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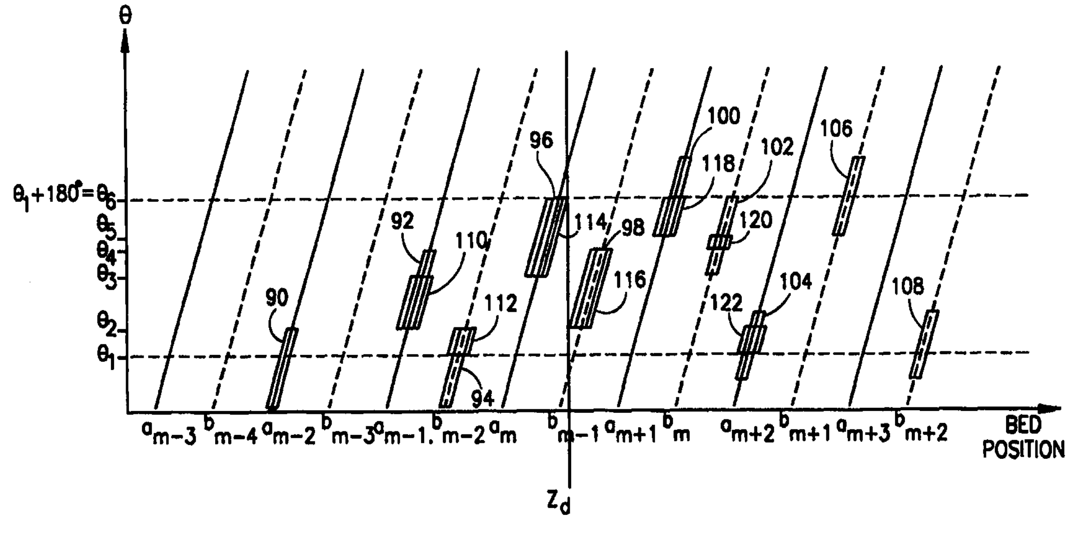

(57) Abstract

A method of CT–imaging a periodically moving object, comprising rotating a source of x–rays more than half a rotation around the object such that the rotation of the source is unsynchronized to the periodic motion of the object; detecting radiation passing through the object to produce attenuation data; associating a phase of the periodic motion and an angular position of the source, with the data; selecting data from the data, which data is acquired over more than one half–rotation and which selected data has an associated phase substantially equal to certain phases corresponding to at least one acquisition window; and reconstructing at least one image of the object using the selected data.

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CARDIAC IMAGING

FIELD OF THE INVENTION

The present invention relates to the field of x-ray computerized tomography of moving structures, such as the heart.

BACKGROUND OF THE INVENTION

Every year, many people die or are severely injured as a result of various heart diseases, including arteriolosclerosis of the coronary blood vessels. Arteriolosclerosis is very difficult to diagnose non-invasively. Usually, arteriolosclerosis is diagnosed using x-ray angiography, in which a radio-opaque contrast material is injected into the blood stream, to enhance the contrast of small blood vessels. In advanced cases of arteriolosclerosis, calcium deposits are formed on the walls of the afflicted blood vessels. These calcium deposits can be readily detected using x-ray CT imaging, as can narrowing of blood vessels (if a contrast material is injected into the blood stream). However, some of the most important blood vessels are in the heart itself, which is in continuous motion, and conventional CT devices fail to overcome blurring of the images which is caused by the motion of the heart. Even in third and fourth generation x-ray CT devices, the rotation of a gantry is about 1 second, which is approximately the length of an entire heart cycle. It can therefore be appreciated that imaging an in-vivo beating heart is a very important medical imaging application. Other applications for cardiac imaging include: stroke volume estimation, detection of aneurysms and diagnosis of structural pathologies in the heart.

Some specialized CT devices are known for the in-vivo imaging of the heart. For example, a scanning electron beam CT imager can image the entire heart in under 40 ms, a time period during which the heart does not move substantially. However the electron beam x-ray CT is very specialized and expensive and therefore, may not be a viable solution for many medical facilities.

U.S. Patent 4,547,892 suggests synchronizing the rotation of a CT gantry to the patient's heart beat. This solution has not found wide acceptance for two reasons. First, it is difficult to construct a CT device in which the rotation speed can be so precisely controlled, and second, many ill people do not have a steady heart beat.

SUMMARY OF THE INVENTION

It is an object of some aspects of the present invention to provide a method of cardiac imaging which can be practiced on general purpose x-ray CT devices.

Another object of some aspects of the present invention is to provide a method of overcoming image blur caused by periodic motion of body organs.

In a preferred embodiment of the invention a method of cardiac imaging includes:

adjusting the rotation speed of the gantry so that it is not synchronized to the period motion of the heart;

acquiring data in multiple scans of the heart;

selecting portions of the data which correspond to a segment of the cardiac cycle in which there is relatively little motion of a part of the heart which is of interest; and

reconstructing an image of the part of the heart from the selected data portions. Preferably, the image of the part of the heart is an image of blood vessels in the heart.

Preferably, the rotation of the gantry is chosen so that it is different from the average heart rate of the patient. Both the heart rate and the phase of the cardiac cycle may be measured using an ECG device.

Preferably, the heart image is reconstructed from the data acquired during end systole. Additionally or alternatively, the image is reconstructed from data acquired during end diastole. These are the two segments of the heart cycle where the entire heart is relatively motionless for a substantial period of time. Thus, it is possible to determine the stroke volume by subtracting the left ventricular volume during systole from the left ventricular volume during diastole.

Preferably, a multi-slice x-ray CT device is used, so that multiple slices of the heart can be imaged simultaneously. As a result, the entire heart can be imaged in a shorter number of cardiac cycles. As the motion of the heart is not perfectly periodic, by reducing the number of imaging cycles utilized in reconstruction, the effect of the irregular motion of the heart on image quality is reduced.

In another preferred embodiment of the invention, the x-ray CT device uses a helix type scan, in which the bed is continuously advanced while the gantry rotates around the bed. In helix-acquired data, image voxels are reconstructed by interpolating between acquired data. Preferably the helix is tightened in cardiac imaging to compensate for data which cannot be used, for example when imaging at end diastole, data acquired during the diastole. This tightening may be achieved by reducing the table speed, thereby achieving greater data redundancy.

In a preferred embodiment of the invention, the CT machine is a multi-slice CT machine, preferably using a cone-beam.

There is therefore provided in accordance with a preferred embodiment of the invention, a method of CT-imaging a periodically moving object, comprising:

rotating a source of x-rays more than half a rotation around the object such that the rotation of the source is unsynchronized to the periodic motion of the object;

detecting radiation passing through the object to produce attenuation data;

associating a phase of the periodic motion and an angular position of the source, with the data;

selecting data from the data, which data is preferably acquired over more than one half-rotation and which selected data has an associated phase substantially equal to certain phases corresponding to at least one acquisition window; and

reconstructing at least one image of the object using the selected data.

Preferably, the method comprises determining an average periodic time of the periodic motion, where the rotating comprises rotating the source half a rotation around the object in a time different from half the determined average time or a multiple or sub-multiple thereof.

Alternatively or additionally, rotating more than half a rotation comprises rotating at least once.

There is also provided in accordance with a preferred embodiment of the invention, a method of CT-imaging a periodically moving object, comprising:

rotating a plurality of sources of x-rays around the object such that the rotation of the source is unsynchronized to the periodic motion of the object;

detecting radiation passing through the object to produce attenuation data;

associating a phase of the periodic motion and an angular position of at least one of said plurality of sources, with the data;

selecting data from the data, which selected data has an associated phase substantially equal to certain phases corresponding to at least one acquisition window; and

reconstructing at least one image of the object using the selected data.

Preferably, reconstructing comprises reconstructing at least one image of the object using data acquired in less than two rotations of the gantry,

Alternatively, reconstructing comprises reconstructing at least one image of the object using data acquired in less than one rotation of the gantry,

In a preferred embodiment of the invention, rotating comprises:

rotating the source at an angular velocity such that a probability that an angular position at which the periodic motion is at the certain phases repeats itself is minimized.

Alternatively or additionally, where characteristics of the periodic motion may vary, the method preferably comprises:

determining a value of a variation of a characteristic of the periodicity of the periodic motion; and

associating the value with the data.

Preferably, the characteristic comprises rate.

In a preferred embodiment of the invention, the certain phases comprise phases at which the object has minimal motion.

Alternatively or additionally, the at least one acquisition window has a given extent and wherein the given extent is determined in response to the period of the periodic motion at which the data is acquired.

Preferably, the image comprises a plurality of image slices and the extent is different for different slices of the reconstructed image.

Alternatively or additionally, the image comprises a plurality of image slices and wherein the at least one acquisition window has an angular starting position and wherein the position is different for different slices of the reconstructed image.

Alternatively or additionally, the given extent is determined in response to the amount of motion of the object at the certain phases.

Alternatively, the method comprises:

determining a desired level of image quality; and

determining a period of time required for data acquisition for image reconstruction,

wherein the given extent is determined in response to the determined time period and the desired level of image quality.

In a preferred embodiment of the invention, reconstructing an image comprises reconstructing an image from data acquired from an angular extent of at least 180 degrees.

Preferably, data acquired at a first angular position is mirrored through 180 degrees to a second angular position to replace unsuitable data at the second angular position.

In a preferred embodiment of the invention, data is not selected at a certain rotation angle and the method comprises:

interpolated between data acquired at rotation angles near the certain rotation angle to reconstruct the data which is not selected at the certain rotation angle.

Preferably, interpolating comprises assigning weights to data at the near rotation angles responsive to the angular difference between the near angles and the angle.

In a preferred embodiment of the invention, where the image comprises a plurality of image slices and data corresponding to a certain rotation of a certain slice is not selected, the method comprises:

interpolating between data acquired at slices near the certain slice to reconstruct the data which is not selected.

Preferably, interpolating comprises assigning weights to data at the near slices responsive to the distance between the near slices and the certain slice.

In a preferred embodiment of the invention, where data is not selected at a certain phase of the object, the method comprises:

interpolated between data acquired at phases near the certain phase to reconstruct the data which is not selected at the certain phase.

Preferably, interpolating comprises assigning weights to data at the near phases responsive to the difference between the near phases and the certain phase.

Alternatively or additionally, interpolating comprises assigning weights to data at the near phases responsive to the difference in the morphology of the object between the near phases and the certain phase.

In a preferred embodiment of the invention, the object comprises a human heart. Preferably, the method comprises determining a phase of a heart cycle using an ECG device. Alternatively or additionally, the certain phases comprise an end diastolic period. Alternatively or additionally, the certain phases comprise an end systolic period. Alternatively or additionally, data is binned based on a heart-beat morphology.

In a preferred embodiment of the invention, the object comprises a human lung. Preferably, the method comprises determining the phase of a breathing cycle using a belly strap. Alternatively or additionally, the certain phases comprise an end-respiration period. Alternatively or additionally, the certain phases comprise an end-exhalation period.

In a preferred embodiment of the invention, detecting comprises detecting using a stationary detector array.

Alternatively or additionally, detecting comprises:

moving the object along an axial direction relative to the detector; and

detecting radiation at a plurality of axial positions to generate data for a three dimensional image set.

Preferably, the method comprises moving the object during said detecting. Alternatively, the method comprises moving the object while not detecting radiation.

In a preferred embodiment of the invention, detecting comprises detecting radiation using a two-dimensional array of radiation detectors, preferably, a multi-row array.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be more clearly understood from the following detailed description of the preferred embodiments of the invention and from the attached drawings, in which:

Fig. 1 is a schematic diagram of an x-ray CT imaging device in accordance with a preferred embodiment of the invention;

Fig. 2 is a schematic side view of an overlay of a CT image set on a human body showing the intersections between image slices and a heart;

Fig. 3 is a diagram showing preferred data acquisition times on an ECG scale, according to a preferred embodiment of the invention;

Fig. 4 is a schematic diagram showing the acquisition of data for a single slice over time in accordance with acquisition timing as shown in Fig. 3; and

Fig. 5 is a schematic diagram showing selection of data from a spiral scan for interpolation, in accordance with a preferred embodiment of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Fig. 1 is a schematic diagram of an x-ray CT imaging device 20 in accordance with a preferred embodiment of the invention. A patient 22, having a heart 24 to be imaged, is placed on a bed 26. Heart 24 is imaged by irradiating it with x-ray radiation from an x-ray source 28, which is powered by a high voltage power supply 29. The x-ray radiation from source 28 is attenuated by the body of patient 22, and in particular by heart 24, which may be injected with a blood contrast medium, and the attenuated radiation is received by a detector array 30. Source 28 and detector array 30 are typically located in a rotatable gantry 32, which rotation is affected by a gantry rotation system 34. Bed 26 is typically movable in the axial (Z) direction, which motion is affected by a bed motion system 36. It should be appreciated that the present invention may also be used in conjunction with second and fourth generation CT devices. Preferably two images are acquired, one before the dye injection and one after, so that the two images may be subtracted to yield and angiogram.

Radiation which impinges on detectors 30 is acquired by a data acquisition circuit 38. The acquired data is transferred to an image reconstruction circuit 40, optionally stored in a memory 42 and/or displayed on a display unit 44.

The entire CT device 20 is controlled by system control circuitry 46. Motion of the heart may be determined using an ECG device 48 which supplies an ECG tracing of heart 24 to CT device 20 via data acquisition circuit 38.

Fig. 2 is a schematic side view of an overlay of a CT image set on human body 22 showing the intersections between a plurality of image slices 50 and heart 24. In a living human, the heart is continuously beating and moving. On the average, one cardiac cycle takes .8 seconds. Since a typical gantry rotation time is about one second, if heart 24 is imaged using methods as known in the art, many motion artifacts, such as motion blur, will be added to the reconstructed image. Slices 50 are shown to be non-overlapping, for clarity. However, in a preferred embodiment of the invention, slices 50 are lapped or even overlapped.

Fig. 3 is a diagram showing preferred data acquisition times on an ECG scale 52, according to a preferred embodiment of the invention. In should be noted that in most patients the cardiac cycle is not exactly periodic. Heart 24 is relatively motionless during end diastole, indicated in Fig. 3 by acquisition windows 54. Heart 24 is also relatively motionless during end systole, indicated in Fig. 3 by acquisition windows 56. Each chamber of heart 24 enters systole and diastole at different times, therefore, the timing of acquisition windows 54 and 56 may depend on the portion of the heart being imaged. Further, the extent (width) of the acquisition windows, preferably of a single window, depends on the level of motion artifacts which are tolerable in the resulting CT image and/or on the desired acquisition time. In a preferred embodiment of the invention, data which is outside the desired extent of the acquisition window is averaged between several such out-of-window data. Preferably, the data is averaged between data acquired at phases earlier than the reconstructed phase and data acquired at phases after the reconstructed phase. Alternatively or additional, the averaging is a weighted averaging, which weight is responsive to the difference in phase between the data and the reconstructed phase. In many cases, the cardiac cycle changes in length and/or morphology significantly between consecutive cycles. In a preferred embodiment of the invention, the extent of acquisition windows 54 and/or 56 is changed responsive to a measured heart rate and/or ECG morphology. Alternatively or additionally, the amount of data which is selected from the acquired data is determined based on the measured heart rate and/or ECG morphology.

Acquiring attenuation data in windows 54 or windows 56 does not guarantee that a cardiac image can be reconstructed. To reconstruct a CT image, data must be acquired for at least 180 degrees rotation around the body. Therefore, in a preferred embodiment of the invention, the rotation of gantry 32 is adjusted to be unsynchronized with the rhythm of heart 24. As a result of the rotation being unsynchronized to the cardiac rhythm, each time gantry 32 rotates around heart 24, it views heart 24 at a different viewing angle during the acquisition window. After several rotations, enough data can be acquired to reconstruct a CT image. A PCT application No. pct/il97/00128, titled "Direct Tomographic Reconstruction" and filed April 17, 1997, the disclosure of which is incorporated herein by reference describes a method of reconstructing an image, substantially without artifacts, using less than 180 degrees of data. Thus, using this method, less than 180 degrees of data may be acquired for one or more of the slices.

One preferred method of de-synchronizing the gantry rotation from heart 24 is to measure the average heart rate of heart 24 and to adjust the gantry rotation speed to be different from the average heart rate. Different rotation speeds may be preferred, depending on the width of the acquisition window, the variability of the heart rate and the desired overlap between acquisition angles.

In a preferred embodiment of the invention, the rotation speed of gantry 32 is varied to maintain its non-synchronization with heart 24 if the heart rate changes.

Fig. 4 is a schematic diagram showing the acquisition of data for a single slice 50 from multiple passes over time, in accordance with acquisition timing as shown in Fig. 3. In Fig. 4, pass 60 corresponds to a rotation number 1, pass 60' corresponds to a rotation number 2, and so on. Data 62 from pass 60 corresponds to an acquisition window, as do data 64 from pass 60', data 66 from pass 60", data 68 from pass 60'" and data 70 from pass 60"". By combining data 62, 64, 66 and 70, data covering a range of 180 degrees is obtained and CT image slice 50 can be reconstructed from the data. Since the data beyond 180 degrees is substantially a mirror of data between 0 and 180 degrees, data 68 may be used in place of data 64 (in Fig. 4). Since both data 64 and 68 are available, one of them is redundant and is not necessary for the reconstruction. However, it should be appreciated that using data for more than 180 degrees usually improves image quality and is, therefor, desirable.

When heart 24 is beating with substantial regularity a complete set (180 degrees) of data may be acquired in the space of three or four rotations of gantry 32. As can be appreciated, the number of required rotations will depend on the angular extent of the acquisition window. Data which corresponds to angular position for which previous data exists is preferably merged with previously acquired data; or it may be used to replace the previous data. Alternatively, such data may be ignored before or after it is acquired.

In one preferred embodiment of the invention an entire 360 degree data set is acquired, whereby methods which are well known in the art, for example, quarter detector shift, may be used to enhance the resolution of the resulting CT image set.

In another embodiment of the invention, preferred for a single slice CT device, a multi-slice CT device is simulated by the imaging a slice and advancing bed 26 axially. Preferably, the movement of the bed is controlled by data acquisition circuit 36, whereby, the bed is advanced only if enough data is acquired at a certain bed position. Preferably, the bed is also advanced if a significant period of time passed and sufficient data cannot be acquired. Alternatively or additionally in such a case, the rotation speed of gantry 32 is readjusted to be unsynchronized with the rhythm of heart 24.

In general, shorter data acquisition times (for the entire image set) are preferred, however, longer acquisition times also have some benefits.

In a short acquisition time scan, heart 24 is imaged in a minimum number of rotation of gantry 32 and also a minimum number of heart beats, so that beat-to-beat variation and patient movement have less of an effect. Typically, data acquisition is continued only until sufficient data is acquired to reconstruct the heart. Missing angular data or missing slice data may be interpolated from data acquired at nearby slices and/or angles and/or phases, however, this may affect the image resolution and/or add artifacts. Preferably, when interpolating, the data is assigned a weight responsive to its distance and/or difference from the missing data.

In a preferred embodiment of the invention, a tradeoff is effected between image quality, the extent of the angular acquisition window and the phase of the heart beat at which acquisition is performed. Optionally, the tradeoff is determined for each heart beat so as to provide an angular overlap of data, while maintaining image quality. Another parameter which may be considered in the tradeoff is the amount of motion and/or the diastolic interval of the heart in a particular heart beat. It should be noted the motion of the heat is not the same in all directions. In a preferred embodiment of the invention, different window sizes are provided depending on the viewing angle of the heart and/or the heart phase. Data is preferably acquired for the entire rotation of the gantry, so various reconstructions (tradeoffs) can be tested on the same data. In a preferred embodiment of the invention, the amount of image blur in the acquired images is determined manually, alternatively, such image quality analysis is performed by an automatic algorithm.

A multi-slice image device, preferred for this type of scan is the CT-Twin RTS, manufactured by Elscint Ltd., Haifa, Israel or a multi-slice CT device as described in Israel

Patent application No. 119,033, titled "Multi-Slice Detector Array" and filed August 7, 1996 by applicant Elscint Ltd., the disclosures of which are incorporated herein by reference. As may be appreciated, in a multi-slice machine, data from multiple slices are typically acquired at the same phase of the heart cycle.

In one preferred embodiment of the invention, different portions of the imaged tissue, preferably in different slices, are reconstructed using different angular extents of acquisition windows. The extent of each individual acquisition window depends on the amount of motion in each slice of imaged tissue. Preferably also the position of the angular window depends on the amount of motion in the slice.

Alternatively to acquiring data for the entire rotation, source 28 may be turned off for at least part of the rotation, when it is outside the extent of the acquisition window. Thus, source 28 is allowed to cool down, energy is conserved and the patient's radiation dose is reduced. Alternatively, source 28 is blocked when it is outside the acquisition window or when acquisition of data at a particular angle is not needed. Even if such data is acquired, it will usually not be selected for reconstruction, unless suitable data is unavailable, as described above. Thus, data may be unselected either because it is not acquired or if it is acquired and it is not then selected for reconstruction. Further, data may be selected for reconstruction and then discarded, where image quality suffers from the addition of the data.

When the periodicity of the heart beat varies, a characteristic of the heart beat may be determined and associated with the acquired data. This characteristic may be heart rate, beat morphology, ECG morphology or any other measurable characteristic of the heart beat. This type of association (in effect, binning) is especially useful in an arrhythmic heart, where beat-to-beat variation is significant. Moreover, even in non-arrhythmic hearts, during long acquisition times, significant beat-to-beat variation may be expected. Binning is also useful when CT images corresponding to different phases of the heart beat are generated, for example if both a systolic and a diastolic image are reconstructed.

Long acquisition time scans are useful if a high axial resolution is required, or if the axial extent of detector array 30 is smaller than the appropriate dimension of the heart. In these two cases, detector array 30 must be moved relative to heart 24 (such as by moving the table) after sufficient data is acquired on one portion of the heart.

In a preferred embodiment of the invention, a helical scan is utilized to image heart 24. In a helical scan, bed 26 is continuously advanced while gantry 32 is rotated so that a helical cross-section of patient 22 is imaged. In a helical scan, and unlike a multi-slice scan as described above, the data for each slice may be acquired at different phases of the heart beat, since there is no synchronization between the acquisition of different slices. Thus Fig. 4 is reapplied for each slice.

In addition, in a helical scan, data for reconstruction of images is usually interpolated from data acquired during two or more rotations of gantry 32, while in a multi-slice axial image, data is usually individually acquired for each slice.

Fig. 5 is a schematic diagram showing selection of data from a spiral scan for interpolation, in accordance with a preferred embodiment of the invention. It should be appreciated that the ideas described with reference to Fig. 4, regarding mirroring data from over 180 degrees apply also for spiral imaging. The spiral scan data is exemplary of data acquired by a two slice CT device operating in a helical mode, for example, the CT-Twin RTS, manufactured by Elscint Ltd., Haifa, Israel. Solid lines (marked with an indexed "a") are acquired by one detector array and dashed lines (marked with an indexed "b") are acquired by a second detector array.

To reconstruct data at a bed position Z_d, data from a plurality of bed positions, both preceding and following position m are interpolated. In the example of Fig. 5, data from detector "a" at position m-2 through data from detector "b" at position m+2 is available, but only data from a_{m-1} through a_{m+2} and b_{m-2} through b_m is actually interpolated.

Optionally, the extent of bed positions used for interpolation may be determined by the amount of data acquired at each rotation. Thus, the angular extent of the acquisition window affects the image quality by requiring interpolation over more (or fewer) bed positions. When more useable data is acquired per bed position, data from fewer bed positions are required to reconstruct an image. When less useable data is acquired per bed position, data from more bed position are required to reconstruct an image.

One preferred method of determining which data to use in the reconstruction is to choose the "closest data" available for each angular position theta (of the range 0-180, since the data in the range 180-360 degrees is equivalent, for reconstruction purposes, to data in the range 0-180 degrees). The closest data depends on the distance between the bed position at which an image is reconstructed and the bed position at which the data was acquired. Preferably, data at each position Z_d is interpolated both from data acquired at position before position Z_d and from data acquired at positions thereafter. Only data which is acquired within the acquisition window is used. Alternatively or additionally, the extent of the acquisition window may be changed for each bed position during the reconstruction to limit the number of bed position from which data is used for reconstruction. In a preferred embodiment of the invention, data is assigned a higher weight for reconstruction purposes, responsive to the difference in bed positions between the acquisition of the data and the reconstructed bed position. Alternatively or additionally, such differential weighting is also used based on the difference in phase between the reconstructed phase and the phase at which the data is acquired. Preferably, such phase-related weights are dependent on the amount of change in the shape of the heart between the two phases.

To reconstruct an image corresponding to a particular bed position Z_d (denoted on the Fig. as a solid vertical line), data covering 180 degrees (as described above) is required. Thin sleeves surrounding dashed or dotted lines, for example sleeves 90, 92, 94, 96, 98, 100, 102, 104, 106 and 108, denote data which is acquired during the acquisition window, which acquisition window may be based on the ECG, as described above. Thick sleeves surrounding the thin sleeves, such as sleeves 110, 112, 114, 116, 118, 120 and 122 denote data which when combined together yield a 180 degrees extent of data.

As may be appreciated, when imaging the heart a tighter helix than usual in helical scanning is generally preferred, since only a portion of the data is useable.

Another aspect of the invention is related to multi-slice CT imaging. Preferably, a cone beam is used to illuminate a plurality of parallel detector arrays. However, in some cases, the extent of illumination of one detector array, which is near the center of the cone, may be greater than the extent the illumination of a second detector array which is nearer the edge of the cone. In a preferred embodiment of the invention, only enough data for the first array is collected. Data missing for the second array is preferably interpolated from data acquired at the first array on previous and/or subsequent rotations. Alternatively or additionally, the detectors are moved relative to the heart, so that the detector with a wider angular illumination views a slice previously viewed with a detector having a narrower angular illumination. Alternatively or additionally, the detectors are not stopped at each bed position, and missing data is interpolated from data acquired at slices at either side thereof.

In a preferred embodiment of the invention, multiple x-ray sources are used, as described for example in Israel Patent application 118,989, "Multiple Source CT Scanner", filed on August 1, 1996, by applicant Elscint Ltd., the disclosure of which is incorporated herein by reference, which describes a multiple source x-ray scanner, for multi-slice and/or spiral imaging for third or fourth generation machines. By using more than one x-ray source, it is possible to acquire data at more than one rotation angle simultaneously. As a result, it may be possible to acquire enough data for reconstruction within a single heart beat. Alternatively, the rotation speed of the gantry can be made proportionally higher. For example, if three sources are used, a 60 degree rotation of the gantry will provide data from over 180 degrees, which is enough for reconstruction. Assuming the gantry rotates at one rotation per second, this data can be acquired in 116 milliseconds. In most hearts, there is a period of no-motion of at least this amount of time at end diastole. Alternatively to faster acquisition, a multi-source gantry may be used for increasing the resolution of the image, either in the axial direction or in the longitudinal direction.

Various embodiments and variants thereon have been described it should be understood that while variants may have been described in conjunction with one of the embodiments, they should not be understood to be so limited, rather, various combinations of the variants may be applied separately or together to the various embodiments described.

Although the present invention has been described mainly with respect to cardiac imaging. It will be appreciated that it applies equally to CT imaging of any periodically moving structures of the body, for example, those moving as a result of breathing. It should be appreciated that most periodic motion in the body is actually quasi-periodic.

In a preferred embodiment of the invention, the above described methods are used for imaging the lungs and/or the abdomen. Preferably, the respiration cycle is monitored using a belly strap, although other monitoring devices, such as chest impedance measurement, as known in the art, may be used. The two phases of the respiration at which the motion is minimal and are, therefore, preferred for imaging, are end-inspiration and end-exhalation. However, imaging using breath-hold may be practiced at any point in the breathing cycle. It should be noted that the image acquisition of both an end-inspiration and an end-exhalation volume images, using continuos irradiation of the patient, without breath holding is faster and/or easier on the patient than sequential acquisition of two such volume images, especially when using spiral scanning. Since the breathing cycle is relatively slow, in a preferred embodiment of the invention, data may be acquired also while the phases where more rapid motion is evident and be combined (for reconstruction purposes) with other data acquired at the same phase. Preferably, data is binned based on the length and/or other morphological features of the respiratory cycle, as measured by the monitoring device.

It will be appreciated by a person skilled in the art that the scope of the present invention is not limited by what has thus far been described. Rather, the scope of the present invention is limited only by the claims which follow.

CLAIMS

1. A method of CT-imaging a periodically moving object, comprising:

rotating a source of x-rays more than half a rotation around the object such that the rotation of the source is unsynchronized to the periodic motion of the object;

detecting radiation passing through the object to produce attenuation data;

associating a phase of the periodic motion and an angular position of the source, with the data;

selecting data from the attenuation data, which selected data has an associated phase substantially equal to certain phases corresponding to at least one acquisition window; and

reconstructing at least one image of the object using the selected data.

2. A method according to claim 1, comprising determining an average periodic time of the periodic motion,

wherein said rotating comprises rotating the source half a rotation around the object in a time different from half the determined average time or a multiple or sub-multiple thereof.

3. A method according to claim 1 or claim 2, wherein said attenuation data is acquired over more than one half-rotation.

4. A method according to any of the preceding claims wherein rotating more than half a rotation comprises rotating at least once.

5. A method of CT-imaging a periodically moving object, comprising:

rotating a plurality of sources of x-rays around the object such that the rotation of the source is unsynchronized to the periodic motion of the object;

detecting radiation passing through the object to produce attenuation data;

associating a phase of the periodic motion and an angular position of at least one of said plurality of sources, with the data;

selecting data from the attenuation data, which selected data has an associated phase substantially equal to certain phases corresponding to at least one acquisition window; and

reconstructing at least one image of the object using the selected data.

6. A method according to any of the preceding claims, wherein reconstructing comprises reconstructing at least one image of the object using selected data acquired in less than two rotations of the gantry,

7. A method according to any of the preceding claims, wherein reconstructing comprises reconstructing at least one image of the object using selected data acquired in less than one rotation of the gantry,

8. A method according to any of the preceding claims, wherein said rotating comprises:

rotating the source at an angular velocity such that a probability that an angular position at which the periodic motion is at the certain phases repeats itself is minimized.

9. A method according to any of the preceding claims, wherein characteristics of the periodic motion may vary, comprising:

determining a value of a variation of a characteristic of the periodicity of the periodic motion; and

associating the value with the selected data.

10. A method according to claim 9, wherein the characteristic comprises the rate of the periodic motion.

11. A method according to any of the preceding claims, wherein the certain phases comprise phases at which the object has minimal motion.

12. A method according to any of the preceding claims, wherein the at least one acquisition window has a given extent and wherein the given extent is determined in response to the instantaneous period of the periodic motion.

13. A method according to any of the preceding claims, wherein the at least one acquisition window has a given extent and wherein the given extent is determined in response to the instantaneous phase of the periodic motion.

14. A method according to claim 12 or 13, wherein the image comprises a plurality of image slices and wherein the extent is different for different slices of the reconstructed image.

15. A method according to any of claims 12-14, wherein the image comprises a plurality of image slices and wherein the at least one acquisition window has an angular starting position and wherein the position is different for different slices of the reconstructed image.

16. A method in accordance with any of claims 12-15, wherein the given extent is determined in response to the amount of motion of the object at the certain phases.

17. A method in accordance with any of claims 12-15, comprising:

determining a desired level of image quality; and

determining a period of time required for data acquisition for image reconstruction,

wherein the given extent is determined in response to the determined time period and the desired level of image quality.

18. A method according to any of the preceding claims, wherein reconstructing an image comprises:

reconstructing an image from selected data acquired from an angular extent of at least 180 degrees.

19. A method according to claim 18, wherein data acquired at a first angular position is mirrored through 180 degrees to a second angular position to replace data, which is unsuitable for reconstruction, at the second angular position.

20. A method according to any of the preceding claim, wherein data is not selected at a certain rotation angle, comprising:

interpolated between data acquired at rotation angles near the certain rotation angle to reconstruct the data which is not selected at the certain rotation angle.

21. A method according to claim 20, wherein interpolating comprises assigning weights to data at the near rotation angles responsive to the angular difference between the near angles and the angle.

22. A method according to any of the preceding claims, wherein the image comprises a plurality of image slices and wherein data corresponding to a certain rotation of a certain slice is not selected, comprising:

interpolating between data acquired at slices near the certain slice to reconstruct the data which is not selected.

23. A method according to claim 22, wherein interpolating comprises assigning weights to data at the near slices responsive to the distance between the near slices and the certain slice.

24. A method according to any of the preceding claim, wherein data is not selected at a certain phase of the periodic motion of the object, comprising:

interpolated between data acquired at phases near the certain phase to reconstruct the data which is not selected at the certain phase.

25. A method according to claim 24, wherein interpolating comprises assigning weights to data at the near phases responsive to the difference between the near phases and the certain phase.

26. A method according to claim 24 or 25, wherein interpolating comprises assigning weights to data at the near phases responsive to the difference in the morphology of the object between the near phases and the certain phase.

27. A method according to any of the preceding claims, wherein the object comprises a human heart.

28. A method according to claim 27, comprising determining a phase of a heart cycle using an ECG device.

29. A method according to claim 27 or claim 28, wherein the certain phases comprise an end diastolic period.

30. A method according to any of claims 27-29, wherein the certain phases comprise an end systolic period.

31. A method according to any of claims 27-30, wherein data is binned based on a heart-beat morphology.

32. A method according to any of the preceding claims wherein the object comprises a human lung.

33. A method according to claim 32, comprising determining the phase of a breathing cycle.

34. A method according to claim 33, wherein determining the phase of a breathing cycle comprises determining using a belly strap.

35. A method according to any of claims 32-34 wherein the certain phases comprise an end-respiration period.

36. A method according to any of claims 32-35 wherein the certain phases comprise an end-exhalation period.

37. A method according to any of the preceding claims wherein said detecting comprises detecting using a stationary detector array.

38. A method according to any of the preceding claims, wherein said detecting comprises:

moving the object along an axial direction relative to the detector; and

detecting radiation at a plurality of axial positions to generate data for a three dimensional image set.

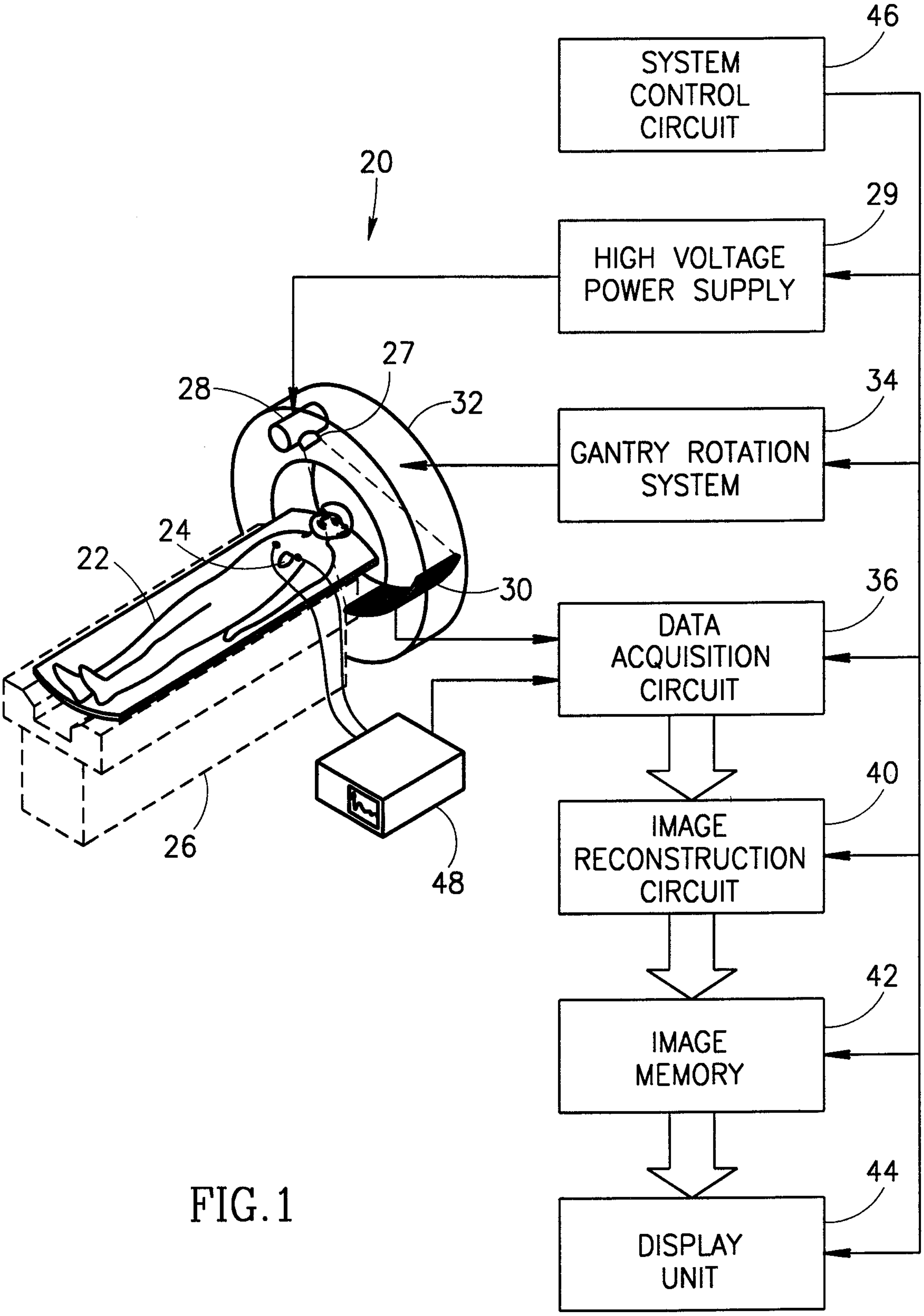
39. A method according to claim 38, comprising:

moving the object during said detecting.

40. A method according to claim 38, comprising:

moving the object while not detecting radiation.

41. A method according to any of the preceding claims, wherein detecting comprises: detecting radiation using a multi-row array of radiation detectors.



46
SYSTEM CONTROL CIRCUIT
20
29
HIGH VOLTAGE POWER SUPPLY
27
28
32
34
GANTRY ROTATION SYSTEM
24
22
30
36
DATA ACQUISITION CIRCUIT
40
IMAGE RECONSTRUCTION CIRCUIT
26
48
42
IMAGE MEMORY
44
DISPLAY UNIT

FIG.1

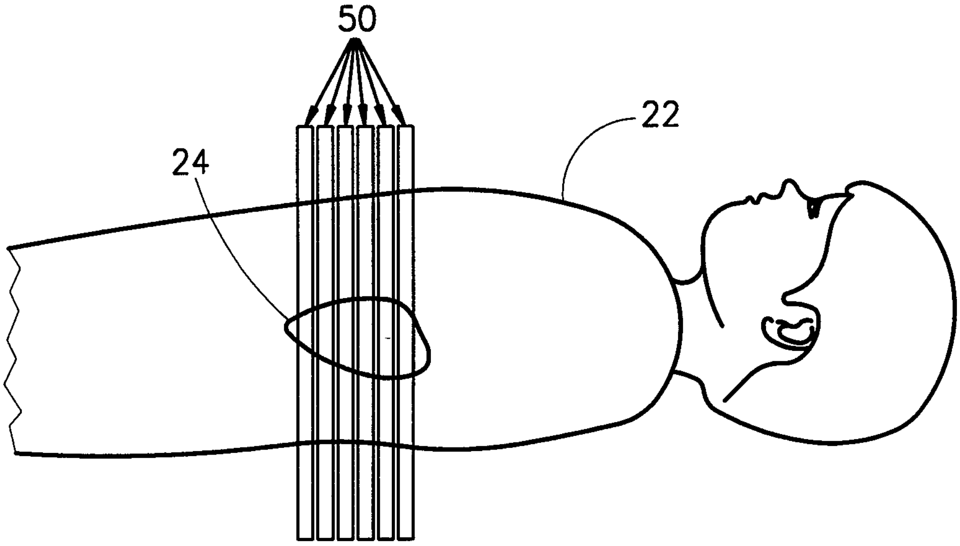


FIG.2

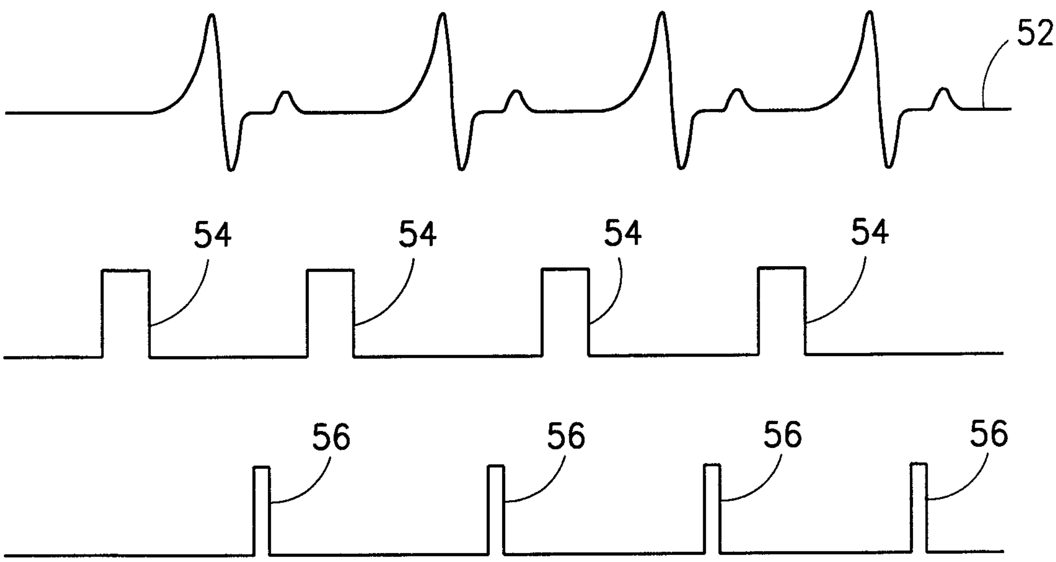


FIG.3

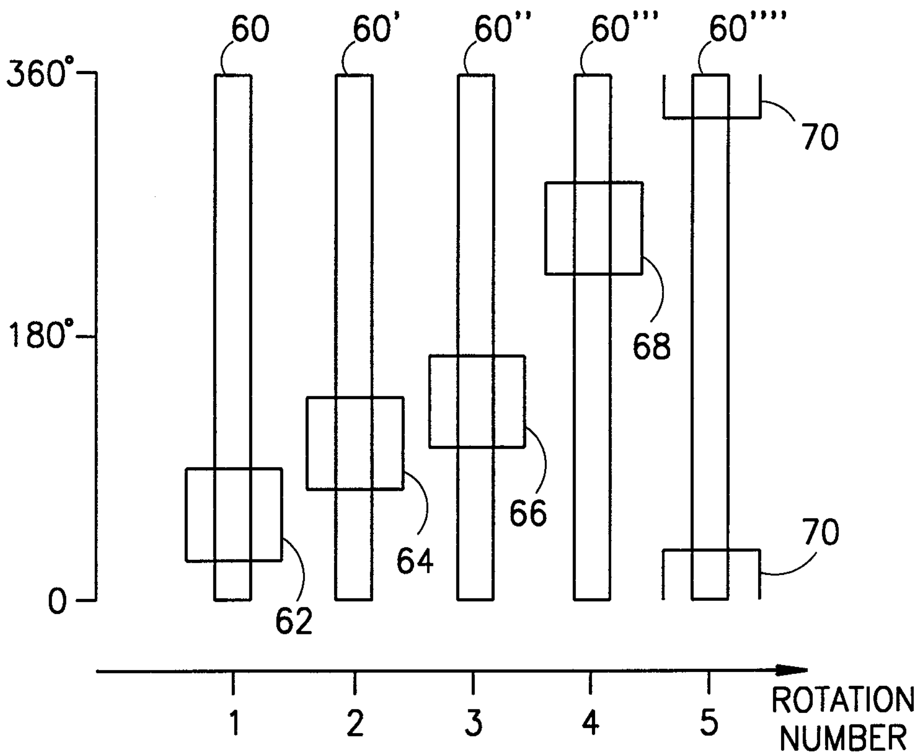


FIG.4

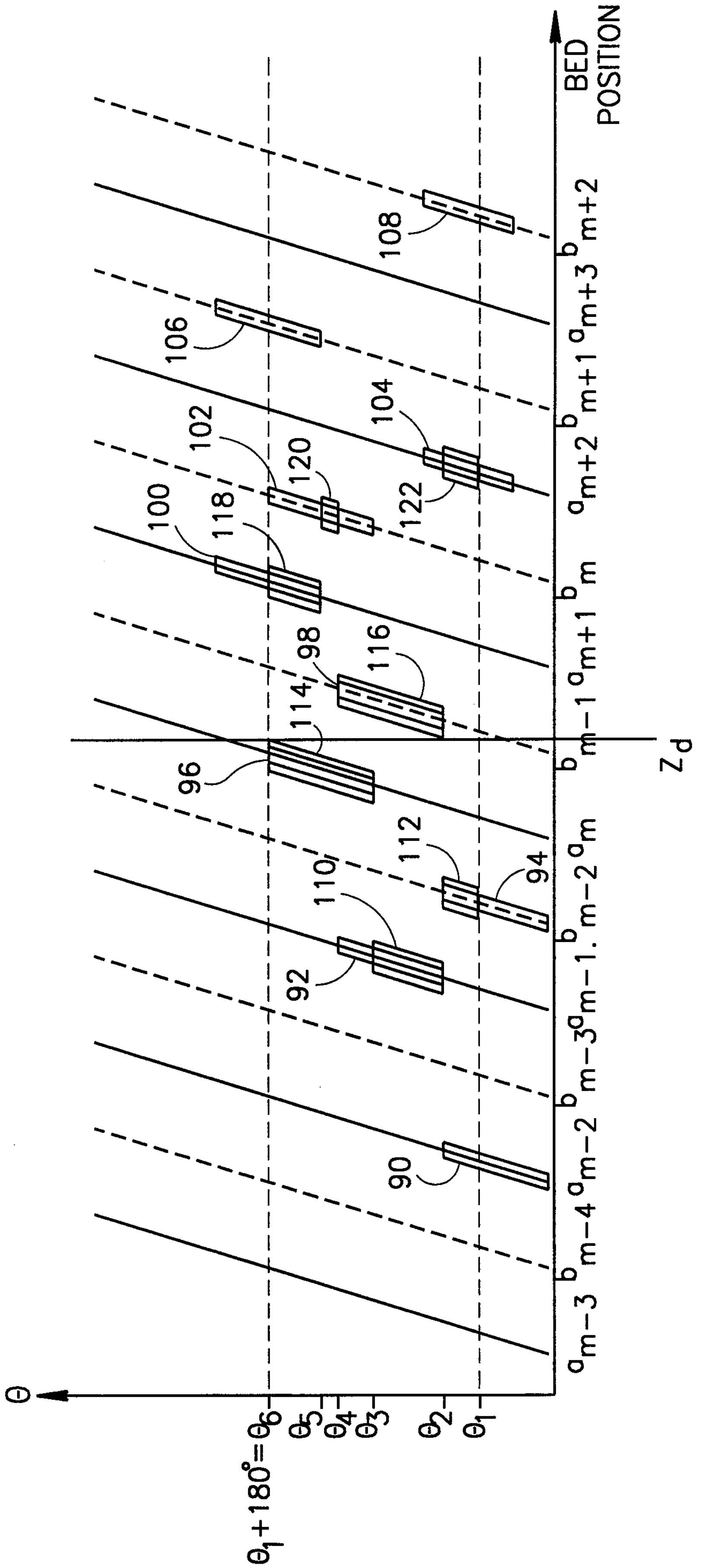

BED POSITION
Zd
θ
θ1+180°=θ6
θ5
θ4
θ3
θ2
θ1
90
92
94
96
98
100
102
104
106
108
110
112
114
116
118
120
122

FIG.5

INTERNATIONAL SEARCH REPORT

International Application No
PCT/IL 98/00295

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 A61B6/03

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 A61B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	EP 0 341 143 A (GENERAL ELECTRIC) 8 November 1989 see column 4, line 59 - column 11, line 47 ---	1-8, 18-26, 38-41
A	FR 2 442 041 A (CARDIAC IMAGING) 20 June 1980 see page 4, line 2 - page 28, line 13 ---	1,5, 27-31
A	US 4 930 508 A (SHIMONI YAIR) 5 June 1990 see column 4, line 15 - column 9, line 51 -----	1,5, 32-36

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
3 November 1998	10/11/1998

Name and mailing address of the ISA	Authorized officer
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/IL 98/00295

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