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(56) Documents cited
None

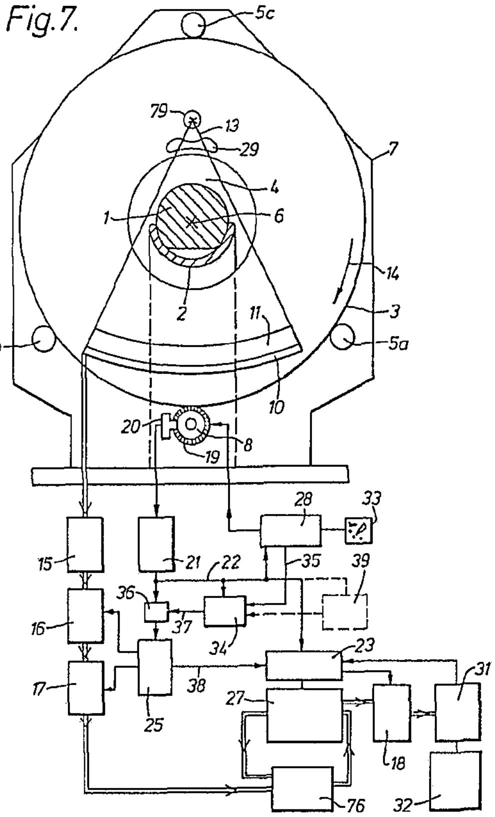
(58) Field of search
H4F

(54) Computed tomography apparatus

(57) In fan-beam computed tomography apparatus, timing reference pulses, normally occurring at intervals t, for data transfer and reset of the many integrators (approx. 500) in the signal path from the detector array 10, are generated from the scan displacement, e.g. using a graticule 19 and optical sensor 20, to relate the measurement paths geometrically to the body section 1. Sometimes, a slow scan rate (e.g. selected by a switch 33) is required to provide a time-averaged density image, e.g. for planning irradiation therapy and then the sensed impulses will occur at extended intervals and can cause integrator overload.

The improvement provides a pulse generator 34 which responds to a reduced scan rate, either as selected via 35 or as measured 39, by generating a succession of further transfer and reset pulses at intervals approximately equal to t starting a time t after each timing reference pulse, and accumulating, e.g. using an adding device 76 and RAM 27, all the transferred signals integrated in the interval t' between two successive slow scan reference pulses, in order to form a corresponding measurement signal.

Fig. 7.



The drawings originally filed were informal and the print here reproduced is taken from a later filed formal copy.

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Fig.1.

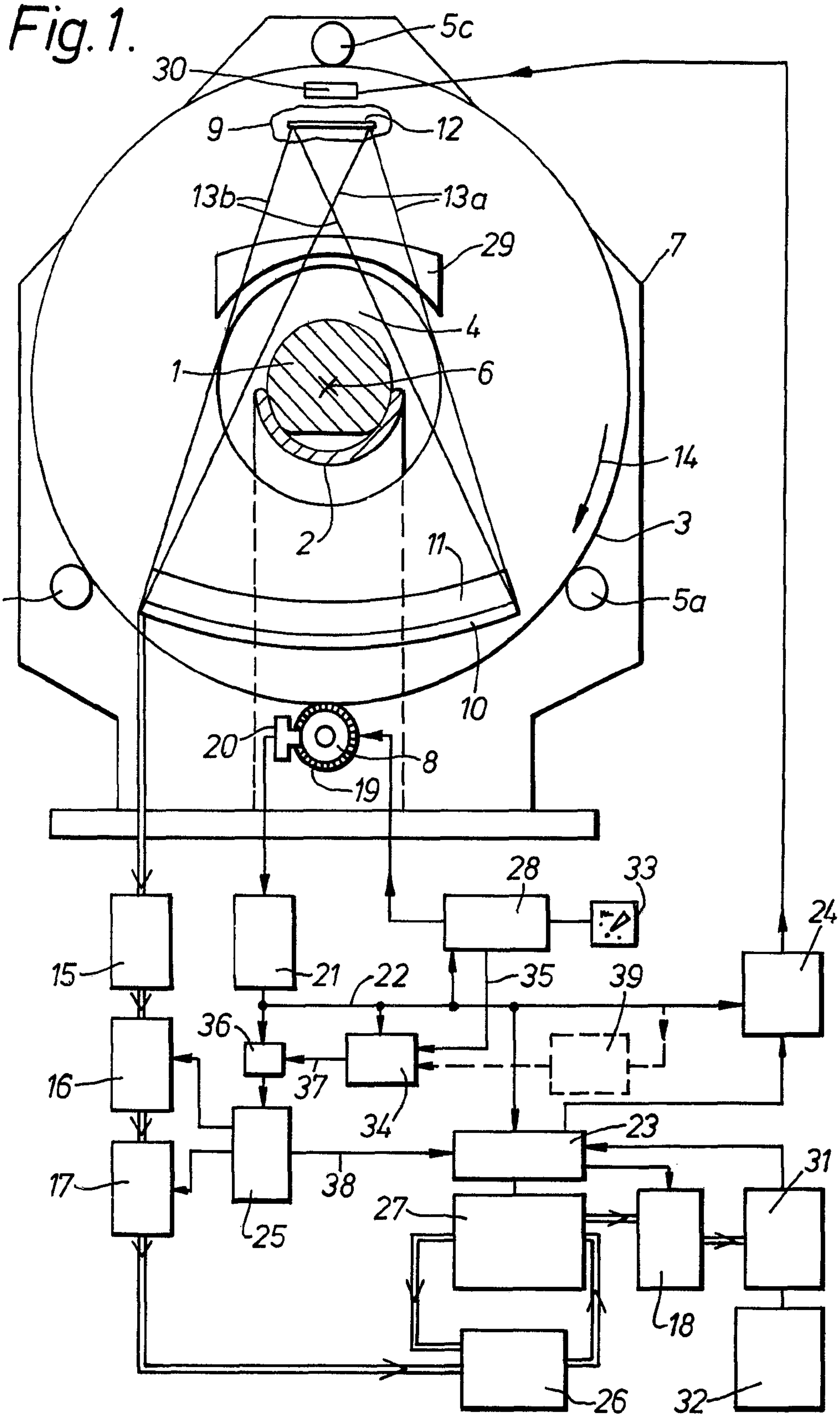
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Fig.2.

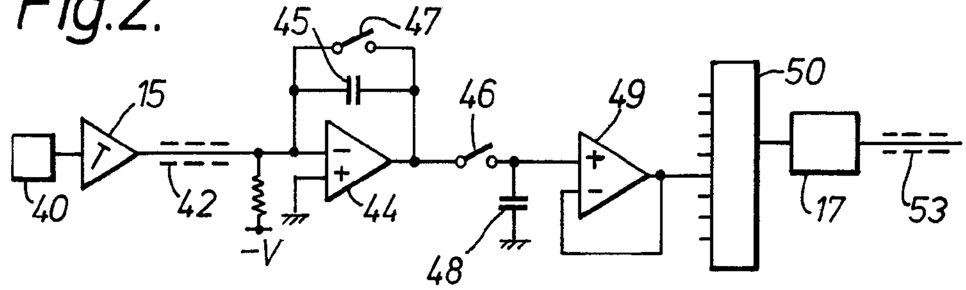
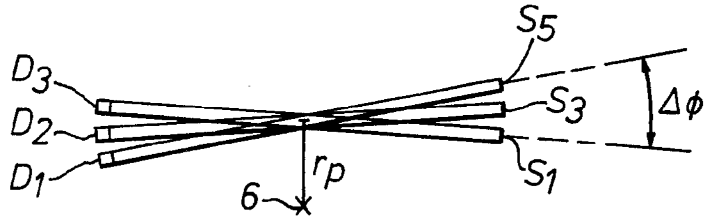


Fig.5.



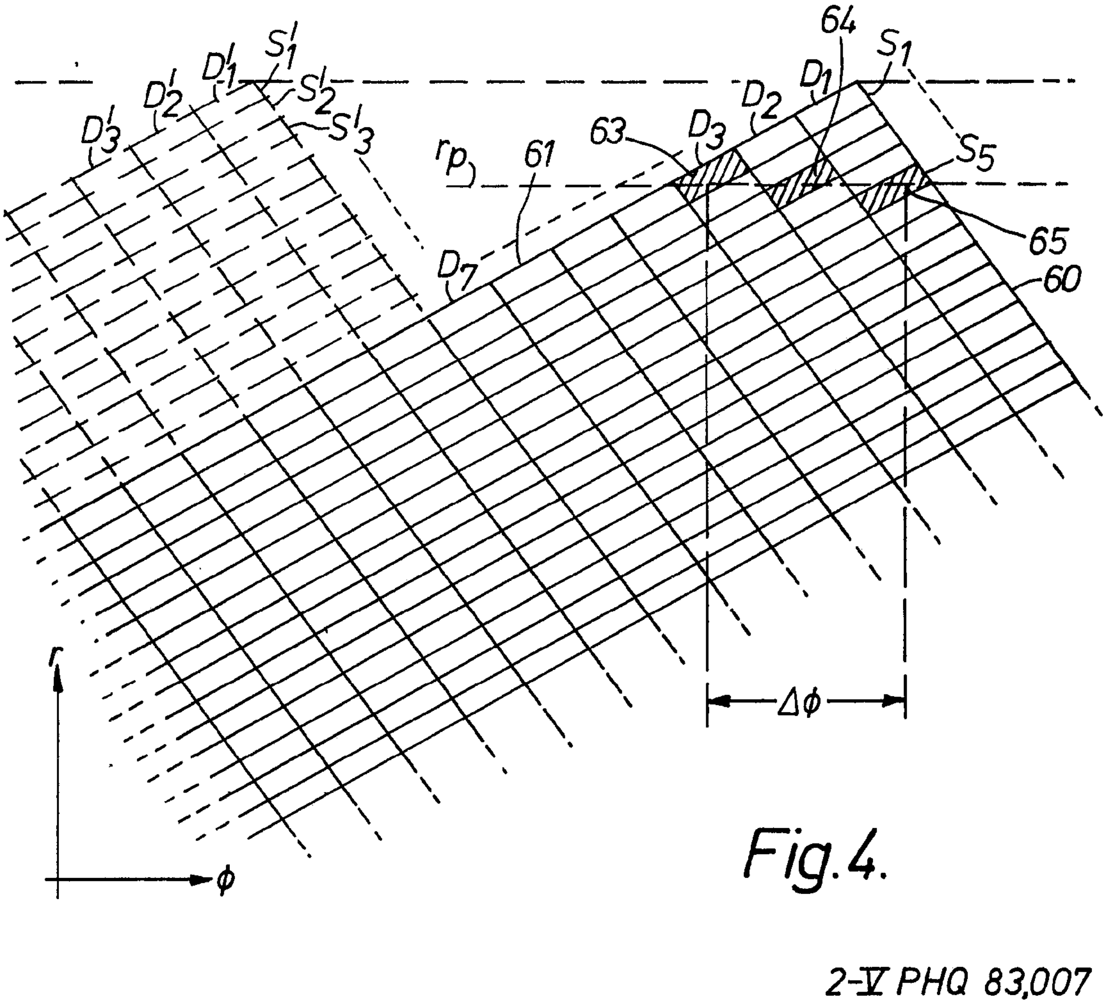


Fig.4.

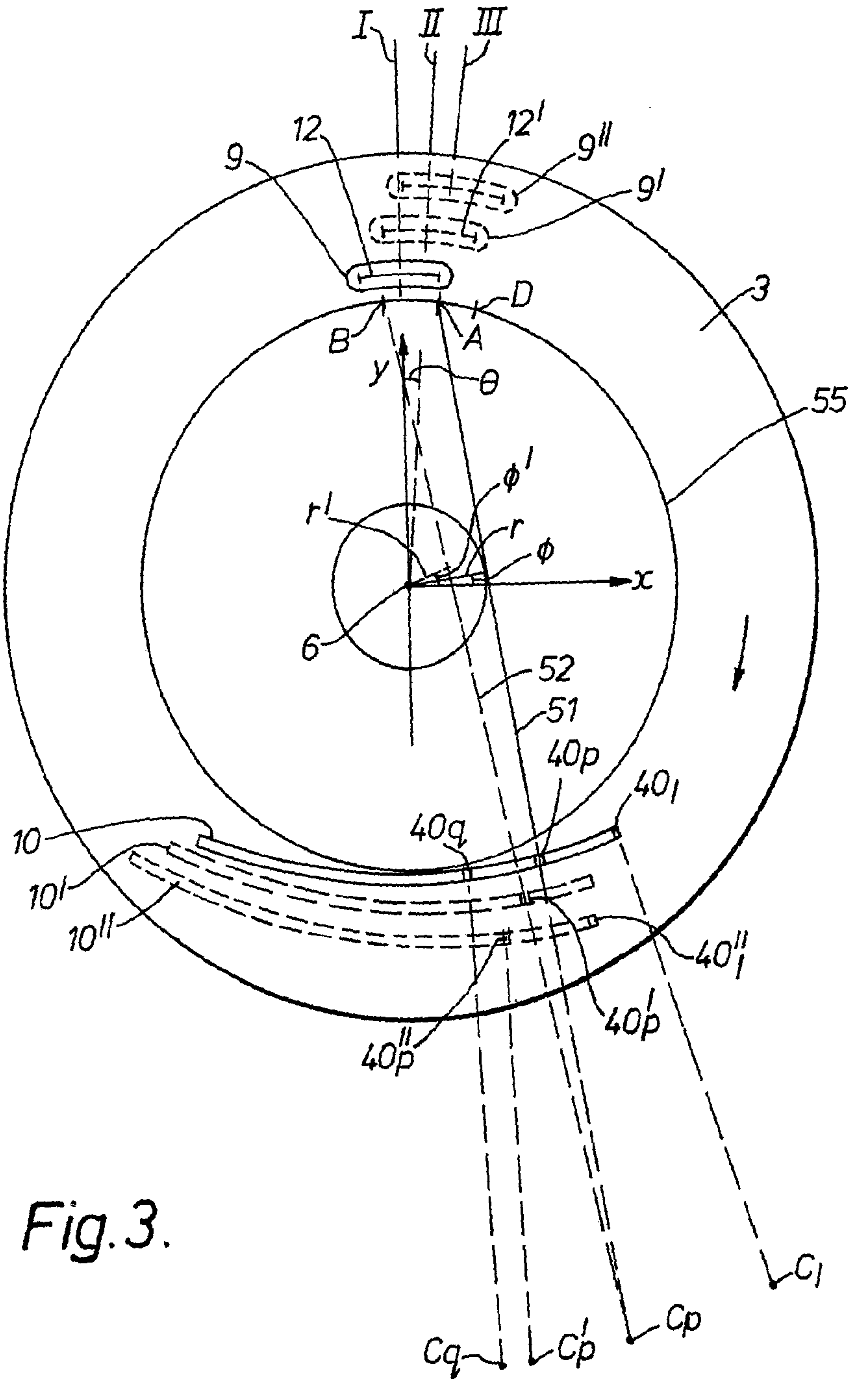


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Fig. 3.

Fig.6.

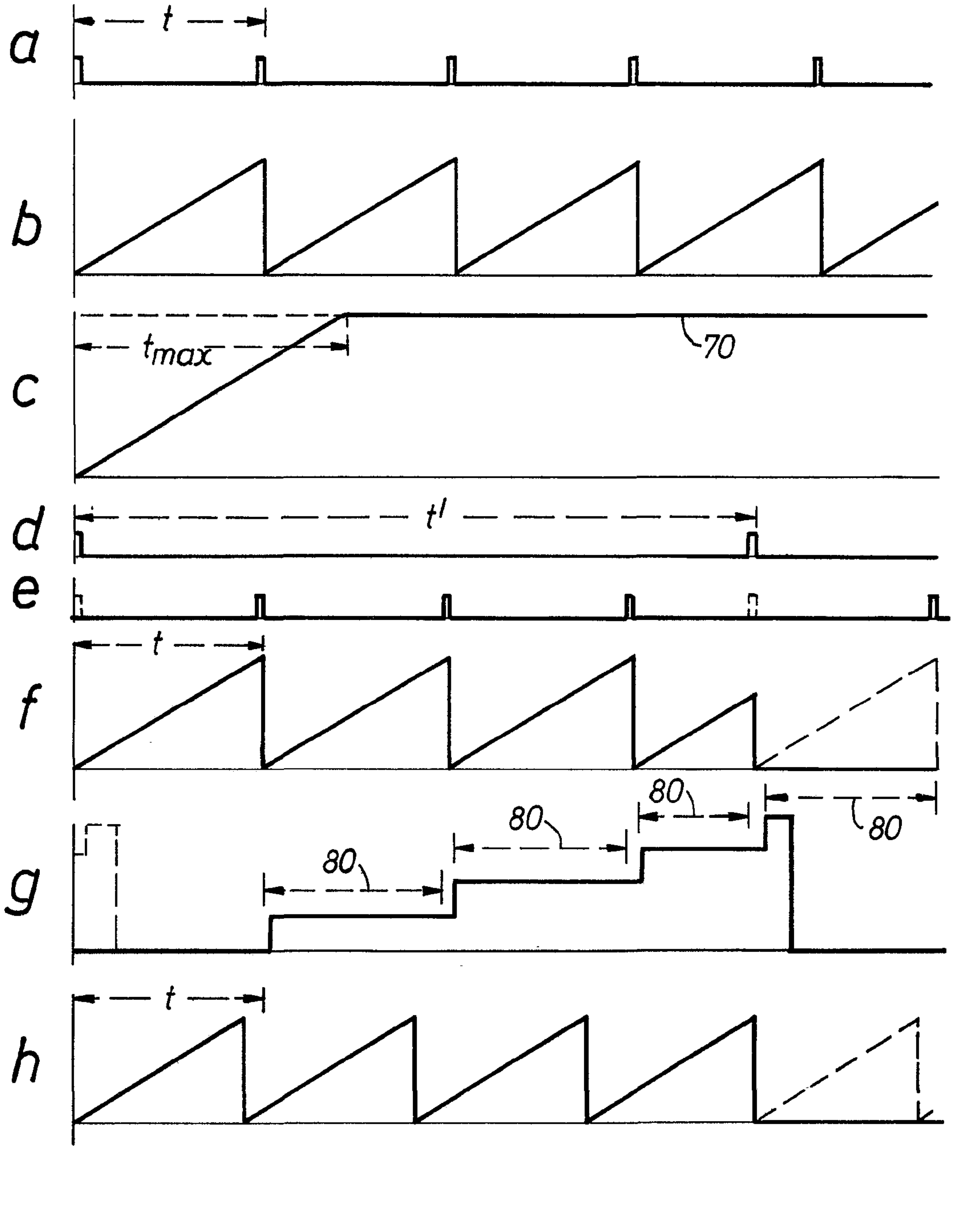
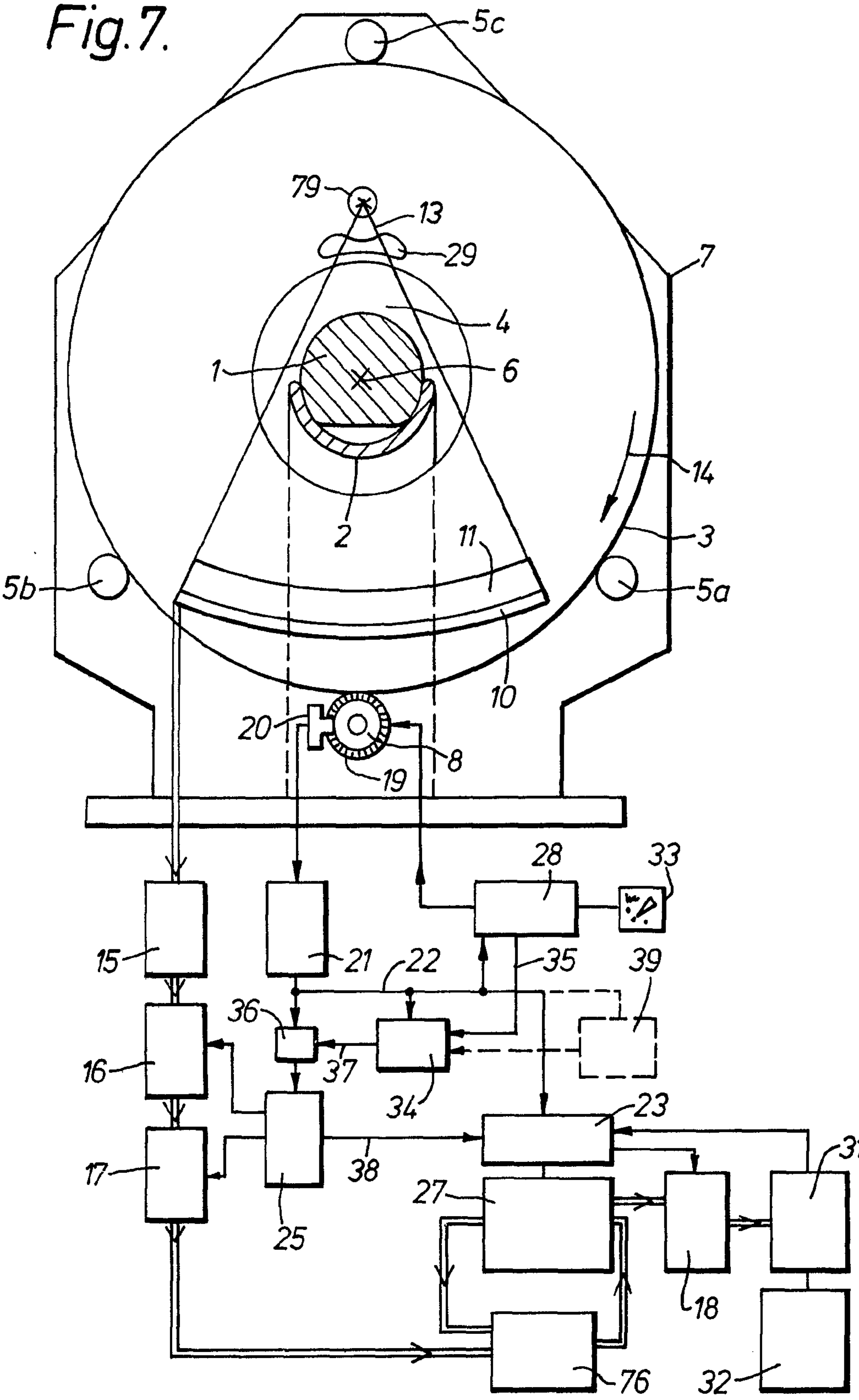


Fig.7.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SPECIFICATION

Computed tomography apparatus

This invention relates to computed tomography apparatus for measuring the attenuation of penetrating radiation along each of a plurality of measurement paths directed in the plane of a planar sectional region of the body of a patient under examination, and computing therefrom the distribution of local attenuation and hence of a physical variable such as density in the sectional region, said apparatus comprising means defining a patient position, a source of penetrating radiation arranged to irradiate the sectional region of a patient under examination with a substantially planar fan-shaped spread of radiation, supporting means arranged to support said source rotatably about the patient to irradiate the sectional region from different directions, detector means including an array of individual detectors also supported by said supporting means so as to detect radiation emergent from the irradiated sectional region and a plurality of associated integration circuits in which the detector outputs are integrated, either singly or in combination with other outputs from a group of adjacent detectors, to provide respective measurement signals each relating to a corresponding measurement path through the sectional region defined by the position of the source and the detector or group of adjacent detectors during a corresponding integration period t, scanning means including displacement means for moving the supporting means angularly about the patient at a substantially constant normal angular rate of scan and sensing means for sensing the occurrence of each successive predetermined increment in angular displacement and generating in response thereto a reference pulse for initiating a transfer and reset instruction for said integration circuits at the end of the integration period t, defined by the normal angular rate of scan and the magnitude of said predetermined increment in the angular displacement, and data processing means for processing the respective measurement signals to derive a representation of attenuation of radiation in said sectional region. Such apparatus will be referred to herein as computed tomography apparatus of the kind specified.

This invention further relates to computed tomography apparatus of the kind specified including source scanning means arranged to cause the source of the spread of radiation to repeatedly shift with respect to the detectors suring an angular displacement of said supporting means about a substantial angle so that each detector and associated integrator circuit detects and integrates sequentially in response to said reference pulses and during each said shift, radiation emerging from said sectional region along several mutually inclined substantially co-planar measurements paths, and combining means for combining measurement signals produced by different said detectors and associated integrators for each respective group of measurement paths which can pass through substantially the same respective part of the region, to provide corresponding composite measurement signals, each of which relates to a corresponding composite measurement path passing through said respective part of the sectional region, for processing to derive a representation of attenuation of radiation in said sectional region. Such apparatus will be referred to herein as computed tomography apparatus of the kind further specified.

In a computed tomography apparatus of the kind specified, the resolution of the computed output matrix image will depend *inter alia* on the resolution of the detector array, and in a typical array as many as 1000 similar detector elements may be used to span the spread of radiation after it has passed through the irradiated body section, although the full resolution is only used near the centre of the array. Thus on passing outwards from the central high resolution region of the array, a lower resolution is provided by connecting the outputs of adjacent groups of two or of four detectors together before feeding the corresponding integrator circuit thus reducing the total number of integrators required. Nevertheless the number of integrators would normally be quite large, e.g. from 300 to 400 individual units, and these would be arranged to provide an optimum performance for an integration time of t during a normal scan, and during that time would be arranged to provide an integrated signal magnitude which would be properly matched to the operation range of subsequent analog to digital converters used to convert the integrated detector signals into digital form for further processing.

Recently there has been a demand for a slow scan facility in which the scan speed can be reduced significantly, e.g. in steps by factors of 2,4,8 and 16, in order to provide a picture of the average disposition of organs such as the heart or lungs in the body cavity for the purposes of, for example, dose determination in relation to a proposed irradiation treatment.

If the apparatus hereinbefore referred to were operated at a reduced scan speed, the integration period would be correspondingly increased since the generation of a tranfer and reset instruction is coupled to the angular scanning displacement.

As a consequence, the resultant integral for a given detected signal, will be correspondingly greater and would pass out of range of (overload) an optimally specified integrator. In order to overcome such a difficulty all the integrators could be provided with an extended range but would then no longer be optimal for a normal speed scan. In this case the analog to digital converters would also require a greater conversion range and this would add up to considerable additional expense.

Alternatively the integrators could be provided with individually switchable time constants in order to provide the same output for a longer integration period thus enabling the same analog to digital converters to be used. Again, such a provision would be costly and would necessitate loss of data which could have been accumulated during the longer integration period.

Similar considerations apply with respect to computed tomography apparatus of the kind further specified such as that described in U.K. Patent Number GB 1,558,062. In this arrangement, each path attenuation value used as a basis for computing the output image matrix, is made up of a plurality of measurements made by different detectors along substantially the same measurement path, and this enables the effect of variations in the sensitivity of detectors relative to one another, to be significantly reduced.

It is an object of the invention to provide an improved computed tomography apparatus of the kind specified in which a selectable slow-scan facility can be provided with relatively little additional cost.

According to the invention there is provided computed tomography apparatus of the kind specified, characterised in that said apparatus further includes means for selecting a slow scan mode in which the rate of angular scan is less than said normal scan rate, and timing pulse generating means for generating during a scan in the slow scan mode and in response to the occurrence of each reference pulse, at least the first pulse of a regular succession of further pulses to initiate corresponding transfer and reset instructions for said integration circuits so that a succession of n integration periods each of a duration less than that at which the integrators would overload with a maximum signal to be integrated and preferably approximately equal to t, is or are provided in each period t' between successive occurrences of said reference pulses during a said slow scan, where n is an integer such that $1 \leq n \leq t'/t$, thereby to form corresponding measurement signals or respective successions of measurement signals, each measurement signal or succession of measurement signals relating to a corresponding measurement path substantially as defined during a scan performed at the normal angular scan rate. It will be apparent that the measurement signals forming each succession relating to a corresponding measurement path, can be fed individually to the data processing means and therein accumulated to provide a combined measurement signal representative of the corresponding measurement path as defined during a scan carried out at a normal scan rate. However apparatus in accordance with the invention can be provided with combining means for respectively accumulating each succession of measurement relating to a corresponding normal scan measurement path to provide a corresponding measurement signal input to the data processing means.

The invention is based on the realisation that in a computed tomography apparatus of the kind specified, an extension of the integration range or modification of the integration time constant, both of which must be applied to each one of the 500 or so individual integrators and in the first case to the corresponding analog to digital converters, can be rendered unnecessary for operation at a slow scan rate if the integration period were maintained the same as during a normal scan, or at least less than the limiting length of period at which a maximum detected signal would cause an integrator to go out-of-range, and that the integration period can be thus maintained by causing each reference pulse to initiate a train of further pulses which can also be used as transfer and reset pulses such as to cause a succession of integrations to be performed during the slow scan of a measurement path which latter is defined for computing purposes during a normal scan by two successive reference pulses and by the source and corresponding detector positions therebetween, while using corrresponding integration periods during such a succession, which are at least approximately equal to the integration period set during a normal scan rate by the time interval between successive reference pulses, and then adding together, i.e. accumulating, all the integrated values formed during such a succession to provide a measurement value which is to be associated with the said measurement path for the purposes of image computation. In this way the integrators and associated analog to digital converters can be permitted to perform with the same timings and within the same operational ranges as during a normal scan rate, and the only additional component required, other than a generator for the further pulses, would be some form of combining, i.e. accumulation, means for accumulating the integrated values provided during a said sequence, and such combining means can be provided relatively inexpensively with an extended digit range as required to make use of the additional measurement information and hence an increase in accuracy, made available by the extended, slow-scan, measurement period. The combining means may in fact be present at the input of the data processing means, or may be provided as part of the scanner circuitry.

According to the invention there is further provided computed tomography apparatus of the kind further specified, characterised in that said apparatus further includes means for selecting a slow scan mode in which the rate of angular scan is less than said normal scan rate, and timing pulse generating means for generating during a scan in the slow scan mode and in response to the occurrence of each reference pulse, at least the first pulse of a regular succession of further pulses to initiate corresponding transfer and reset instructions for said integration circuits so that a succession of n integration each of a duration less than that at which the integrators would overload with a maximum signal to be integrated and preferably approximately equal to t, is or are provided in each period t' between successive occurrences of said reference pulses during a said slow scan where n is an integer such that $1 \leq n \leq t'/t$, thereby to form corresponding measurement signals or respective successions of measurement signals, each measurement signal or succession of measurement signals relating to a corresponding measurement path substantially as defined during a scan performed at the normal angular scan rate, said combining means being arranged to combine the individual measurement signals forming each corresponding succession of measurement signals provided respectively by the different detectors and associated integrators for each group of measurement paths relating to a respective composite measurement path to provide corresponding composite measurement signals.

The invention is further based on the realisation that, in a computed tomography apparatus of the kind further specified in which combining means have already been provided for combining measurements signals produced by different detectors for each group of measurement paths passing through substantially the same respective part of the region under examination, it is a simple matter to employ such combining means to accumulate the individual integrated signals (measurement signals) making up each corresponding succession of measurement signals provided by the detectors associated with each said group of measurement paths to provide the corresponding composite signals during a slow scan.

Embodiments of the invention will now be described by way of example, with reference to the accompanying drawings, of which:-

Figure 1 schematically illustrates computed tomography apparatus embodying the invention,

Figure 2 is a block schematic of an analog signal path in Figure 1,

Figure 3 is a diagram illustrating the scan geometry of the apparatus of Figure 1,

Figure 4 is an r, ϕ diagram relating to Figure 1,

Figure 5 is a diagram illustrating the formation of a combined measurement path,

Figures 6a and *h*, are waveform and timing diagrams illustrating the operation of apparatus in accordance with the invention, and

Figure 7 schemtically illustrates a further form of computed tomography apparatus embodying the invention.

Referring to Figure 1, this illustrates diagrammatically an example of computed tomography apparatus of the kind further specified and emboding the invention. In Figure 1, a transverse section 1 is shown of a body under examination which latter is supported on a patient support 2. The body section 1 to be examined, may be surrounded in conventional manner by water bags (not shown) so that the boundary of the absorption field is rendered approximately circular to facilitate subsequent computation.

The apparatus comprises supporting means in the form of a rotatable member 3 having a central aperture 4 in which the body section 1 is centrally located by the patient support 2. The rotatable member 3 bears on rollers 5a, 5b and 5c so as to be rotatable about a central axis 6 which is longitudinal with respect to the body, and perpendicular to the plane of the body section, and of the drawing of Figure 1. The rollers 5 are journalled in a main supporting frame 7 which may take any form suitable to support the apparatus and to allow the necessary rotation. The member 3 is caused to rotate about the axis 6 by scanning means including a drive motor 8 suitably coupled to the member 3 *via* toothed drive coupling means (not shown), for example a toothed belt engaging peripheral teeth forming part of the member 3.

The rotatable member 3 carries an X-ray source 9, and an array 10 of detectors and associated collimators 11. The detectors are of any suitable type, for example scintillation crystals with associated optical-electrical signal converters such as photodiodes or photomultipliers. It is desirable that the detector elements of the array 10, should have a high efficiency in converting X-rays into optical radiation so as to provide a high sensitivity, thus enabling the dose to the patient to be kept to a minimum for a given noise-defined performance limit, and a high spatial resolution should be provided in the vicinity of the centre of the array.

An example of a convenient form of detector is a caesium iodide scintillation crystal coupled directly to a silicon photodiode. The detector elements in a typical array may number 1000, but the outputs of some of the elements would normally be taken together in groups of two or more towards the ends of the array where less resolution is required.

The X-ray source 9 includes an elongate target/anode 12 along which the electron beam impact spot is periodically deflected by suitable deflection means indicated diagrammatically by a block 30, and the emergent radiation is limited to form a fan-shaped beam 13 directed in the plane of the body section 1 and scanning the detector array 10. The source point of origin of the fan-beam 13, is scanned from the position 13a to the position 13b. Suitable forms of scanned spot X-ray tube are described in U.S. Patents Numbers 4,002,917 and 4,039,807, and will not be further described. The fan beam is arranged to extend laterally beyond the boundary of the body section 1 to one side, and preferably to both sides, so that a terminal detector element at the end of the array 10, or preferably a respective element at each end of the array, receives direct radiation from the source unattenuated by the body section 1 to provide a reference measurement for detector sensitivity comparison. In the present example the fan beam extends over an angle of 50°, and the scan of the origin of the X-rays along the target is about 4cms, although it may be more or less than this if desired.

It should be understood that, as an alternative, a stationary spot X-ray tube could be employed and mechanically scanned relative to the member 3 to achieve a similar result, but the attainable normal scanning speed would be considerably lower making it unattractive in the current state of the art.

In the present example, the scanned-spot X-ray source 9 is located approximately 60cms from the central axis 6, with the detectors 10 a further 60cms on the opposite side of the axis. However, the respective distances from the axis to the source 9, and to the detectors 10, may be unequal, if desired. The detector collimators 11 are arranged so that their longitudinal collimating axes intersect at the centre of the anode 12, and the detector array 10 is arranged to conform approximately to a circular arc also centred at the centre of the anode 12, and therefore having a radius of about 120 cms.

In accordance with usual practice, a graded attenuating body 29 is mounted on the rotatable member 3 and located between the X-ray source 9 and the body section 1. Because a scanned-spot source is used the body 29 should be as far from the source 9 and as close to the body section 1 as is practicable to reduce the effects of source shift, although linear effects will tend to be corrected for during the initial calibration process. The attenuating body 29 can alternatively be located between the body section 1 and the detector array 10, where it can equally well compensate for varying mean path attenuation across the body and be less subject to the effects of source shift, but in this position the patient dose will be undesirably increased. As a compromise a respective attenuating body can be disposed at both locations each effecting a partial compensation.

The radiation output (I_o) of the X-ray source is monitored by a stable detector (not shown) which is located on the source side of the usual beam limiting diaphragm (not shown) and outside the path of radiation forming the irradiating fan beam 13a, 13b. The output from the source monitoring detector can be integrated and sampled in conventional manner, converted to digital form and then, if desired, logarithmically converted to facilitate computation so that subsequent multiplication and division can be performed by addition and subtraction, and because attenuation is expressed as the logarithm of an intensity ratio.

In normal operation, the rotatable member 3 is rotated at a steady speed about the axis 6 by the motor 8 is a clockwise direction indicated by the arrow 14 so as to perform a scan of the patient at a normal angular rate of scan under the control of a scan motor control circuit 28. At the same time the X-ray spot is deflected at a uniform speed from the right hand end of the anode 12, beam 13a, to the left hand end, beam 13b, the electron beam is then interrupted during a flyback period during which the spot deflection is restored to the right-hand end, as shown in Figure 1. As explained in U.S. Patent 4,178,511, by selecting an appropriate contradisplacement speed for the X-ray source, the elements of the detector array can measure attenuation along a plurality of adjacent measurement paths relative to the body section, which intersect at a virtual point some distance beyond the detector array. The effective width of each measurement path will be defined by the effective size of the detector element, the size of the X-ray source spot, and the length of the integration period t applied to the detector output relative to the displacement speed of a notional line joining the source and the detector, as it is scanned across the body section.

As mentioned hereinbefore, the detector resolution at the centre of the array 10 is arranged to be greatest, consequently, in this region the analog output signal from each detector element is applied to a corresponding amplifier 15 and then to an associated integrator 16 to provide a corresponding measurement signal. To either side of the central region less resolution is required so that the outputs of two adjacent detectors, after amplification, are fed together to the input of a common integrator 16 to provide a measurement signal relating to a detector having an effective width twice that of a single element, and therefore to a wider measurement path. Similarly at the outer extremeties of the array 10, if desired, a common output from a group of four adjacent detector elements can be used to feed one integrator to provide a measurement signal relating to a correspondingly wider measurement path. Each integrated output signal is converted to digital form in an analog-digital converter 17 preparatory to subsequent data processing, including storage and logarithmic conversion.

The integrated detector signal sampling times are synchronised to the rotation of the rotatable member 3 by sensing means comprising a graticule or a coding disc 19 attached or coupled without backlash to the member 3, and a corresponding optical sensor 20 mounted on the support frame 7 and comprising, conventionally, a light source and a photocell. The sensing means also includes an amplifying and pulse forming circuit 21 which receives the photocell output and generates a reference pulse each time a mark corresponding to a predetermined angular increment in the rotation of the member 3 is sensed by the sensor 20. In order to reduce any jitter that may be present when using sensed graticule marks, the circuit 21 may include a phase locked loop in order to smooth out irregularities if desired.

Reference pulse generated by the circuit 21 are distributed, via a line 22, to an address selector 23 which keeps a count in conventional manner of the angular displacement θ of the member 3 about the patient scan axis 6 during a scan. The reference pulses are further distributed to an X-ray spot scan generator circuit 24 to which further angular synchronising signals can be fed from the address selector in order to adjust the flyback and spot blanking occurrence. The reference pulses are also fed to an instruction generator 25 which provides transfer and reset instructions for the integrators 16, and the analog to digital converters 17 in suitable sequence for a succession of identifiable measurement signals to be fed in digital form, to combining means 26 in the form of adding devices, together with appropriate data recalled from a random access memory (RAM) 27 under the control of the address selector 23. The corresponding outputs from the combining means 26 being stored in the appropriate location (usually the same) in the memory 27. In this way measurement signals produced by different detectors for measurement paths which pass through a sufficiently similar part of the body section 1 so to form together a composite measurement path, can be readily combined as described in U.K. Patent No. 1,558,062, to provide a corresponding composite measurement signal which can be stored at an address in the memory 27 related to the location with respect to the body section 1, of the composite measurement path.

At suitable intervals during the course of a rotary scan performed by the member 3, the data in the memory 27 can be transferred via logarithmic conversion means 18 to image data processing means 31, conventionally a computer, for transforming the path attenuation data into an output matrix image representing the distribution of local attenuation or density for display or recording by means of an image display unit 32. Alternatively, logarithmic conversion of the measurement data can be carried out within the data processing means 31. To this point the apparatus is of kind described in U.K. Patent Number 1,558,062. The scan motor control circuit 28 is provided with a scan speed selector 33 and is arranged so that, in addition to providing the normal angular rate of scan of the member 3, a slow scan mode can be selected in which one or more alternative slow scan rates can be selected which are less than the normal scan rate. Preferably the or each slow scan rate is made an integral submultiple of the normal angular rate of scan for the sake of convenience, though this is not essential.

The apparatus of Figure 1, in accordance with the invention, further includes a timing pulse generator 34 which is caused to become operative in response to a slow scan mode instruction signal fed from the scan motor control circuit 28 *via* a line 35. It will be assumed that the slow scan rate is l/n times the normal angular rate where n is an integer and may in practice take the value 8 for example. During a slow scan, the generator 34, in response to each reference pulse input thereto on the line 22 generates a succession of (n-1) pulses at intervals t commencing a time t after the occurrence of the initiating reference pulse, and these pulses will be referred to as further pulses to distinguish them from reference pulses generated by the sensing device 19, 20, 21.

The further pulses from the output of the generator 34 are fed *via* a line 37 to an OR connection 36 at the input of the instruction generator 25 to which the reference pulses on the line 22 are also fed. In this way, for each interval t' between successive reference pulses during a slow scan, the corresponding transfer and reset instructions initiated by the combined train of pulses input to the instruction generator 25 will result in the generation of a succession of *n* integration periods each of duration t in the integrators 16, and a corresponding succession of sets of measurement signals at the output of the analog to digital converters 17, which are fed to respective inputs of the combining means 26 in step with recalled values from the RAM 27 under the control of the address selector and in response to coordinating instructions from the instruction generator 25 as will be described hereinafter.

Figure 2 illustrates schematically in block form the analog signal path from a detector 40 in the array 10. The detector output is amplified in an amplifier 15 which has a low noise input stage and current gain adjustment facilities for initial adjustment. The amplifier output is fed to an integrator stage 16 formed conventionally by an amplifier 44, integrating capacitor 45, and transfer and reset gates 46, 47 respectively indicated by switches. The output of the integrator consists of a hold circuit formed by a capacitor 48 with output buffer amplifier 49. From the reset condition, the amplified output of the detector 40 is integrated in the circuit 44, 45 until the end of the integration period t. At the occurrence of a reference pulse or a further pulse, the instruction generator 25 provides a transfer signal which momentarily operates (opens) the transfer gate 46 to transfer the output voltage of the integrator to the hold capacitor 48. After the gate 46 has closed again, the instruction generator 25 momentarily operates the reset gate 47 to reset the integrator, and a new integration period then commences. It will be understood that a corresponding integrator and sample-and-hold circuit must be provided in respect of each individual measurement path simultaneously sensed by the detectors of the array 10, and a typical scanner may require for example 300 to 500 integrators, and about 1000 detectors and associated amplifiers.

There will be an interval t between the transfer of successive integrated detector values to a corresponding hold circuit enabling an analog multiplex switch 50 to feed the respective outputs of a group of several integrators in succession to a fast analog to digital converter 17 and thence to the appropriate inputs of the combining circuit 26. This is effected, conventionally, under the control of the instruction generator 25 which at the same time informs the address generator 23 as to which of the detectors are providing a measurement signal output from a given analog to digital converter at a given moment. The address generator 23 is conventionally arranged to convert a given detector position and a given scan rotation position θ implying also a given deflected source position along the anode 12 synchronised thereto, into an address r, ϕ for the corresponding measurement path where r and ϕ will be defined with reference Figure 3. In this way the memory 27 can recall appropriate stored values to the corresponding other inputs of the combining means 26.

It will be understood that some form of data coupling must be provided between the rotatable member 3 and the stationary support 7 in order to carry, for example, measurement data from the detectors of the array 10 mounted on the member 3, to that part of the apparatus which is stationary, notably the data processor 31. Suitable forms of data coupling include a flexible cable or an optical data transmission link. A flexible cable can be introduced at any convenient point in the signal path, either for analog signals for example at the point 42 shown in Figure 2, or for digital signals, namely at a convenient point, e.g. 52, after the analog to digital converters 17. If an optical data link were employed it would preferably be introduced into the digital signal path after the converters 17.

Figure 3 illustrates diagrammatically the scan geometry of the apparatus of Figure 1. A rotational scan of the member 3 is indicated at three successive values of the angular displacement 0 from an arbitrary reference (y-axis) represented by the direction lines I, II, III, indicating the respective relative positions of th source 9, 9', and 9" and of the detector array 10, 10' and 10" at the start and finish of an X-ray source spot scan, and after flyback, respectively. For the sake of clarity the successive positions of the source 9 and of the detector array 10 are drawn radially displaced outwardly although, of course, the source is alway located on the source locus 55, and in the present example the detector array 10 is tangential thereto. At the start of the spot scan the source position is as indicated at A on the source locus 55, which together with the position of a detector 40_p of the detector array 10 define a measurement path 51 through the patient section 1. The path 51 is identified relative to the image coordinates x, y, relating to the patient by the perpendicular distance r from the origin and rotation axis 6 and the angle ϕ subtended by that perpendicular with the x-axis. Each measurement path through the patient section will have a unique value of (r, ϕ) which can be used to generate a storage address for corresponding measurement signal values.

At the end of the X-ray spot scan, the spot will be deflected to the other end of the anode of the X-ray tube but the tube itself will have been carried round by the member 3 to the position 9′ to provide a source position indicated at B on the source locus 55. Similarly the corresponding detector will have been carried round to the position $40_p'$ to define a further measurement path 52 having coordinates r′ ϕ'. By suitably selecting the spot scan relative to the angular scan θ, the paths 51 and 52 together with intermediate paths relating to the same detector 40_p during a given spot scan, are made to intersect at a point C_p some way beyond the detector array 10. During the same spot scan, corresponding paths (not shown) relating to other detectors, e.g. 40_1 and 40_q, in the array 10, will intersect at other corresponding points e.g. C_1 and c_q. As explained in U.S. Patent 4,178,511, complete fans of measurement paths spanning the body section from a respective common point, can be obtained from different detectors during successive spot scans, and use of measurement data in this form can be less expensive to sort and store than the use of parallel sets of measurement paths, usually requiring in respect of fast fan-beam apparatus, a considerable number of interpolated values which will increase computing time and processing complexity.

Figure 4 is a diagrammatic r, ϕ diagram in rectangular format indicating the distribution of measurement paths in relation to corresponding source and detector positions during a combined source spot deflection and rotational scan. Successive X-ray spot positions determined by the deflection velocity and the occurences of reference pulses, are indicated, e.g. S_1, S_2,...., along the right hand side 60 of the full line diagram.

As will be apparent from consideration of Figure 3, the progress of an X-ray spot scan from the right hand end of the anode 12 to the far end at the rotated position 12′, will cause the value of r corresponding to the associated measurement path to a given detector correspondingly moving 40_p to $40_p'$ to become more negative, i.e. the source position will move downwards in Figure 4, but the resultant angular position ϕ of the perpendicular to the path from the centre 6 (Figure 3) will increase positively i.e. to ϕ'. Thus the source position line 60 in Figure 4 slopes downwards to the right. Similarly for a given source position the measurement paths relating to successive 40_1,...40_n, will have negatively increasing values for both ϕ and r, consequently a line 61 representing an axis of detector positions D_1, D_2 ....., slopes downwards to the left. Each rectangle is therefore associated with a source position and a detector position in the interval between two successive reference pulses, and represents a measurement path related to a normal rate of scan. After a spot flyback to the point D on the source locus (55 in Figure 3) the measurement path defined by the first source position S_1' of a scan and the detector D_1' ($40_1''$ in Figure 3) will correspond to a value ϕ'' shifted negatively, i.e. to the left in Figure 4, but to a value r which is the same as in the previous spot scan. This and other source and detector positions are indicated by the dashed line diagram to the left in Figure 4.

The diagram of Figure 4 indicates measurement paths 63, 64, 65, which pass through substantially the same part of the region 1 and relate to, for example three substantially co-planar measurement paths illustrated with their relative mutual inclination exaggerated for the sake of clarity in Figure 5, and of which the corresponding measurement values can be combined by the combining means 26 as described in U.K. Patent Number 1,558,062. Thus the paths 63, 64, 65, relate to successive source positions S_1, S_3, S_5, when cooperating respectively with detectors D_3, D_2 and D_1.

The values to be combined relate to paths having substantially the same value for r but with the angular values distributed over a small range of ϕ so that the measurement paths effectively pass through a common region of intersection, particularly when in the vincinity of the centre of rotation where greater resolution of measurement is required for subsequent image reconstruction.

The measurement paths 63, 64, 65 are defined as explained hereinbefore, by the timing of the reference signals generated by the optical sensor 20, and relate to a scan at normal speed during which one measurement is carried out for each path. When a slow scan is selected by the selector 33, in accordance with the invention, a succession of n measurement signals are generated for each detector-integrator combination for each of the said measurement paths, e.g. 63, 64, 65, and the individual measurement signals for each detector-and-source position, are added cumulatively in succession by combining means 26 to the value stored in 27 for that detector-and-source position, e.g as depicted by the corresponding intersection regions 63, 64, 65, addressed by appropriate values of r and ϕ. This can be carried out by suitably programming the address selector 33 only to address a storage location having the address of the path represented by 64 whenever the respective combination of source position and detector defining any of the paths 63, 64, 65, occurs, and in fact not to allocate a separate location in the RAM 27 for the paths 63 and 65. Thus the address of path 64 is applied during a slow scan for each occurrence of a measurement signal contained in the succession generated from detector D_3 during the source position S_1 and in the succession from D_2 for S_3 and from D_1 for S_5.

In this way a great deal of the organisation of control instructions employed during a normal speed scan can be employed unaltered during a slow speed scan. Further advantages are that the integrators and analog to digital converters will operate over the same amplitude and timing ranges in both normal and slow scan, and any increased digit capacity can be restricted to the memory 27, combining means 26, logarithmic converter 18 and the image data processor 31 and to the extent desired.

It will be apparent that the address selector 23 must select the next source position after the occurrence of a reference pulse defining the end of each integration period t at the normal scan rate after the transfer of the corresponding measurement signal to the memory 27 *via* the combining means 26. This selection of the following source position must also be complete before data produced during a slow scan in response to the first further pulse of the next succession of further pulses is transferred to the combining means 26.

Modifications can be made to the apparatus in accordance with the invention as shown in Figure 1. For example, the control signal on line 35 which instructs the function generator 34 that a slow speed scan is to be performed and at what speed, i.e. how many further pulses have to be generated to form each succession, can be derived alternatively from the output of a scan velocity measurement circuit 39, shown as dashed lines, which is fed with reference pulses from the line 22. Thus at normal speed the velocity measurement signal (pulse rate) provides an inhibit signal to the generator 34. During a slow scan, the velocity measurement signal generates an instruction to the generator 34 to provide pulse successions containing the appropriate number of further pulses.

Figures 6a to h are waveform and timing diagrams illustrating the operation of the integrators during a normal scan and during a slow scan.

The reference pulses generated by the graticule 19 and sensor 20 during a normal scan are shown in Figure 6a, and Figure 6b illustrates the output of a typical integrator to a detector output signal of maximum amplitude. The time between successive reference signals and hence the integration period is t, after which the integrator is reset.

Figure 6c illustrates the integration range of an integrator in terms of the maximum integration period t_{max} which is permissible for an input signal of maximum amplitude before the integrator goes out-of-range, as indicated by the level response 70 after a time t_{max}. It will be apparent that the integration period used in practice must always be less than the period indicated by t_{max}.

In apparatus in accordance with the invention it is not necessary for the slow-scan reference pulse period t' to be an integral multiple of the normal scan reference pulse period t, and Figure 6d shows an example of reference pulses generated by the graticule 19 and the sensor 20 during a slow scan, and occurring with a time interval t' which is a little less than four times the period t. When compard with Figure 6c, it will be seen that the integrators would be far out-of-range for a maximum detector signal. Figure 6e illustrates, by a continuous line, the further pulses generated by the timing pulse generator 34 in accordance with the invention, in response to the selection of a low scan rate, the corresponding reference pulses being indicated by dashed lines. In the example shown by Figure 6e, the further pulses form, together with the initial reference pulse, a succession of pulses having a period equal to the integration period t for the normal scan rate. The effect of using this succession of pulses as transfer and reset pulses for the integrators, is illustrated by Figure 6f from which it will be seen that, because the slow scan reference pulses occur at an interval which is not an integral multiple of the normal scan pulse interval, the last integration period before the next reference pulse is shorter than the remainder. This shortened period will not affect the performance adversely provided that it is the same at all parts of the scan, or that any variation is measured and allowed for during computation.

Figure 6g illustrates to a different vertical scale, the accumulation in the combining means 26 of a succession of digitally converted integrated (measurement) signals corresponding to a measurement path as defined during a normal scan by the source-and-detector positions between two successive reference pulses. Although the transfer steps appear to coincide with the occurrence of pulses in Figure 6e, it will be apparent from the description of Figure 2 that because each integrated value is held and is applied to the analog to digital converter via a multiplex link, each step can occur at almost any time during the next integration period, as can the final transfer of the accumulated total after the occurrence of the next reference pulse and this is indicated by dashed-line time-ranges 80.

It will be apparent from such considerations that difficulties of timing in the multiplexing and data transfer operations could arise if the last integration period were allowed to become too short relative to t. One way of avoiding this would be to suppress the last integrated signal and with it any data transfer occurring in the shortened period. This is undesirable since it would mean discarding data that had been measured.

An alternative solution is to alter the interpulse period for the succession of further pulses so that all the integration periods occurring between two successive reference pulses during a slow scan are of the same duration. This is illustrated in Figure 6h for the example shown. The integration period can alternatively be extended slightly beyond the duration t if a slow scan period t' is required which is slightly greater than an integral multiple of the normal scan period t, provided always that the resultant integration period is less than t_{max}. Clearly it is convenient to make $t' = nt$ where n is an integer if possible.

A further embodiment of the invention is illustrated diagrammatically in Figure 7 which represents a computed tomography apparatus of the kind specified. The apparatus is generally similar to that shown in Figure 1 except that a fixed spot X-ray tube 79 is employed, and corresponding reference numerals have been used to identify items common to both forms of apparatus. The description and mode of operation of the apparatus of Figure 7 in respect of features in common with those of Figure 1, will be similar and will not be repeated. As in Figure 1, the scan motor control circuit 28 is provided with a scan speed selector 33 for selecting, in addition to the normal angular rate of scan, one or more alternative slow scan rates.

In accordance with the invention, the apparatus includes the timing pulse generator 34 whose function has also been described with reference to Figure 1 together with that of the instruction generator 25. Fan-beam computed tomography apparatus of the kind specified, normally stores the digitally converted outputs from the respective detector-integrator paths 15, 16, 17, directly at appropriate corresponding addresses in the random access buffer store 27 to await periodic transfer to the image data processing means 31, and this would be convenient to employ in apparatus in accordance with the invention since the data transfer rate will remain the same for a slow scan in response to the further pulses generated by the generator 34, as would occur during a normal scan. The data processor 31 would, however have to be instructed to accumulate each succession of measurement signals formed during a slow scan and relating to a corresponding measurement path substantially as defined during a normal scan by two successive reference pulses. However, in the apparatus shown in Figure 7, combining means 76 has been provided which is arranged to operate in conjunction with the RAM 27 in a manner which can be identical with that of combining means 26 described with reference to Figure 1, so as to carry out this process of accumulating the measurement signals belonging to each succession. In this way the transfer of data from the RAM 27 to the data processor 31 can remain the same, apart from the digit span, in both the normal and slow scan modes.

In the operation of the apparatus of Figure 7 identical consideration apply concerning the timing of the further pulses and of the transfer of data as were discussed with reference to Figures 6c to h.

While apparatus in accordance with the invention has been described in terms of a slow scan including a succession of integration periods contained within the reference pulse period t', the further pulse generator can also be beneficially employed to generate a reset pulse when it is desired to reduce the scan speed by a lesser amount than a factor of two, in order to prevent the integrators from going out-of-range, although it would be preferable to make use of two shortened integration periods in succession, if possible, provided that the transfer of data is not adversely affected.

CLAIMS

1. Computed tomography apparatus for measuring the attenuation of penetrating radiation along each of a plurality of measurement paths directed in the plane of a planar sectional region of the body of a patient under examination, and computing therefrom the distribution of local attenuation and hence of a physical variable such as density in the sectional region, said apparatus comprising means defining a patient position, a source of penetrating radiation arranged to irradiate the sectional region of a patient under examination with a substantially planar fan-shaped spread of radiation, supporting means arranged to support said source rotatably about the patient to irradiate the sectional region from different directions, detector means including an array of individual detectors also supported by said supporting means so as to detect radiation emergent from the irradiated sectional region and a plurality of associated integration circuits in which the detector outputs are integrated either singly or in combination with other outputs from a group of adjacent detectors to provide respective measurement signals each relating to a corresponding measurement path through the sectional region defined by the position of the source and the detector or group of adjacent detectors during a corresponding integration period t, scanning means including displacement means for moving the supporting means angularly about the patient at a substantially constant normal angular rate of scan and sensing means for sensing the occurrence of each successive predetermined increment in angular displacement and generating in response thereto a reference pulse for initiating a transfer and reset instruction for said integration circuits at the end of the integration period t, defined by the normal angular rate of scan and the magnitude of said predetermined increment in the angular displacement, and data processing means for processing the respective measurement signals to derive a representation of attenuation of radiation in said sectional region, characterised in that said apparatus further includes means for selecting a slow scan mode in which the rate of angular scan is less than said normal scan rate, and timing pulse generating means for generating during a scan in the slow scan mode and in response to the occurrence of each reference pulse, at least the first pulse of a regular succession of further pulses to initiate corresponding transfer and reset instructions for said integration circuits so that one or a succession of n integration periods each of a duration less than that at which the integrators would overload with a maximum signal to be integrated and preferably approximately equal to t, is or are provided in each period t' between successive occurrences of said reference pulses during a said slow scan, where n is an integer such that $1 \leqslant n \leqslant t'/t$, thereby to form corresponding measurement signals or respective successions of measurement signals, each measurement signal or succession of measurement signals relating to a corresponding measurement path substantially as defined during a scan performed at the normal angular scan rate.

2. Computed tomography apparatus as claimed in Claim 1, characterised in that combining means are provided for respectively accumulating each succession of measurement signals relating to a corresponding normal scan measurement path to provide a corresponding measurement signal input to the data processing means.

3. Computed tomography apparatus for measuring the attenuation of penetrating radiation along each of a plurality of measurement paths directed in the plane of a planar sectional region of the body of a patient under examination, and computing therefrom the distribution of local attenuation and hence of a physical variable such as density in the sectional region, said apparatus comprising means defining a patient position, a source of penetrating radiation arranged to irradiate the sectional region of a patient under examination with a substantially planar fan-

shaped spread of radiation, supporting means arranged to support said source rotatably about the patient to irradiate the sectional region from different directions, detector means including an array of individual detectors also supported by said supporting means so as to detect radiation emergent from the irradiated sectional region and a plurality of associated integration circuits in which the detector outputs are integrated either singly or in combination with other outputs from a group of adjacent detectors to provide respective measurement signals each relating to a corresponding measurement path through the sectional region defined by the position of the source and the detector or group of adjacent detectors during a corresponding integration period t, scanning means including displacement means for moving the supporting means angularly about the patient at a substantially constant normal angular rate of scan and sensing means for sensing the occurrence of each successive predetermined increment in angular displacement and generating in response thereto a reference pulse for initiating a transfer and reset instruction for said integration circuits at the end of the integration period t, defined by the normal angular rate of scan and the magnitude of said predetermined increment in the angular displacement, source scanning means arranged to cause the source of the spread of radiation to repeatedly shift with respect to the detectors during an angular displacement of said supporting means about a substantial angle so that each detector and associated integrator circuit detects and integrates sequentially in response to said reference pulses and during each said shift, radiation emerging from said sectional region along several mutually inclined substantially co-planar measurement paths, combining means for combining measurement signals produced by different said detectors and associated integrators for each respective group of measurement paths which can pass through substantially the same respective part of the region, to provide corresponding composite measurement signals, each of which relates to a corresponding composite measurement path passing through said respective part of the sectional region, and data processing means for processing the respective composite measurement signals to derive a representation of attenuation of radiation in said sectional region, characterised in that said apparatus further includes means for selecting a slow scan mode in which the rate of angular scan is less than said normal scan rate, and timing pulse generating means for generating during a scan in the slow scan mode and in response to the occurrence of each reference pulse, at least the first pulse of a regular succession of further pulses to initiate corresponding transfer and reset instructions for said integration circuits so that a succession of n integration periods each of a duration less than that at which the integrators would overload with a maximum signal to be integrated and preferably approximately equal to t, is or are provided in each period t' between successive occurrences of said reference pulses during a said slow scan where n is an integer such that $1 \leq n \leq t'/t$, thereby to form corresponding measurement signals or respective successions of measurement signals, each measurement signal or succession of measurement signals relating to a corresponding measurement path substantially as defined during a scan performed at the normal angular scan rate, said combining means being arranged to combine the individual measurement signals forming each corresponding succession of measurement signals provided respectively by the different detectors and associated integrators for each group of measurement paths relating to a respective composite measurement path to provide corresponding composite measurement signals.

4. Apparatus as claimed in any one of the preceding claims, characterised in that the slow rate of scan is such that the period t', between successive reference pulses in an integral multiple of t.

5. Apparatus as claimed in any one of the preceding claims, characterised in that each succession of measurement signals commences with the measurement signal value transferred by the first further pulse generated after the occurrence of a said reference pulse and terminates with the measurement signal value transferred by the next reference pulse.

6. Computed tomography apparatus of the kind set forth substantially as herein described with reference to the accompanying drawings.

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