concentric Ring Scanner

Illustrated in Fig. 6 is a perspective drawing of a concentric ring scanning apparatus. A fixed frame 600 supports a rotating frame 601 which is free to revolve about an axis of rotation 602. A motor drive 624 is provided in fixed frame 600 to propel rotating frame 601. Attached to rotating frame 601 are two arms 603, 604 spaced approximately 180 degrees from one another. Arm 603 supports an X-ray tube 605 and an associated X-ray tube collimator control 606. Arm 604 carried a detector assembly 607 and associated detector collimators.

A couch 608 is provided to allow a part of a human body 111 to be positioned in the aperture 701 between X-ray tube 605/-X-ray tube collimator control 606 and detector assembly 607. Couch 608 is supported by couch support 609. A couch control system 610 is provided which translates the couch 608 parallel to the axis of rotation 602, thereby positioning body 111 to a point where beams from X-ray tube 605 may intersect a desired plane 101 through the body 111. In addition, the couch control system 610 translates the couch 608 in any direction in a plane perpendicular to the axis of rotation, thereby positioning the axis of rotation close to the desired area of the body 111.

Since the X-ray tube 605 is rotatable about the axis of rotation 602, means are provided to cool it and provide it with high voltage electrical power while it is rotating. These means, shown in modular form, are a water cooling rotating assembly 611 and a high voltage slip ring assembly 612. Means must also be provided to send command and control signals to X-ray tube 605 and its associated collimator assembly and collimators associated with detectors 607 while they are rotating. Command and control slip ring assembly 614 is provided for that purpose. Likewise data transmission slip ring assembly 613 is provided to provide a means for transmission of data signals from detectors 607 while they are rotating.

Fig. 7 shows a preferred orientation of X-ray tube 656 and its associated collimator control 606 with respect to detector and detector collimator apparatus 607.

As indicated in Fig. 6, X-ray tube 605 and detector assembly 607 are rigidly connected to each other by arms 603, 604 to rotating frame 601. Rotation of the frame 601 about center line 602 (point O of Fig. 7) causes the X-ray beam pattern 700 to sweep out a fan-shaped pattern, which substantially covers any body to be scanned placed within aperture 701. In a preferred embodiment, the fan shaped beam subtends approximately a 30 degree arc as the X-ray tube-detector assemblies are rotated at speeds of up to one complete rotation per second for at least 10 revolutions. The aperture 701 is approximately 65 cm in diameter. The arms 603, 604 attaching the X-ray housing 605 and detector system 607 are approximately 75 cm long. The rotating frame 601 is supported with respect to fixed frame 600 by a single 90 cm diameter precision ball bearing.

Fig. 8 illustrates the multiple beam scanning aspects of this invention. The X-ray tube 605 emits a continuous fan-shaped array of X-rays, but this continuous array must be collimated into beams in order for the methods described previously in this specification to be applicable. Collimators 806 and 800 are provided to create a plurality of beams passing through a cross section of a body 111 placed within aperture 701. For illustrative purposes three detector system pairs consisting of crystal scintillators and photomultipliers (811, 820; 812, 821; 813, 827) are shown in position 1. A reference scintillator 810 and its associated photomultiplier 823 are stationary. The detector pairs remain in position I for the first rotation of rotating frame 601 (Fig. 6). At the start of the second rotation, the detector system pairs are shifted along track 302 to position II for absorption coefficient detection of beams intersecting that position. The detectors are shifted to position III at the start of the third revolution, and so on. This shifting of detectors at the end of one rotation and the beginning of another rotation assures that the entire body 111 placed within aperture 701 may be scanned.

A preferred embodiment of the scanning system of Fig. 8 consists of an arrangement capable of scanning a test object contained within a 50 cm diameter circle about axis of rotation O. Thirteen detector units are provided one of which is the reference pair 810, 823, the other twelve of which are movable to ten positions along detector track 302. Each detector system is used to scan a 2¼ degree sector of the total scanning area, ten revolutions of the X-ray tube/detector system 604 being used to scan the entire body 111.

Crystal detector 810/photomultiplier 823 is used to generate a reference beam attenuation signal for all the other detectors to account for any variations with time in beam strength eminating from X-ray tube 605. As shown in Fig. 8 a particular beam 855 is collimated by tube collimator 806 and passes through an attenuator 850 located outside the location of the body being examined. The absorption characteristics of attenuator 850 are preferably selected to be similar to that of the body being examined. Tissue equivalent plastic is an example of an attenuator material suitable for this purpose. Detector pair 810, 823 generates a signal, the intensity of which is proportional to the strength of the X-ray beam by attenuator 850 and collimated by collimator 800.

Each detector pair for the beams passing through the body under investigation generates a signal proportional to a particular beam's intensity after it passes through the body 111. The crystal scintillators produce a high-frequency signal (visible light spectrum) proportional to the number of photons in the X- or gamma ray beams impinging on them. The photomultiplier tubes associated with each crystal scintillator, reacting to the light energy from their respective scintillators generate an electrical signal proportional to beam strength impinging on the scintillators. For example, an electrical signal proportional to the beam strength of beam 856 is generated at the output of photomultiplier tube 820. Similarly, crystal scintillator/photomultiplier pairs generate output signals proportional to the strength of other beams at position I, position II, etc. for the entire beam pattern after successive rotations of system 604.

In a preferred embodiment of this invention the X-rays generated by X-ray tubes 605 are collimated by means of a 15 cm long collimator 806 at the X-ray tube source, and a 20 cm long collimator 800 at the detector system 604. This collimation at the X-ray source and detector defines radiation beams having a rectangular profile of 1 mm by 5 mm width as measured by scanning a lead edge at the mid-point of the beam path.

The range of values for which the photomultiplier must respond can be reduced by covering the body being examined with a material, the absorption of which is known, so that beam intensities received by the detectors are kept as constant as possible as they pass through the body.

Fig. 9 shows an alternate embodiment of detector orientation. Detectors 910 and 911 are located on track 901, and detectors 920 and 921 are located on track 902. As shown, detectors 910 and 911 measure beam attenuation through circular rings defined about rotation axis O different from those measured by detectors 920 and 921. Multiple positions on each track can be established and the detectors shifted in position with each rotation until a defined ring matrix is entirely scanned and detected. Collimators 906 are provided at the X-ray source and collimators 930 at the detectors are also provided.

The X-ray tube appropriate for the particular embodiment discussed above is a modified version of a Philips 160 kV Beryllium Window Tube Model MCN 160.

Appropriate detectors include scintillation detectors such as NaI, CaF_2, BGO and proportional counters such as high pressure xenon detectors and solid state detectors.

Fig. 10 indicates how the beam attenuation data measured by the detectors systems including the photomultipliers 1000_1, 1000_2, ... 1000_3, are processed during the rotational scanning of a body. An information signal is generated in each photomultiplier at each defined increment for each rotation of the X-ray source/detector system. These signals are individually amplified by amplifiers 10101, 10102, ... 10103, are each taken up in turn by serializer 1020, converted to digital form by analog to digital converter 1030, and stored in a data storage medium 1040 such as magnetic tape, disk, or drum or solid state memory. This data collection process continues for each detector position for each defined increment step for the complete rotation. During or after the data collection process, a computer 1050 under direction of a stored program, processes the collected data according to the method with reference to Fig. 4 as hereinbefore described. The output of the computer 1050 is a sequence of digital signals proportional to the absorption coefficients of each element in the defined circular ring matrix. These signals are stored in a data storage unit 1060 which may be the identical unit 1040 or similar to it. The output digital signals can then be printed and/or converted to analog form and used to drive a display on a cathode-ray tube thereby pictorially indicating the absorption coefficients for the defined matrix in the cross section of the body being investigated.

Fig. 11 discloses a flow chart which serves as an outline for the construction of a computer program for localized reconstruction according to the method claimed in our copending application number 7927100, (Serial No. 1571490).

Details of the Flowchart in Fig. 11

After START 500 follows reading of the measured attenuation values and necessary constants at 501 and 502, respectively.

At 503 reading of parameters for the image reconstruction, such as number of rings, elements.

At 504 and 505, respectively, initiating the program variables L and J, respectively.

At 506 the coordinates r, θ of a reconstruction point are determined, as well as the value βj from the attenuation values.

At 507 the coordinates (r, θ) are calculated and βj by means of the compensation formula.

At 508 and 509, respectively, the indicated calculations are carried out.

At 510 $\bar{\mu}$, $\mu-\bar{\mu}$ and μ is computed, after which at 511 follows a print of numbers or drawings.

The calculations terminate at STOP 512.

The parts 520 and 530, respectively, denote feedback loops AA, BB which are followed if the conditions imposed in 521 and 531, respectively, are not (N) satisfied.

Various changes and modifications may be made in the details of performing, constructing and designing the above specifically described embodiment of this invention without departing from the spirit thereof, such changes and modifications being restricted only by the scope of the following claims.

WHAT WE CLAIM IS:—

1. A method of examining by X- or gamma rays a thin cross-section of plane through a body, said plane depicted for examination purposes as a two-dimensional matrix of elements, having a plurality of concentric circles forming a plurality of concentric rings, the outermost ring being denoted as the R ring, the next inner ring to said outermost ring being denoted as the R-1 ring and so on, each of said rings being divided into N_r elements, the notation N_R representing a plurality of equally angularly spaced elements of said R concentric ring, the R-1 ring being divided into N_{R-1} elements, and so on, the method comprising the steps of:

rotating X- or gamma ray beams, 360 degrees around the outside of said body, each beam being transmitted from outside of said body in a tangential direction through one of said concentric rings, and being continuously tangential with respect to said concentric ring, that is a constant distance from the centre of said ring,

recording for each of said beams emerging from said body, at N_r discrete angular intervals during the beams' 360 degree rotation, a discrete output signal representing the total attenuation of the X- or gamma ray beams through the elements in each respective concentric ring intersected by the respective beam,

generating in response to said N_R discrete output signals from the beam tangent to the R ring, signals proportional to the individual attenuation coefficients associated with each of the N_R elements in said R ring,

generating in response to said N_{R-1} discrete output signals from the beam tangent to the R-1 ring and in response to said signals proportional to the individual attenuation coefficients associated with the elements in said R ring, through which the beam tangent to the R-1 ring passes at each of the N_{R-1} discrete angular intervals, signals proportional to the individual attenuation coefficient associated with each of the N_{R-1} elements in said R-1 ring,

repeating the preceding step for each succeeding concentric ring in turn from ring R-2 toward the center of said concentric circles, to generate for each concentric ring, signals proportional to the individual attenuation coefficients associated with each of the N_r elements in the ring, in response to the N_r discrete output signals from the beam tangent to that ring and the previously derived signals proportional to the individual attenuation coefficients associated with the elements in all outer rings through which the beam passes at each of the N_r discrete angular intervals, and

producing in response to said signals proportional to the individual attenuation coefficients associated with each of the N_r elements in each ring a representation of the attenuation of the elements of the plane through the body.

2. The method of claim 1 wherein each ring is divided into an equal number of elements N_r.

3. The method of claim 1 wherein said rotating step proceeds with sequential rotations of said X- or gamma ray beams, with at least one beam being directed to at least one particular ring on a first 360 degree rotation around the outside of said body, and redirecting the beam to at least one particular additional ring on each subsequent 360 degree rotation around the outside of said body.

4. The method of claim 1 wherein each generating step is achieved through the use of a digital computer machine manipulation of electrical signals representing N_r simultaneous equations of N_r unknown absorption or transmission coefficients.

5. Apparatus for examining by X- or gamma rays a thin cross-section or plane through a body, said plane depicted for examination purposes as a two-dimensional matrix of elements, having a plurality of concentric circles forming a plurality of concentric rings, the outermost ring being denoted as the R ring, the next inner ring to said outermost ring being denoted as the R-1 ring and so on, each of said rings being divided into N_r elements, the notation N_R representing a plurality of equally angularly spaced elements of said R concentric ring, the R-1 ring being divided into N_{R-1} elements, and so on, the apparatus comprising:

means for rotating X- or gamma ray beams, 360 degrees around the outside of said body, each beam being transmitted from outside of said body in a tangential direction through one of said concentric rings, and being continuously tangential with respect to said concentric ring, that is a constant distance from the centre of said ring,

means for recording for each of said beams emerging from said body, at N_r discrete angular intervals during the beams' 360 degree rotation, a discrete output signal representing total attenuation of the X- or gamma ray beams through the elements in each respective concentric ring intersected by the respective beam,

means for generating in response to said N_R discrete output signals, from the beam tangent to the R ring, signals proportional to the individual attenuation coefficients associated with each of the N_R elements in said R ring,

means for generating in response to said N_{R-1} discrete output signals from the beam tangent to the R-1 ring and in response to said signals proportional to the individual attenuation coefficients associated with the elements in said R ring, through which the beam tangent to the R-1 ring passes at each of the N_{R-1} discrete angular intervals, signals proportional to the individual attenuation coefficient associated with each of the N_{R-1} elements in said R-1 ring,

means for repeating the proceeding step for each succeeding concentric ring in turn from ring R-2 toward the center of said concentric circles, to generate for each concentric ring, signals proportional to the individual attenuation coefficients associated with each of the N_r elements in the ring, in response to the N_r discrete output signals from the beam tangent to that ring and the previously derived signals proportional to the individual attenuation coefficients associated with the elements in all outer rings through which the beam passes at each of the N_r discrete angular intervals, and

means for producing in response to said signals proportional to the individual attenuation coefficients associated with each of the N_r elements in each ring a representation of the attenuation of the elements of the plane through the body.

6. The apparatus of claim 5 wherein said means for rotating X- or gamma ray beams 360 degrees around the outside of said body comprises,

a fixed frame,

a rotating frame supported with respect to said fixed frame by a ball bearing, said rotating frame being rotatble with respect to said fixed frame about an axis of rotation by a motor, and

a source of X- or gamma rays mounted on a first arm rigidly attached to said rotating frame, said source of X- or gamma rays directed to transmit rays tangent to concentric rings defined in a plane of a stationary body placed in or near said axis of rotation.

7. The apparatus of claim 6 wherein said means for recording from each of said beams emerging from said body comprises:

a detector system mounted on a second arm rigidly attached to said rotating frame in an orientation approximately 180 degrees from said first arm and in the path of said rays from said source of X- or gamma rays mounted on said first arm, said detector systems generating attenuation signals proportional to the total X- or gamma ray attenuation of beams passing through said concentric rings defined in said body plane at discrete rotational increments as said source of X- or gamma rays and said detectors rotate about said axis of rotation,

means for converting said signals into digital signals corresponding to said attenuation signals, and

means for recording said digital signals.

8. The apparatus of claim 7 further comprising:

collimating means placed between said source of X- or gamma rays and said detector system for shaping said beams.

9. The apparatus of claim 7 wherein said detector system comprises a reference detector for measuring X- or gamma ray attenuation of a beam not passing through said body and a group of one or more measurement detectors, said group of detectors being movable to a plurality of positions along a track mounted on said second arm, said positions corresponding to the locations corresponding to beams passing through different groups of concentric rings defined in said body about said axis of rotation and

photomultiplier tubes, one for each of said measurement detectors, the input signal to each tube being responsive to the detector signal, the output signal from each photomultiplier tube corresponding to the measured attenuation of a beam passing through said body.

10. The apparatus of claim 5 wherein said means for generating said attenuation coefficients as digital signals in response to said recorded beam

attenuation signals is a digital computer under control of a stored program for solving a set of N_r linear simultaneous equations having N_r variables, the apparatus further comprising storage unit means for storing said digital signals representing said attenuation coefficients for each element of said matrix in said body plane.

11. The apparatus of claim 10 wherein said means for producing a presentation of the attenuation of the elements of the plane through the body comprises:

means responsive to said stored digital signals for converting said attenuation coefficient digital signals into corresponding analog signals proportional to said derived attenuation coefficients, and

cathode ray tube means responsive to said analog signals for generating a pictorial representation of the element matrix of said body plane by displaying each element in intensity proportional to its attenuation coefficient analog signal strength.

12. The apparatus of claim 5 wherein said

means for recording for each of said beams emerging from said body, at N_r discrete angular intervals during the beams' 360 degree rotation, a discrete output signal representing total attenuation of the X- or gamma ray beams through the elements in each respective concentric ring intersected by the respective beam comprises, detector means associated with each of said beams for generating, at N_r discrete angular intervals during the beams' 360 degree rotation, an analog signal proportional to the X- or gamma ray attenuation of the beam as each beam traverses the elements in each respective concentric ring to which it is tangent at each discrete angular interval,

amplifying means associated with each of said detector means for amplifying said analog signals,

Serializing means responsive to said amplifying means for generating analog signals in time sequence corresponding to the order of, first the N_R signals generated in the R ring, next the N_{R-1} signals generated in the R-1 ring and so on,

analog to digital converting means for converting said analog signals in time sequence to digital signals in the same time sequence, and

means responsive to said analog to digital converting means for storing said digital signals.

13. A method of examining by X- or gamma rays a thin cross-section or plane through a body, substantially as herein described with reference to Figure 4 of the accompanying drawings.

14. Apparatus for examining by X- or gamma rays a thin cross-section or plane through a body, substantially as herein described with reference to Figures 3, 4, 6, 7, 8, 9 and 10 of the accompanying drawings.

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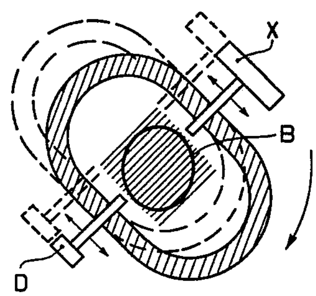

Fig. 1a

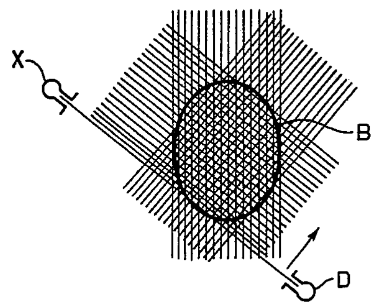

Fig. 1b

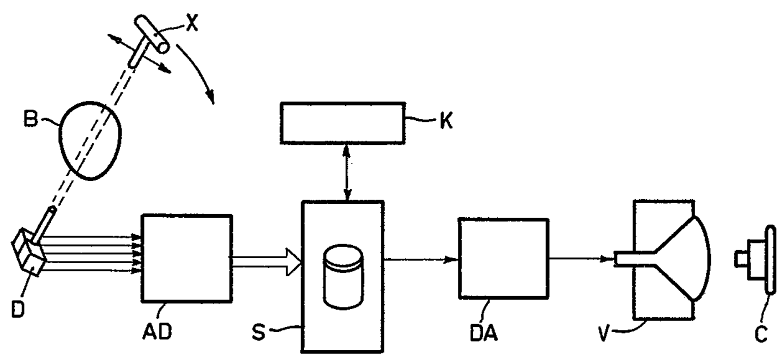

Fig. 2

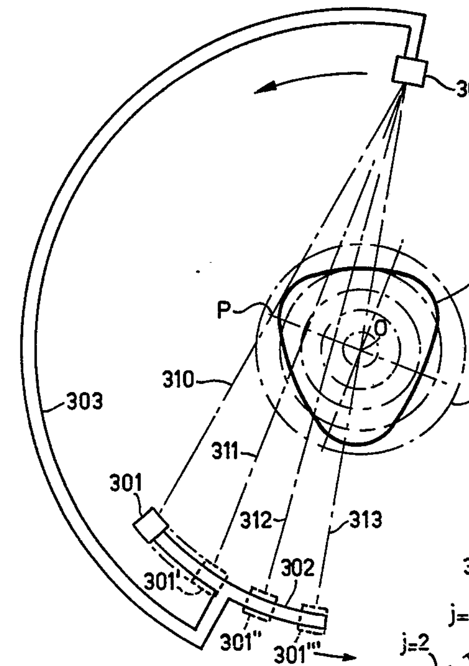
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Fig. 3

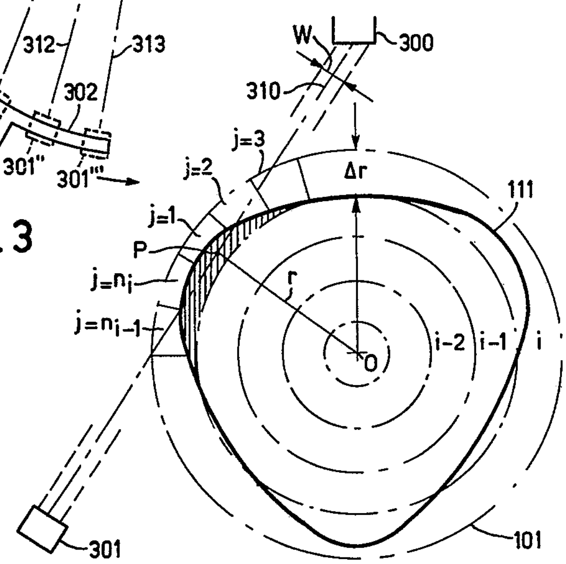
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Fig. 4

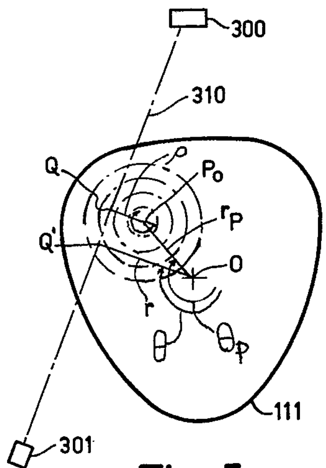

Fig. 5

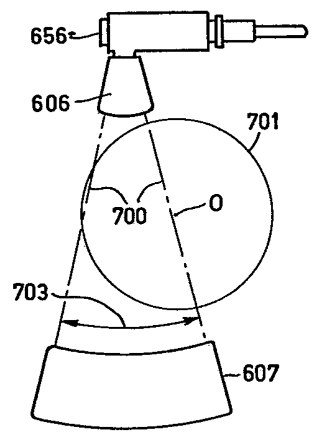

Fig. 7

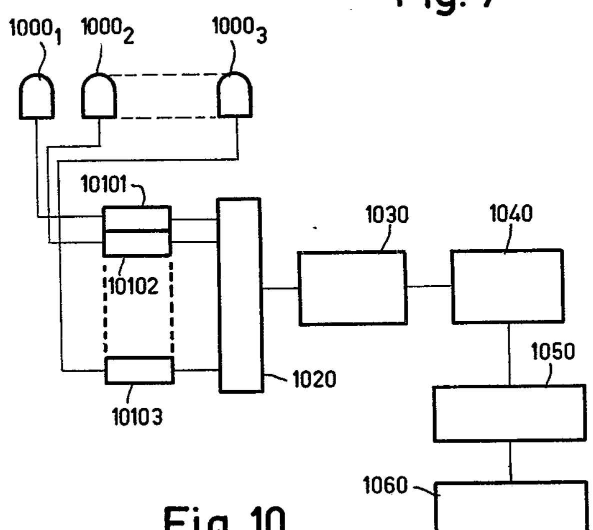

Fig. 10

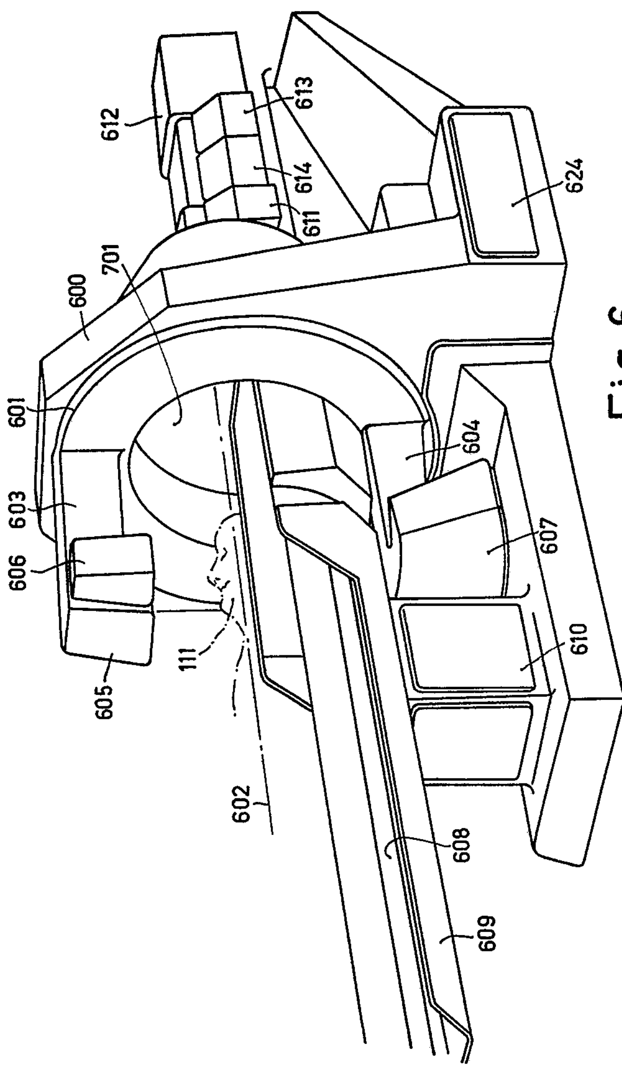
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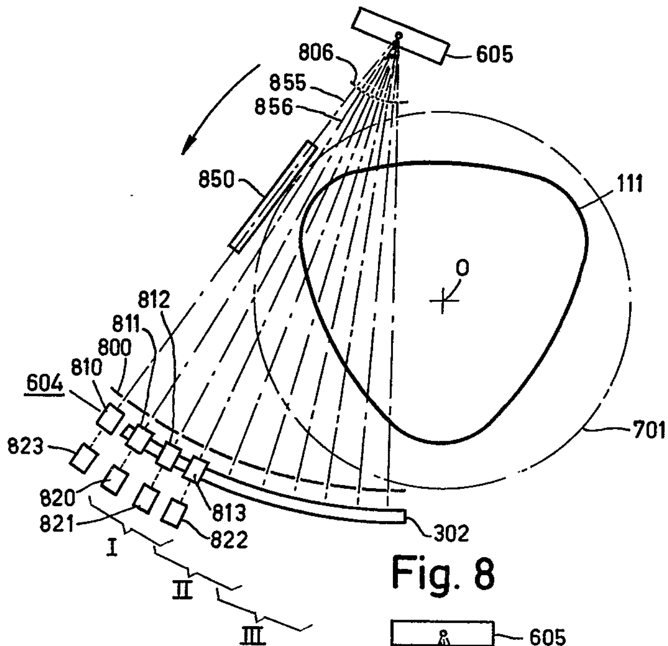
Fig. 6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II
III

Fig. 8

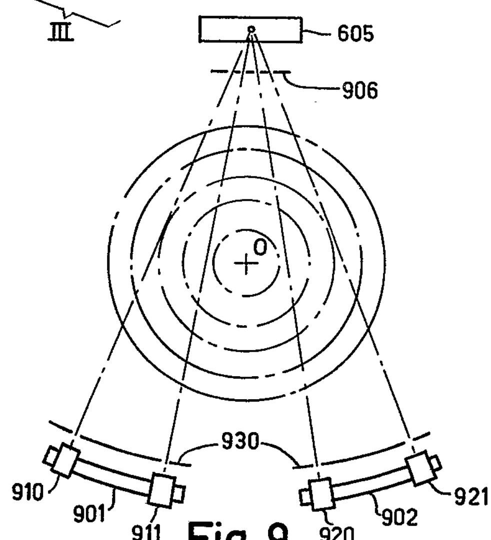
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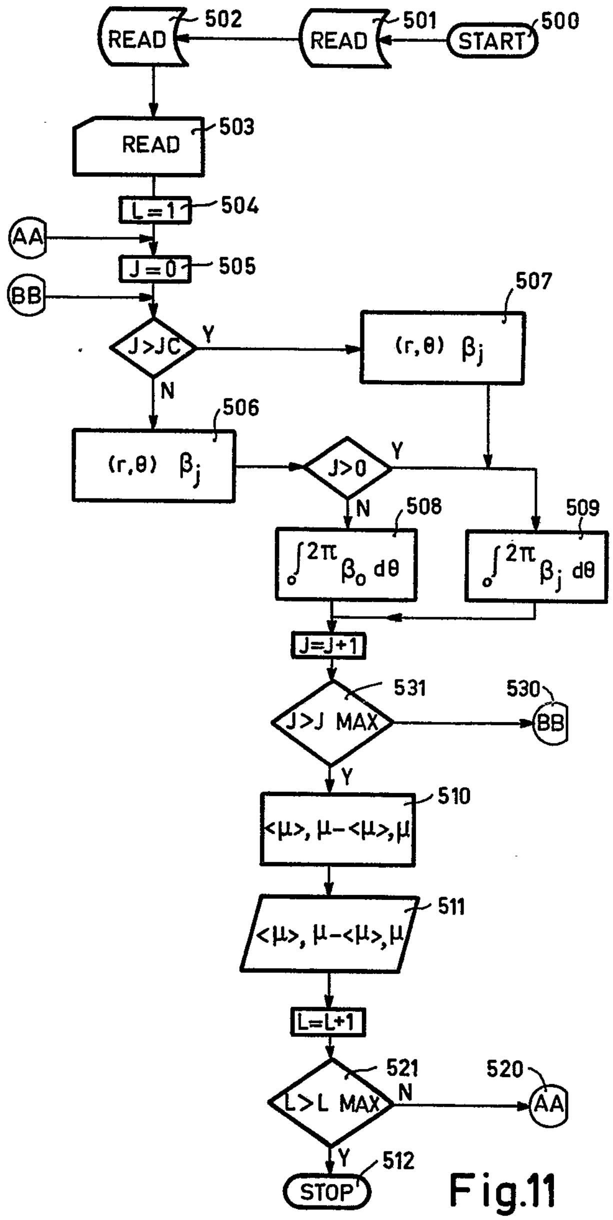
Fig. 9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(r,θ) βj
506
(r,θ) βj
J>0
Y
N
508
∫0 2π β0 dθ
509
∫0 2π βj dθ
J=J+1
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J>J MAX
530
BB
Y
510
<μ>, μ−<μ>, μ
511
<μ>, μ−<μ>, μ
L=L+1
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L>L MAX
N
520
AA
Y
512
STOP

Fig.11