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Description

TECHNICAL FIELD

[0001] The present invention relates to a technique of reconstructing a cross-sectional image of an object from the radiographic projections of the object.

BACKGROUND ART

[0002] Computerized tomography (CT) is a technique of reconstructing a cross-sectional image of an object from the radiographic projections of the object. FIG. 1 is a diagram schematically showing a typical X-ray CT apparatus.

[0003] In the typical CT apparatus, an X-ray source is moved around a target object, and irradiates X-rays to obtain the projections of the target object in many different directions. A cross-sectional image is obtained by subjecting the projections thus obtained to a computational operation, so-called reconstruction. The Filtered Back-Projection method (FBP) is commonly used to reconstruct a cross-sectional image from the projections. FBP is a kind of a transformation operation. In FBP, the projections are subjected to a filtering essentially equivalent to the differential filtering, followed by "back projection," in which each projection is projected back along the original projection direction, thereby a cross-sectional image is obtained. In this case, the differential filtering usually amplifies noise or errors, which can be the source of artifacts (errors or false images which do not actually exist). Moreover, the back propagation operation spreads the artifacts thus created allover the cross-sectional image. Therefore, in CT, the artifacts often are not limited within a local portion around the source of the artifacts, and impairs the entire cross-sectional image, resulting in a fatal flaw.

[0004] Most artifacts are caused by the filtering operation and/or the back projection operation involved in FBP. Therefore, if FBP is not used, a cross-sectional image substantially can be free from most of artifacts. As a method of calculating a cross-sectional image other than FBP, the Algebraic Reconstruction Technique (ART) is historically important. ART was a major reconstruction method before FBP was proposed. In ART, the process of reconstruction is considered as a fitting problem where the cross-sectional image is a parameter and the projections are a target dataset to be fit. The cross-sectional image is iteratively modified so that projections (p) calculated from the cross-sectional image fit projections (p_0) experimentally obtained. A feature of ART is that a cross-sectional image is asymptotically modified so that ($p-p_0$) becomes zero. ART usually requires a vast computation time in comparison to FBP. Therefore, ART is currently used only for particular applications (the analysis of seismic waves, etc.). Although ART does not produce as extreme artifacts as FBP does, FBP often provides a more natural cross-sectional image than ART does.

[0005] Besides the filtering operation and the back projection operation, artifacts may be caused by a lack or shortage of data in projections. It is known that a lack or shortage of data often results in a fatal artifact especially in FBP. Other reconstruction techniques based on fitting, such as ART, are expected to be more robust against a lack or shortage of data than FBP. However, a lack of data is known to make CT an extremely "ill-posed problem," under which it is essentially difficult to obtain reasonable solutions. One of the reasons why ART often fails in fitting is that ART uses ($p-p_0$) for the target function of fitting. So it is quite natural to consider the use of the $(p-p_0)^2$ instead of ($p-p_0$). In these cases, the least square method is one of the most popular way to minimize $(p-p_0)^2$. In the least square method, the inversion of a square matrix whose elements on one side is equal to the number of parameters is employed. Parameters in CT are values of pixels in the cross-sectional image, and therefore, the number of the parameters is huge. If a cross-sectional image has 1000×1000 pixels, the number of the parameters becomes a million, and the number of elements in the matrix is as huge as a trillion. Therefore, if the ordinary least square method is used, the matrix is too huge to calculate. Instead of the ordinary least square method, the Simultaneous Iterative Reconstruction Technique (SIRT) and the Iterative Least Square Technique (ILST) have been proposed. In these techniques, the calculation of a cross-sectional image is considered as a fitting problem as in ART. FBP is utilized as an inverse operation to calculate the cross-sectional image from projections partway through the calculation in both SIRT and ILST so as to circumvent the use of the ordinary least square method as described above. Therefore, none of SIRT and ILST does not substantially solve the problems involved with the filtering operation and the back projection operation as in FBP. This is probably why there have been reports that SIRT and ILST just "reduce" artifacts.

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DISCLOSURE OF THE INVENTION

PROBLEMS TO BE SOLVED BY THE INVENTION

[0006] As can be seen from the discussion above, no use of FBP and robustness against a lack of data are important so as to obtain a cross-sectional image free of artifacts. To achieve this, it is easily contemplated that a square error may be used as an evaluation function for fitting without using FBP as in ART. Nevertheless, the artifact problem of CT has not been substantially solved, since this simple idea cannot be straightforwardly realized. Firstly, the amount of calculation of a cross-sectional image by fitting is too huge to calculate quickly. It is essentially required to appropriately speed up the calculation. Secondly, the least square method, as a fitting algorithm, is weak (not effective) against "ill-posed" problems. Therefore, any extension of the existing algorithms (ILST, etc.) based on the least square method would not be able to solve the artifact problem. Thirdly, other existing algorithms as well as SIRT and ILST cannot completely eliminate the necessity of FBP.

SOLUTION TO THE PROBLEMS

[0007] A first novelty of the present invention is to employ Simulated Annealing (SA) as a fitting method. SA is a known technique, which requires a long time to perform fitting, and is inherently considered not to be not suitable for CT. Despite this, by the sue of SA in CT, a cross-sectional image can be calculated by minimizing square errors without using FBP. SA is also stable even when fitting is performed under ill-posed conditions, such as a lack of data or the like. Also in this regard, the present invention is advantageous in terms of a fundamental solution to artifacts. In view of the properties above, the present invention has an important novelty that a fundamental solution to artifacts is obtained by applying SA to CT. When SA is simply applied to CT, we need to iterate the calculation of projections from a cross-sectional image so many times. The amount of the calculation of projections from a cross-sectional image is substantially the same as that of FBP. When SA is applied to CT, it takes several million times as long a time as that of FBP. The calculation time can be of the order of "years" even if a state-of-the-art high-speed computer is used. In the present invention, this problem is solved by significantly reducing the amount of calculation by transformation of expressions. This solution is a technique required when SA is applied to CT, which is an important feature of the present invention.

[0008] A second novelty is the introduction of a smoothing term and an entropic term, which actively destroy artifacts, into an evaluation function for fitting in addition to square errors. In conventional CT, only a difference between p and po or their square errors is employed. In this case, there is always a possibility that a more satisfactory result (small errors) of fitting can be achieved while artifacts are left. Actually, this is often the case. Specifically, it is commonly expected that artifacts would be canceled with other artifacts. That is one of the reasons for the difficulties to eliminate artifacts. Even in the present invention, if only square errors are included in an evaluation function, artifacts were not completely eliminated. This fact indicates that another term is desired in addition to square errors so as to obtain a cross-sectional image free of artifacts. In the present invention, an entropic term and a smoothing term are introduced on the basis of statistical mechanics. These terms mathematically represent a natural requirement that a cross-sectional image should be a "smooth" and "natural" gray image. The entropic term induces fitting so as to destroy artifacts and uniformize image quality of an entire cross-sectional image. The smoothing term suppresses the granular pattern of a cross-sectional image which is caused by the entropic term. By introducing the both terms, a natural cross-sectional image free of artifacts can be obtained. Although the entropic term and the smoothing term can each reduce artifacts singly, a combination thereof is found to be more effective.

[0009] Note that the term "beam of radiation" as used herein refers to electromagnetic waves, such as X-rays, visible light and radio waves, particle beams including electrons or charged particles, sound waves, which are vibration of a medium, and the like, in a broader sense than the general definition.

EFFECT OF THE INVENTION

[0010] A first effect of the present invention is to reduce artifacts which are caused by a lack of data. Examples of a problem caused by a lack of data includes a case where an object to be observed has an opaque portion, a case where there is a limit on a projection angle, a case where projection angular intervals are not uniform, a case where three-dimensional CT (cone beam CT, helical scan CT, etc.) is performed, and the like.

[0011] In particular, it has been demonstrated that metal artifacts which appear when an object to be observed has an opaque portion can be reduced. The term "metal artifact" means that when there is an opaque portion (in many cases, a metal portion) with respect to X-rays in an object to be observed, an entire cross-sectional image (not only the opaque portion) obtained by CT is destructively disturbed. Metal artifacts are caused by a discontinuous change in luminance of a projection at an opaque portion, and a lack of information at the opaque portion. When the differential filtering is applied to the opaque portion in course of FBP, a discontinuous change in luminance takes an extraordinary value. Then, the extraordinary value is radially extended to be a streak artifact via the back protection operation. Moreover, a lack of information causes an unexpected contrast at the portions which are not directly related to the opaque portion. Since the present invention does not use FBP and employ SA which is stable against the lack of information, it is easily understood that the present invention is effective in removal of metal artifacts.

[0012] The present invention may be particularly useful for cone beam or helical scan in terms of practical use. Both are called three-dimensional CT, and are currently rapidly becoming widespread. However, it is known that peculiar artifacts appear in three-dimensional CT. The causes of the artifacts have been identified, but have not been solved. In the case of cone beam, the cause of the artifacts is a lack of data. In the case of cone beam, conditions under which a complete cross-sectional image can be obtained cannot be satisfied, so that artifacts appear due to a lack of data. In the case of helical scan, the fundamental cause of artifacts is a back projection operation. The geometric anisotropy (helix) of the system of helical scan affects a filtering operation and a back projection operation, resulting in windmill artifacts. Since the present invention does not require a filtering operation or a back projection operation, and is robust against a lack of data, the present invention can solve the problems with three-dimensional CT.

[0013] Examples of a case where projection angles are not uniform include analysis of Earth's interior by CT using seismic waves, and analysis of an atmospheric state by CT using radio waves from an artificial satellite. These are known as typical cases where FBP cannot be utilized. It is expected that the present invention may be able to improve the accuracy of analysis.

[0014] A second effect of the present invention is to increase a rate at which projections are taken and decrease the dose of X-rays. Since SA is stable against a lack or shortage of data, the present invention also inherits this feature. In the case of CT, the case where the number of projection angles is small is one of the cases of a shortage of data. Thus, the utilization of the present invention can reduce the number of projection angles as compared to conventional CT. The number of projection angles corresponds to the number of projections in which the object is irradiated. So, the number of projections is proportional to the imaging time and the dose. Therefore, a reduction in the number of projections leads to a decrease in the imaging time and the dose.

[0015] There is also a shortage of data when the image quality of projections is poor (low S/N ratio), for example. It has been demonstrated that the present invention is relatively stable even in such a case. If a decrease in the image quality of projections can be tolerated, this also leads to a reduction in the imaging time and the dose. Also, the present invention would contribute to an improvement in image quality in SPECT and PET in which the S/N ratio is extremely low.

[0016] A third effect of the present invention is that a luminance value of a cross-sectional image can be determined with high accuracy. The present invention provides a cross-sectional image which substantially faithfully reproduces the measured projections. The accuracy of reproduction is higher by about two orders of magnitude than that of FBP. This is a benefit of the fitting algorithm which minimizes square errors. The higher accuracy of determination of a luminance value guarantees the quantitativeness of the cross-sectional image and allows a measurement of density using the luminance value. This feature can be used for an improvement in accuracy of measurement of bone density. Also, this would contribute to an improvement in accuracy of detection of a pathological change (an organ containing a tumor, etc.).

[0017] A fourth effect of the present invention is that a cross-sectional image obtained by the present invention has a higher contrast than that of FBP. As described in the third effect, the present invention has the high accuracy of determination of a luminance value. As its subsidiary effect, the contrast of a cross-sectional image becomes higher. A higher contrast tends to lead to a higher apparent spatial resolution. As a result, a cross-sectional image obtained by the present invention has higher image quality than that of the conventional art. Notably, this effect allows the present invention to be useful for not only CT under special conditions or for special applications, but also ordinary CT.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018]

FIG. 1 is a schematic illustration of an X-ray CT apparatus.

FIG. 2 is a schematic diagram showing a relationship between a cross-sectional image f(x, y) and a projection p(r, θ).

FIG. 3 shows a typical example of $p_0(r, \theta)$, where the abscissa and ordinate are respectively the projection angle and the channel portion of a detector.

FIG. 4 is a flowchart showing a basic procedure of the present invention.

FIG. 5(a) is a schematic diagram of a fitting process of steps (I) to (VI). FIG. 5(b) is a schematic diagram of a fitting process of steps (1) to (9).
FIG. 6 is the result of a technique described in Non-Patent Document 1.
FIG. 7 is a sinogram obtained from FIG. 6(a) by simulation (a white portion is an opaque region).
FIG. 8(a) is an enlarged diagram of FIG. 6(c). FIG. 8(b) is a diagram showing a result of the present invention.
FIG. 9 is a schematic diagram showing an effect of each term in a virtual energy E.
FIG. 10 is a diagram showing artifacts and an artifact reducing effect of the present invention in the case with a limit on an angle.

BEST MODE FOR CARRYING OUT THE INVENTION

(First Embodiment)

[0019] FIG. 1 shows a schematic diagram of an X-ray CT apparatus according to an embodiment of the present invention. The X-ray CT apparatus includes an imaging unit and a computer. The imaging unit includes a light source for irradiating a target object (usually X-rays), and a detector for X-rays transmitted through the target object. The imaging unit obtains projections by emitting X-rays toward the target object in many different directions. The computer includes a controller for the entire X-ray CT apparatus, and an image reconstruction processor for generating a cross-sectional image of a region of interest of the target object based on X-ray projections obtained by the imaging unit. Note that the configuration of FIG. 1 is common to this and the following embodiments, but the image reconstruction processors of each embodiment performs different process.

[0020] The image reconstruction processor of this embodiment employs Simulated Annealing (SA) as a fitting method for obtaining a cross-sectional image from projections. Firstly, a framework of Simulated Annealing (SA) will be described. SA is a fitting algorithm derived from a Monte Carlo method, and is characterized in that the fitting is performed based on random numbers, and in that virtual energy and virtual temperature are handled in the analogy to thermodynamics. SA is a known technique, which is performed in steps (i) to (vi).

(i) A parameter is randomly chosen, and then, the parameter is changed based on a random number (random number).
(ii) Evaluation is performed after the changing. A virtual energy E is considered as an evaluation function. In typical SA methods, E is taken as the sum of square errors. The change in E between before and after the changing is represented by ΔE (evaluation).
(iii) If the result of evaluation is improved ($\Delta E<0$), the changing is accepted (changing).
(iv) If the result of evaluation is worsened, the changing is accepted in a probability of $\exp(-\Delta E/T)$.
(v) The temperature T is decreased by a small amount.
(vi) The procedure above is repeated from (i).

[0021] In SA, since the changing is accepted according to Boltzmann statistics as indicated in (iv) if the result of evaluation is worsened, the possibility of escaping from a local minimum of ΔE is secured. Therefore, the method can reach a global solution without trapping in a local minimum, and therefore, can stably function even under ill-posed conditions for fitting. Also, by gradually decreasing T, the method gradually approaches a global solution (soft landing). A set of (i) to (v) is referred to as a single Monte Carlo step. In SA, the Monte Carlo step is infinitely repeated, the fitting process progresses. A time required for the calculation is obtained by a time required for one Monte Carlo step × a required number of times of the Monte Carlo steps. The required number of times of the Monte Carlo steps is proportional to the number of parameters (or the degree of freedom).

[0022] Next, this embodiment will be described according to the claims. If CT is considered as a fitting problem, a fitting parameter is a cross-sectional image ($f(x, y)$). Data to be fit is projections ($p_0(r, \theta)$) where r indicates a channel position of a one-dimensional detector used in the imaging unit, and θ indicates a projection angle. A definition of coordinates is shown in FIG. 3. $p_0(r, \theta)$ is a set of data which is the measuring projections while changing the angle θ, and can represent a two-dimensional image if it is plotted in a graph where the horizontal axis represents r and the vertical axis represents θ. Such data is referred to as a sinogram. A typical sinogram is shown in FIG. 3.

[0023] Roughly speaking, CT is a technique of obtaining a cross-sectional image from a sinogram. In this embodiment, square errors between a temporary cross-sectional image $f(x, y)$ and the measured projections $p_0(r, \theta)$ are used. In order to calculate the square errors, projections ($p(r, \theta)$) are calculated from $f(x, y)$ by:

[Expression 101]

$$p(r,\theta)=\sum_{s} f(r\cos\theta - s\sin\theta, r\sin\theta + s\cos\theta)$$

[0024] Expression 101 represents the calculation of a projection of f(x, y) along a direction s by summing on s in FIG. 2. By using p(r, θ) thus obtained, the sum of square errors H can be calculated as follows:

[Expression 102]

$$H=\sum_{r,\theta}\{p(r,\theta)-p_0(r,\theta)\}^2$$

[0025] In typical fitting, Expression 102 is directly used as the virtual energy E. This embodiment is characterized in that a smoothing term and an entropic term are introduced in addition to H. The virtual energy E is defined as follows:

[Expression 103]

$$E = H - TS + c\sigma$$

where T represents a virtual temperature (temperature parameter), S represents an entropy, σ represents a standard deviation of pixel values, and c represents a coefficient which represents the strength of the smoothing term. In Expression 103, TS is an entropic term and cσ is a smoothing term. The definitions and calculation methods of S and σ will be described below. In this embodiment, a cross-sectional image is calculated in accordance with a procedure as shown in FIG. 4 using these expressions.

- Step (a): An evaluation function (hereinafter referred to as an "energy") (E_0) is obtained with respect to a temporary cross-sectional image f(x, y) which is prepared in some manner (ST10 and ST20).
- Step (b): (x_0, y_0) and $\Delta\mu$ are selected using random numbers, and a portion of the cross-sectional image f(x, y) is modified (ST30).
- Step (c): An evaluation function E_1 is obtained with respect to the modified cross-sectional image f(x, y) (ST40 and ST50).
- Step (d): A differential (ΔE) between the energy (E_0) and the energy (E_1) is obtained (ST60).
- Step (e): It is determined whether or not the modification is accepted, based on an acceptance function (typically Boltzmann statistics) using the differential (ΔE) and the temperature parameter (T) (ST70 to ST110).
- Step (f): Control returns to step (a) (ST120).
- Step (g): The value of the virtual temperature (T) is changed every time the number of iterations of steps (a) to (f) reaches a predetermined value (ST130).
- Step (h): It is determined whether or not the result of determination in step (e) satisfies predetermined stop conditions. If the result of this determination is positive, the process is ended. Here, it is assumed that the change is a "success" if ST80 or ST100 is executed, and is a "failure" if ST110 is executed. If the probability of success becomes lower than 10% (this value is adjustable appropriately), the process is ended. An estimated cross-sectional image at the end of the process is considered as a cross-sectional image of the target object, which may be displayed on a display of the computer or may be recorded into a recording medium.

[0026] A series of operations from step (a) to step (h) corresponds to claim 12. In this embodiment, these operations are performed by the image reconstruction processor of FIG. 1.

[0027] These operations correspond to the basic steps (i) to (vi) of SA as follows: step (b) corresponds to (i); steps (a), (c) and (d) correspond to (ii); step (e) includes (iii) and (iv); step (g) corresponds to (v); and step (f) corresponds to (vi). Therefore, in this embodiment, SA is faithfully applied to CT.

[0028] Note that the determination of whether to end the process in step (h) may not be performed in the image reconstruction processor of FIG. 1. Estimated cross-sectional images may be successively displayed on a display of the computer, and a user who views the images may instruct the computer to end the process.

(Second Embodiment)

[0029] The virtual energy E indicated by Expression 103 is calculated by calculating the sum of a series with respect to s, r and θ via Expression 101 and Expression 102. A triple integral (the sum of a series) is calculated, which takes a considerably long time. In other words, it takes a long time to calculate one Monte Carlo step. In addition, CT has a huge number of parameters. As a result, a total calculation time required for execution of SA is of the order of years even if a state-of-the-art computer is used.

[0030] Therefore, in this embodiment, instead of calculating E, only ΔE, which is the difference when a change is made, is mainly calculated as follows:

[Expression 104]

$$\Delta E = \Delta H + c\Delta\sigma - T\Delta S$$

[0031] Now, a change in a temporary cross-sectional image f(x, y) is represented as Δf(x, y). The change Δf(x, y) is a cross-sectional image which has a value of Δμ only at a coordinate point (x_0, y_0) and zero elsewhere. A projection Δp(r, θ) of Δf(x, y) can be calculated by the same method as that of Expression 101. By using Δp(r, θ), ΔH can be calculated as follows:

[Expression 105]

$$\Delta H = \sum_{r,\theta}\{p(r,\theta) + \Delta p(r,\theta) - p_0(r,\theta)\}^2 - \sum_{r,\theta}\{p(r,\theta) - p_0(r,\theta)\}^2$$

[0032] This expression is transformed as follows:

[Expression 106]

$$\Delta H = \sum_{r,\theta}\{\Delta p(r,\theta)^2 + 2\Delta p(r,\theta)[p(r,\theta) - p_0(r,\theta)]\}$$

[0033] Since Δf(x, y) has a value only at (x_0, y_0), Δp(r, θ) has a value of Δμ only at $r(\theta)=x_0\cos\theta+y_0\sin\theta$ and zero elsewhere. Therefore, the expression within the braces {} in Expression 106 has values only at $r(\theta)= x_0\cos\theta+ y_0\sin\theta$. Therefore, the sum of a series does not need to be calculated with respect to both r and θ, and Expression 106 can be expressed as follows:

[Expression 107]

$$\Delta H = \sum_{\theta}\{\Delta\mu^2 + 2\Delta\mu[p(r(\theta),\theta) - p_0(r(\theta),\theta)]\}$$

[0034] Importantly, Expression 107 is the sum of a series only with respect to θ. As a result, the amount of calculation can be significantly reduced. Since p and p_0 are digital images, interpolation with respect to r(θ) is necessary in advance to the summation in Expression 107. Therefore, the expression within the braces {} in Expression 107 cannot be further expanded. Despite this, if Expression 107 is expanded while admitting errors, the following expression is obtained:

[Expression 108]

$$\Delta H = M\Delta\mu^2 + 2\Delta\mu\sum_{\theta}\{p(r(\theta),\theta) - p_0(r(\theta),\theta)\}$$

[0035] Note that M represents the number of projection angles. If Expression 108 is used instead of Expression 107, the value of ΔH has an error of about 1%. However, Expression 108 can be calculated more quickly than Expression 107, and therefore, is highly useful in the present invention.

[0036] Next, calculation of Δσ will be described. The standard deviation of luminance values in an area around the coordinate point (x_0, y_0) is represented by σ. The area around (x_0, y_0) is assumed to be d×d pixels around (x_0, y_0) (in this example, d=5). The standard deviation of these pixels can be obtained as follows:

[Expression 109]

$$\sigma = \sqrt{\left\langle f(x_0, y_0)^2 \right\rangle - \left\langle f(x_0, y_0) \right\rangle^2}$$

where:

[Expression 110]

$$\left\langle f(x_0, y_0)^2 \right\rangle = \frac{1}{d^2}\sum_{i,j=-d/2}^{d/2} f(x_0 + i, y_0 + j)^2$$

[Expression 111]

$$\left\langle f(x_0, y_0) \right\rangle = \frac{1}{d^2}\sum_{i,j=-d/2}^{d/2} f(x_0 + i, y_0 + j)$$

[0037] By using Expressions 109 to 111, Δσ can be calculated as follows:

[Expression 112]

$$\Delta\sigma = \sqrt{\left\langle f(x_0, y_0)^2 \right\rangle - \frac{f_i^2 - f_j^2}{d^2} - \left\{\left\langle f(x_0, y_0) \right\rangle - \frac{f_i - f_j}{d^2}\right\}^2}$$

[0038] Note that f_i and f_j represent values of f(x_0, y_0) before and after changing.

[0039] The definition of the entropy S will be described before the following calculation of ΔS will be described. In general, images handled by computers are digital images. Not only the coordinates (x, y) of pixels, but also the values of the pixels have digital values. Therefore, it can be assumed that a pixel is a quantum and that a pixel value is a quantum state. In this sense, an image can be considered as a kind of quantum ensemble. According to statistical mechanics, the entropy of such a system is defined as follows:

[Expression 113]

$$S = k \ln \frac{N!}{N_1! N_2! \cdots N_i! \cdots N_n!}$$

[0040] In Expression 113, N represents the total number of pixels in an image, N_i represents the total number of pixels having a pixel value of i, which is a digital value, and k represents the Boltzmann constant in typical physics, but here, any value since the present invention is not directly related to physics. In the present invention, S is also assumed to be defined in the area of d×d pixels around (x_0, y_0) as is similar to σ.

[0041] A differential ΔS of S defined in Expression 113 is considered. It is assumed that by changing, a pixel value (digital value) is changed from i to j. In this case, ΔS can be written as follows:

[Expression 114]

$$\Delta S = k \ln \frac{N!}{N_1! N_2! \cdots (N_i - 1)! \cdots (N_j + 1)! \cdots N_n!} - k \ln \frac{N!}{N_1! N_2! \cdots N_i! \cdots N_j! \cdots N_n!}$$

[0042] Thus, by changing, N_i is decreased by one while N_j is increased by one. If Expression 114 is expanded, a considerably simple expression is obtained as follows:

[Expression 115]

$$\Delta S = k \ln N_i - k \ln (N_j + 1)$$

[0043] In summary, the procedure of this embodiment is as follows.

(I) Using random numbers, (x_0, y_0) and Δμ are selected.
(II) Using Expressions 104, 108 (or 107), 112 and 115, ΔE is calculated.
(III) If the result of evaluation is improved (ΔE<0), Δμ is added to f(x_0, y_0).
(IV) If ΔE>0, Δμ is also added to f(x_0, y_0) with a probability of exp(-ΔE/T).
(V) The temperature T is decreased by a small amount.
(VI) The procedure above is repeated from (I).
(VII) If the predetermined stop conditions are satisfied, the process is ended. For example, the stop condition may be that the probability of success becomes lower than a predetermined value (e.g., 10%, this value is adjustable appropriately) where "success" means the case when Δμ is added in (III) and (IV). An estimated cross-sectional image at the end of the process is considered as a cross-sectional image of the target object, which may be displayed on a display of the computer or may be recorded into a recording medium.

[0044] It is seen that steps (I) to (VI) faithfully correspond to basic steps (i) to (vi) of SA. Note that the processes in steps (I) to (VII) are performed in the image reconstruction processor of FIG. 1.

[0045] Note that the end of the process in step (VII) may not be performed in the image reconstruction processor of

FIG. 1. Estimated cross-sectional images may be successively displayed on a display of the computer, and a user who views the images may stop the process.

(Third Embodiment)

[0046] Next, an important variation of the aforementioned method will be described. In the aforementioned method, Expression 107 or 108 is used to obtain the sum of a series with respect to θ. Therefore, each Monte Carlo step includes M times of summation. On the other hand, this embodiment is provided to further reduce the amount of calculation.

[0047] Firstly, a back projection g(x, y) of p(r, θ) will be considered.

[Expression 116]

$$g(x,y)=\sum_{\theta} p(x\cos\theta + y\sin\theta,\theta)$$

[0048] In Expression 116, since a filtering operation is not performed, g(x, y) becomes a similar image to the cross-sectional image f(x, y), but significantly blurred. If g(x, y) is used, Expression 108 is written as follows:

[Expression 117]

$$\Delta H = M\Delta\mu^2 + 2\Delta\mu\{g(x,y)-g_0(x,y)\}$$

[0049] Note that $g_0(x, y)$ is a back projection of $p_0(r, \theta)$ and is calculated in the manner similar to that of Expression 116. Expression 117 is superior to Expression 108 in terms of the absence of summation. Since $g_0(x, y)$ does not change at all during the calculation process, $g_0(x, y)$ can be calculated in advance. On the other hand, g(x, y) changes a little for every time a point of f(x, y) is changed, and therefore, to be exact, needs to be recalculated every time when a set of steps (I) to (IV) is executed. However, if it is assumed that the change in g(x, y) due to the change in f(x, y) is small, another set of steps is applicable, which is of this embodiment. The steps of this embodiment will be hereinafter described. Note that steps (1) to (9) below are performed in the image reconstruction processor of FIG. 1.

(1) $g_0(x, y)$ is obtained from $p_0(r, \theta)$.
(2) p(r, θ) is calculated from f(x, y), and then g(x, y) is obtained from p(r, θ).
(3) An image $\Delta\mu(x, y)$ whose pixel value is a change value of f(x, y) is generated using a random number.
(4) Expression 117 is applied to each pixel value to calculate an image $\Delta H(x, y)$.
(5) Similarly, Expressions 112 and 115 are applied to each pixel value to calculate images $\Delta\sigma(x, y)$ and $\Delta S(x, y)$.
(6) $\Delta E(x, y)$ is calculated based on Expression 104.
(7) $\Delta\mu(x, y)$ is set to 0 for a coordinate point (x, y) having a positive ΔE.
(8) $\Delta\mu(x, y)$ is added to f(x, y).
(9) T is multiplied by α ($\alpha<1$), and the procedure is repeated from (2).
(10) If the predetermined stop conditions are satisfied, the process is ended. For example, the stop condition may be that the probability of success becomes lower than a predetermined value (e.g., 10%, this value is adjustable appropriately) where "failure" means the case when $\Delta\mu(x, y)$ is set to 0. An estimated cross-sectional image at the end of the process is considered as a cross-sectional image of the target object, which may be displayed on a display of the computer or may be recorded into a recording medium.

[0050] Note that the determination of whether to end the process in step (10) may not be performed in the image reconstruction processor of FIG. 1. Estimated cross-sectional images may be successively displayed on a display of the computer, and a user who views the images may instruct the computer to end the process.

[0051] Schematic concepts of steps (I) to (VII) and steps (1) to (10) are schematically shown in FIG. 5. In FIG. 5, an axis represents a value of a parameter (in this case, a value of a pixel), and the virtual energy E is represented by a gray level (a higher gray level indicates a smaller E). For the sake of convenience, the number of parameters (the number of pixels) is assumed to be two. In the case of steps (I) to (VII) shown in FIG. 5(a), a minimum value of E is eventually reached via a zigzag path while sometimes directs a wrong direction. On the other hand, in the case of steps (1) to (10) of FIG. 5(b), a minimum value of E is searched for while the gradient of E is taken into consideration. The method of FIG. 5(b) would be intuitively recognized as being more efficient. This embodiment is advantageous in terms of calculation speed because of a reduction in the amount of calculation by Expression 117 and an improvement in search efficiency shown in FIG. 5(b). Note that steps (1) to (10) do not faithfully correspond to the basic algorithm (i) to (vi) of SA, and are a natural expansion of steps (I) to (VII).

(Other Embodiments)

[0052] An image reconstruction processor for executing the process described in each embodiment above can be implemented using a program for causing a computer to execute these processes, a computer in which the program is installed, a specialized LSI for executing these processes, or the like.

(Examples)

[0053] As an example, the effect of removing a metal artifact using simulation will be described. Firstly, for comparison, results from the technique of Non-Patent Document 1 are shown in FIG. 6 (fig. 5 in Non-Patent Document 1).

[0054] In FIG. 6, results (a), (d) and (g) in the left column are original phantom images without a metal artifact. Results (b), (e) and (h) in the middle column are images reconstructed by a typical FBP method, where invisible regions are set at predetermined positions in the original phantom images. Results (c), (f) and (i) in the right column are images reconstructed by the method of Non-Patent Document 1, where opaque regions are set as in results (b), (e) and (h). The results (c), (f) and (i) are one of the best achievements in removal of metal artifacts by the conventional arts.

[0055] The image of FIG. 6(a) in Non-Patent Document 1 was used, and the opaque regions were set at the same positions as those in the document. Then, projections were calculated by simulation. The result is shown in FIG. 7. FIG. 7 corresponds to $p_0(r, \theta)$ of this example. An image reconstructed from FIG. 7 by the present invention and an enlarged diagram of FIG. 6(c) for comparison are shown in FIG. 8. The effect of the present invention can be clearly seen from FIG. 8. In FIG. 8(b) of this embodiment, it is difficult to find even a feature of metal artifacts.

[0056] Note that, in FIG. 8(b) of this embodiment, edge portions are slightly blurred. This is because a "factor which smoothes a cross-sectional image" (smoothing term $c\sigma$) is strong to some extent. It is known that the factor needs to be set to be strong to some extent so as to reduce metal artifacts. In any case, according to this embodiment, metal artifacts can be considerably removed, although there is still room for an improvement in the balance between each factor when the virtual energy E is calculated.

[0057] Note that, for reference, a result obtained by executing the algorithm of this embodiment without setting the smoothing term $c\sigma$ or the entropic term TS is shown in FIG. 9. FIG. 9(a) shows a result obtained in the absence of the smoothing term $c\sigma$ (in the presence of only the entropic term TS), FIG. 9(b) shows a result obtained in the absence of the entropic term TS (in the presence of only the smoothing term $c\sigma$), and FIG. 9(c) shows a result obtained in the absence of both the entropic term TS and the smoothing term $c\sigma$. When FIG. 9 is compared to FIG. 8(b), it is found that, in this embodiment, metal artifacts can be removed to a greater extent when both smoothing term $c\sigma$ and the entropic term TS are introduced to the energy E than when only either of them is set and when none of them is set. When only the smoothing term is set, streaks extending radially from an opaque region are left as artifacts. On the other hand, when only the entropic term is set, a cross-sectional image becomes granular and has a low S/N. For final image quality, the ratio of the coefficient c of the smoothing term and the virtual temperature T during a slow cooling process seems to be important.

[0058] Next, an example with the limitation on a rotational angle is shown in FIG. 10. FIG. 10(a) shows a result from reconstruction only by FBP (typical CT). FIG. 10(b) shows a result from application of ILST (an image reconstruction method based on the least square method). FIG. 10(c) shows a result from reconstruction by this embodiment. When these results are compared, it is found that this embodiment is effective against artifacts which appear in the case of the limitation. Artifacts due to the angle limitation are characterized in that a circular region is altered to an almond-shaped region having two opposite sharp ends and luminance is reversed across round side edges connecting the sharp ends of the almond-shaped region. In this embodiment, both of the characteristics are reduced.

INDUSTRIAL APPLICABILITY

[0059] The present invention is significantly effective against metal artifacts, and therefore, is particularly useful in a field where metal artifacts are serious, such as CT for teeth, CT for an object including a metal implant, or the like.

[0060] Also, the present invention is generally effective in reconstruction from a set of projections having a lack of information. For example, there is a significant lack of information when there is a limit on a projection angle. The projection angle limitation causes a problem with three-dimensional electron microscopy, CT mammography, translation CT (Japanese Unexamined Patent Application Publication No. 2006-71472) or the like. The lack-of-information problem also occurs in three-dimensional CT, such as cone beam CT, helical scan CT or the like. The present invention is also effective in removal of artifacts appearing in three-dimensional CT.

[0061] Moreover, the present invention is applicable to a system in which the amount of information is considerably small. For example, the present invention is useful for fluorescent X-ray CT, seismic CT for imaging Earth's interior, and the like.

[0062] The present invention also has a subsidiary benefit that a luminance value (corresponding to an absorption coefficient in the case of X-ray) in a cross-sectional image can be determined with higher accuracy than that of the conventional art, for example. This effect can be applied so as to improve the accuracy of measurement of bone density or the like.

[0063] The present invention can be used to obtain a reconstructed image having a higher contrast than that of the conventional art. Therefore, the present invention is also highly useful for typical X-ray CT in which artifacts or the like do not cause a problem. Also, since the present invention is stable even when there is a shortage of data, the present invention is effective in a reduction in time required for measurement of projections, and therefore, a reduction in X-ray dose. According to these features, the present invention has the potential to replace all existing X-ray CT techniques.

Claims

1. An image reconstructing device for obtaining a cross-sectional image of an object from radiographic projections obtained by irradiating the object with a beam of radiation, comprising:

   means (a) for obtaining an energy E_0 including differences between projections calculated from a current estimated cross-sectional image of the object and the radiographic projections, wherein the energy E_0 is given by

$$E_0 = H_0 + c_0\sigma_0 - TS_0$$

   where

   H_0: differences between projections calculated from the current estimated cross-sectional image and the radiographic projections,
   c_0: a coefficient which represents a strength of a smoothing term,
   σ_0: a standard deviation of a local region of the current estimated cross-sectional image,
   T: a virtual temperature parameter, and
   S_0: an entropy, calculated based on a number of pixels having the same pixel value, of a local region of the current estimated cross-sectional image;

   means (b) for modifying a portion of the current estimated cross-sectional image;
   means (c) for obtaining an energy E_1 including differences between projections calculated from the modified estimated cross-sectional image and the radiographic projections, wherein the energy $E_1$is given by

$$E_1 = H + c\sigma - TS$$

   where

   H: differences between projections calculated from the modified estimated cross-sectional image and the radiographic projections,
   c: a coefficient which represents a strength of a smoothing term,
   σ: a standard deviation of a local region of the modified estimated cross-sectional image,
   T: the virtual temperature parameter, and
   S: an entropy, calculated based on a number of pixels having the same pixel value, of a local region of the modified estimated cross-sectional image;

means (d) for obtaining a differential ΔE between the energy E_0 and the energy E_1;
means (e) for determining whether or not the modification is to be accepted, based on an acceptance function using the differential ΔE and the temperature parameter T for controlling an acceptance probability, and reflecting a result of the determination on the current estimated cross-sectional image; and
means (f) for changing a value of the temperature parameter T every time the number of iterations of a series of processes of the means (a) to (e) reaches a predetermined value.

2. The image reconstructing device of claim 1, comprising:

instead of the means (a) and (c) for obtaining E_0 and E_1,
means (h) for calculating ΔH using

$$\Delta H = \sum_{\theta} \left\{ \Delta\mu^2 + 2\Delta\mu \left[p(r(\theta),\theta) - p_0(r(\theta),\theta) \right] \right\},$$

and obtaining ΔE in means (d) including the calculated ΔH as a component,
where, when the current estimated cross-sectional image of the object is represented by f(x, y) and the portion modified by the means (b) is represented by Δf(x, y), Δf(x, y) is a cross-sectional image having a value of Δμ only at a coordinate point (x_0, y_0) and zero elsewhere, and p(r, θ) represents a projection calculated from the current estimated cross-sectional image of the object, $p_0(r, \theta)$ represents a radiographic projection of the object, r represents a channel position of a one-dimensional detector taking the projection, θ represents a projection angle, and $r(\theta)=x_0\cos\theta+y_0\sin\theta$.

3. The image reconstructing device of claim 1, comprising:

instead of the means (a) and (c) for obtaining E_0 and E_1,
means (h) for calculating ΔH using

$$\Delta H = M\Delta\mu^2 + 2\Delta\mu \sum_{\theta} \left\{ p(r(\theta),\theta) - p_0(r(\theta),\theta) \right\},$$

and obtaining ΔE in means (d) including the calculated ΔH as a component,
where, when the current estimated cross-sectional image of the object is represented by f(x, y) and the portion modified by the means (b) is represented by Δf(x, y), Δf(x, y) is a cross-sectional image having a value of Δμ only at a coordinate point (x_0, y_0) and zero elsewhere, and p(r, θ) represents a projection calculated from the current estimated cross-sectional image of the object, $p_0(r, \theta)$ represents a radiographic projection of the object, r represents a channel position of a one-dimensional detector taking the projection, θ represents a projection angle, $r(\theta)=x_0\cos\theta+y_0\sin\theta$, and M represents the number of projection angles.

4. The image reconstructing device of claim 2 or 3, wherein
the means (h) calculates Δσ using ,

$$\Delta\sigma = \sqrt{\left\langle f(x_0,y_0)^2 \right\rangle - \frac{f_i^2 - f_j^2}{d^2} - \left\{ \left\langle f(x_0,y_0) \right\rangle - \frac{f_i - f_j}{d^2} \right\}^2}$$

and obtains ΔE including as a component a sum of a product cΔσ of the calculated Δσ and a coefficient c, and the ΔH, where σ represents a standard deviation of luminance values of dxd pixels around the coordinate point (x_0, y_0) and is calculated by

$$\sigma = \sqrt{\left\langle f(x_0, y_0)^2 \right\rangle - \left\langle f(x_0, y_0) \right\rangle^2}$$

and f_i and f_j represent values of $f(x_0, y_0)$ before and after the modification by the means (b), where

[Expression 5]

$$\left\langle f(x_0, y_0)^2 \right\rangle = \frac{1}{d^2} \sum_{i,j=-d/2}^{d/2} f(x_0 + i, y_0 + j)^2$$

[Expression 6]

$$\left\langle f(x_0, y_0) \right\rangle = \frac{1}{d^2} \sum_{i,j=-d/2}^{d/2} f(x_0 + i, y_0 + j)$$

.

5. The image reconstructing device of claim 2 or 3, wherein the means (h) calculates ΔS using

$$\Delta S = k \ln N_i - k \ln (N_j + 1)$$

and obtains ΔE including as a component a sum of a product $-T\Delta S$ of the calculated ΔS and the temperature parameter T, and the ΔH,
where S represents an entropy of a local region image of dxd pixels around the coordinate point (x_0, y_0) and is calculated by

$$S = k \ln \frac{N!}{N_1! N_2! \cdots N_i! \cdots N_n!}$$

where

N: a total number of pixels in the local region image,
N_i: a total number of pixels whose pixel value is a digital value of i,
N_j: a total number of pixels whose pixel value is a digital value of j ,
k: a constant,

a pixel value is changed from the digital value i to the digital value j by the modification by the means (b).

6. The image reconstructing device of claim 1, comprising:

   instead of the means (e) and (f),
   means (e1) for determining whether or not the modification is to be accepted, based on an acceptance function using the differential ΔE and the temperature parameter T for controlling an acceptance probability, and reserving reflection of a result of determination on the current estimated cross-sectional image; and
   means (f1) for reflecting the reservation(s) in the means (e1) on the current estimated cross-sectional image and changing a value of the temperature parameter T every time the number of iterations of a series of processes of the means (a) to (d) and (e1) reaches a predetermined value.

7. An image reconstructing device for obtaining a cross-sectional image of an object from projections obtained by irradiating the object with a beam of radiation, comprising:

   means (m1) for calculating a back projection $g_0(x, y)$ of a radiographic projection $p_0(r, \theta)$ of the object by a back projection operation without filtering;
   means (m2) for calculating a projection $p(r, \theta)$ from a current estimated cross-sectional image $f(x, y)$ of the object, and calculating a back projection $g(x, y)$ of the projection $p(r, \theta)$ by a back projection operation without filtering;
   means (m3) for generating an image $\Delta\mu(x, y)$ whose pixel value is a change value
   of the current estimated cross-sectional image $f(x, y)$ of the object;
   means (m4) for generating an image $\Delta H(x, y)$ by applying

$$\Delta H = M\Delta\mu^2 + 2\Delta\mu\{g(x, y) - g_0(x, y)\}$$

   to each pixel value,
   where

      M: the number of projection angles;

   means (m5) for calculating $\Delta E(x, y)$ using the $\Delta H(x, y)$,
   where

      $\Delta E(x, y)$ represents a differential between evaluation functions $E_0(x, y)$ and $E_1(x, y)$,
      $E_0(x, y)$ represents an evaluation function including a difference between the projection $p(r, \theta)$ calculated from the estimated cross-sectional image $f(x, y)$ and the radiographic projection $p_0(r, \theta)$, and
      $E_1(x, y)$ represents an evaluation function including a difference between a projection $p(r, \theta)+\Delta p(r, \theta)$, calculated from a sum $f(x, y)+\Delta\mu(x, y)$ of the estimated cross-sectional image $f(x, y)$ and the image $\Delta\mu(x, y)$ obtained by the means (m3), and the radiographic projection $p_0(r, \theta)$;

   means (m6) for setting the $\Delta\mu(x, y)$ to 0 at a coordinate point (x, y) where the ΔE is positive; and
   means (m7) for setting a sum of the estimated cross-sectional image $f(x, y)$ and the image $\Delta\mu(x, y)$ obtained by the means (m6) as a new estimated cross-sectional image $f(x, y)$ and repeating processes of the means (m2) to (m6) with respect to the new estimated cross-sectional image $f(x, y)$.

8. An image reconstructing device for obtaining a cross-sectional image of an object from projections obtained by irradiating the object with a beam of radiation, comprising:

   means (m1) for calculating a back projection $g_0(x, y)$ of a radiographic projection $p_0(r, \theta)$ of the object using

$$g_0(x, y) = \sum_{\theta} p_0(x\cos\theta + y\sin\theta, \theta)$$

r: a channel position of a one-dimensional detector taking the projection,
θ: a projection angle,

means (m2) for calculating a projection p(r, θ) from a current estimated cross-sectional image f(x, y) of the object, and calculating a back projection g(x, y) of the projection p(r, θ) using

$$g(x, y) = \sum_{\theta} p(x\cos\theta + y\sin\theta, \theta)$$

means (m3) for generating an image Δμ(x, y) whose pixel value is a change value of the current estimated cross-sectional image f(x, y) of the object;
means (m4) for generating an image ΔH(x, y) by applying

$$\Delta H = M\Delta\mu^2 + 2\Delta\mu\{g(x_0, y_0) - g_0(x_0, y_0)\}$$

to each pixel value,
where

M: the number of projection angles;

means (m5) for generating Δσ(x, y) by applying

$$\Delta\sigma = \sqrt{\left\langle f(x_0, y_0)^2 \right\rangle - \frac{f_i^2 - f_j^2}{d^2} - \left\{ \left\langle f(x_0, y_0) \right\rangle - \frac{f_i - f_j}{d^2} \right\}^2}$$

to each pixel value,
where σ represents a standard deviation of luminance values of dxd pixels around a coordinate point (x_0, y_0) and is calculated by

$$\sigma = \sqrt{\left\langle f(x_0, y_0)^2 \right\rangle - \left\langle f(x_0, y_0) \right\rangle^2}$$

and f_i and f_j represent values of f(x_0, y_0) before and after a change,
where

$$\left\langle f(x_0, y_0)^2 \right\rangle = \frac{1}{d^2} \sum_{i,j=-d/2}^{d/2} f(x_0 + i, y_0 + j)^2$$

,

.

$$\left\langle f(x_0, y_0) \right\rangle = \frac{1}{d^2} \sum_{i,j=-d/2}^{d/2} f(x_0 + i, y_0 + j)$$

means (m6) for generating an image ΔS by applying

$$\Delta S = k \ln N_i - k \ln(N_j + 1),$$

to each value,
where S represents an entropy of a local region image of dxd pixels around the coordinate point (x_0, y_0) and is calculated by

$$S = k \ln \frac{N!}{N_1! N_2! \cdots N_i! \cdots N_n!},$$

where

N: a total number of pixels in the local region image,
N_i: a total number of pixels whose pixel value is a digital value of i,
N_j: a total number of pixels whose pixel value is a digital value of j ,
k: a constant,
a pixel value is changed from the digital value i to the digital value j by the modification by the means (b);

means (m7) for calculating ΔE(x, y) based on

$$\Delta E = \Delta H + c\Delta\sigma - T\Delta S,$$

where

c: a coefficient,
T: a virtual temperature parameter,

means (m8) for setting the Δμ(x, y) to 0 at a coordinate point (x, y) where the ΔE is positive;
means (m9) for setting a sum of the estimated cross-sectional image f(x, y) and the image Δμ(x, y) obtained by the means (m8) as a new estimated cross-sectional image f(x, y); and
means (m10) for multiplying the T by α, α<1, and repeating processes of the means (m2) to (m9).

9. A method for obtaining a cross-sectional image of an object from radiographic projections obtained by irradiating the object with a beam of radiation, comprising the steps of:

(a) obtaining an energy E_0 including differences between projections calculated from a current estimated cross-sectional image of the object and the radiographic projections, wherein the energy E_0 is given by

$$E_0 = H_0 + c_0\sigma_0 - TS_0$$

where

H_0: differences between projections calculated from the current estimated cross-sectional image and the radiographic projections,
c_0: a coefficient which represents a strength of a smoothing term,
σ_0: a standard deviation of a local region of the current estimated cross-sectional image,
T: a virtual temperature parameter, and
S_0: an entropy, calculated based on a number of pixels having the same pixel value, of a local region of the current estimated cross-sectional image;

(b) modifying a portion of the current estimated cross-sectional image;
(c) obtaining an energy E_1 including differences between projections calculated from the modified estimated cross-sectional image and the radiographic projections, wherein the energy E_1 is given by

$$E_1 = H + c\sigma - TS$$

where

H: differences between projections calculated from the modified estimated cross-sectional image and the radiographic projections,
c: a coefficient which represents a strength of a smoothing term,
σ: a standard deviation of a local region of the modified estimated cross-sectional image,
T: the virtual temperature parameter, and
S: an entropy, calculated based on a number of pixels having the same pixel value, of a local region of the modified estimated cross-sectional image;

(d) obtaining a differential ΔE between the energy E_0 and the energy E_1;
(e) determining whether or not the modification is to be accepted, based on an acceptance function using the differential ΔE and the temperature parameter T for controlling an acceptance probability;
(f) reflecting a result of the determination on the current estimated cross-sectional image, and returning to the step (a);
(g) changing a value of the temperature parameter T every time the number of iterations of the steps (a) to (f) reaches a predetermined value; and
(h) determining whether or not the result of the determination in the step (e) satisfies predetermined stop conditions, and if the result of the determination in the step (e) satisfies predetermined stop conditions, ending the process.

10. An image reconstructing program for obtaining a cross-sectional image of an object from radiographic projections obtained by irradiating the object with a beam of radiation, wherein
the program causes a computer to execute the steps of:

(a) obtaining an Energy E_0
including differences between projections calculated from a current estimated cross-sectional image of the object and the radiographic projections, wherein the energy E_0 is given by

$$E_0 = H_0 + c_0\sigma_0 - TS_0$$

where

H_0: differences between projections calculated from the current estimated cross-sectional image and the radiographic projections,
c_0: a coefficient which represents a strength of a smoothing term,
σ_0: a standard deviation of a local region of the current estimated cross-sectional image,
T: a virtual temperature parameter, and
S_0: an entropy, calculated based on a number of pixels having the same pixel value, of a local region of the current estimated cross-sectional image;

(b) modifying a portion of the current estimated cross-sectional image;
(c) obtaining an energy E_1 including differences between projections calculated from the modified estimated cross-sectional image and the radiographic projections, wherein the energy E_1 is given by

$$E_1 = H + c\sigma - TS$$

where

H: differences between projections calculated from the modified estimated cross-sectional image and the radiographic projections,
c: a coefficient which represents a strength of a smoothing term,
σ: a standard deviation of a local region of the modified estimated cross-sectional image,
T: the virtual temperature parameter, and
S: an entropy, calculated based on a number of pixels having the same pixel value, of a local region of the modified estimated cross-sectional image;

(d) obtaining a differential ΔE between the energy E_0 and the energy E_1;
(e) determining whether or not the modification is to be accepted, based on an acceptance function using the differential ΔE and the temperature parameter T for controlling an acceptance probability;
(f) reflecting a result of the determination on the current estimated cross-sectional image, and returning to the step (a); and
(g) changing a value of the temperature parameter T every time the number of iterations of the steps (a) to (f) reaches a predetermined value.

11. A CT apparatus comprising:

means (A) for obtaining radiographic projections by irradiating an object with a beam of radiation; and
means (B) for obtaining a cross-sectional image of the object from the projections,
wherein the means (B) includes:

means (b1) for obtaining an energy E_0 including differences between projections calculated from a current estimated cross-sectional image of the object and the projections by irradiating the object with the beam of radiation (hereinafter referred to as "radiographic projections"), wherein the energy E_0 is given by

$$E_0 = H_0 + c_0\sigma_0 - TS_0$$

where

H_0: differences between projections calculated from the current estimated cross-sectional image and the radiographic projections,

c_0: a coefficient which represents a strength of a smoothing term,
σ_0: a standard deviation of a local region of the current estimated cross-sectional image,
T: a virtual temperature parameter, and
S_0: an entropy, calculated based on a number of pixels having the same pixel value, of a local region of the current estimated cross-sectional image;

means (b2) for modifying a portion of the current estimated cross-sectional image;
means (b3) for obtaining an energy E_1 including differences between projections calculated from the modified estimated cross-sectional image and the radiographic projections, wherein the energy E_1 is given by

$$E_1 = H + c\sigma - TS$$

where

H: differences between projections calculated from the modified estimated cross-sectional image and the radiographic projections,
c: a coefficient which represents a strength of a smoothing term,
σ: a standard deviation of a local region of the modified estimated cross-sectional image,
T: the virtual temperature parameter, and
S: an entropy, calculated based on a number of pixels having the same pixel value, of a local region of the modified estimated cross-sectional image;

means (b4) for obtaining a differential ΔE between the energy E_0 and the energy E1:
means (b5) for determining whether or not the modification is to be accepted, based on an acceptance function using the differential ΔE and the temperature parameter T for controlling an acceptance probability, and reflecting a result of the determination on the current estimated cross-sectional image; and
means (b6) for changing a value of the temperature parameter T every time the number of iterations of a series of processes of the means (b1) to (b5) reaches a predetermined value.

Patentansprüche

1. Bildrekonstruktionsvorrichtung zum Erhalten eines Querschnittsbildes eines Objekts von Röntgenprojektionen, die durch Bestrahlen des Objekts mit einem Strahlenbündel erhalten werden, die Folgendes umfasst:

Mittel (a) zum Erhalten einer Energie E_0, die Differenzen zwischen Projektionen, die von einem gegenwärtigen geschätzten Querschnittsbild des Objekts berechnet werden, und den Röntgenprojektionen umfasst,
wobei die Energie E_0 gegeben ist durch:

$$E_0 = H_0 + c_0\sigma_0 - TS_0$$

WO:

H_0: Differenzen zwischen Projektionen, die von dem gegenwärtigen geschätzten Querschnittsbild berechnet werden, und den Röntgenprojektionen,
c_0: ein Koeffizient, der eine Stärke eines Glättungsterms darstellt,
σ_0: eine Standardabweichung einer lokalen Region des gegenwärtigen geschätzten Querschnittsbildes,
T: ein Ersatztemperaturparameter, und
S_0: eine Entropie einer lokalen Region des gegenwärtigen geschätzten Querschnittsbildes, die auf der Grundlage einer Anzahl von Pixeln berechnet wird, die denselben Pixelwert aufweisen,

Mittel (b) zum Ändern eines Abschnitts des gegenwärtigen geschätzten Querschnittsbildes;
Mittel (c) zum Erhalten einer Energie E_1, die Differenzen zwischen Projektionen, die von dem geänderten geschätzten Querschnittsbild berechnet werden, und den Röntgenprojektionen umfasst, wobei die Energie E_1

gegeben ist durch:

$$E_1 = H + c\sigma - TS$$

wo:

H: Differenzen zwischen Projektionen, die von dem geänderten geschätzten Querschnittsbild berechnet werden, und den Röntgenprojektionen,
c: ein Koeffizient, der eine Stärke eines Glättungsterms darstellt,
σ: eine Standardabweichung einer lokalen Region des geänderten geschätzten Querschnittsbildes,
T: der Ersatztemperaturparameter, und
S: eine Entropie einer lokalen Region des geänderten geschätzten Querschnittsbildes, die auf der Grundlage einer Anzahl von Pixeln berechnet wird, die denselben Pixelwert aufweisen;

Mittel (d) zum Erhalten eines Differentials ΔE zwischen der Energie E_0 und der Energie E_1;
Mittel (e), um auf der Grundlage einer Annahmefunktion, die das Differential ΔE und den Temperaturparameter T verwendet, um eine Annahmewahrscheinlichkeit zu steuern, zu bestimmen, ob die Änderung anzunehmen ist oder nicht, und ein Ergebnis der Bestimmung auf dem gegenwärtigen geschätzten Querschnittsbild widerzuspiegeln; und Mittel (f) zum Ändern eines Werts des Temperaturparameters T, jedes Mal, wenn die Anzahl der Iterationen von einer Reihe von Prozessen der Mittel (a) bis (e) einen vorbestimmten Wert erreicht.

2. Bildrekonstruktionsvorrichtung nach Anspruch 1, die Folgendes umfasst:

anstatt der Mittel (a) und (c) zum Erhalten von E_0 und E_1,
Mittel (h) zum Berechnen von ΔH unter Verwendung von:

$$\Delta H = \sum_{\theta} \{\Delta\mu^2 + 2\Delta\mu[p(r(\theta),\theta) - p_0(r(\theta),\theta)]\}$$

und Erhalten von ΔE in den Mitteln (d), das das berechnete ΔH als eine Komponente umfasst,
wo, wenn das gegenwärtige geschätzte Querschnittsbild des Objekts durch f(x, y) dargestellt wird und der durch die Mittel (b) geänderte Abschnitt durch $\Delta f(x, y)$ dargestellt wird, $\Delta f(x, y)$ ein Querschnittsbild ist, das einen Wert von $\Delta\mu$ nur an einem Koordinatenpunkt (x_0, y_0) und sonst null aufweist, und $p(r, \theta)$ eine Projektion darstellt, die von dem gegenwärtigen geschätzten Querschnittsbild des Objekts berechnet wird, $p_0(r, \theta)$ eine Röntgenprojektion des Objekts darstellt, r eine Kanalposition eines eindimensionalen Detektors darstellt, der die Projektion erfasst, θ einen Projektionswinkel darstellt und $r(\theta) = x_0\cos\theta + y_0\sin\theta$.

3. Bildrekonstruktionsvorrichtung nach Anspruch 1, die Folgendes umfasst:

anstatt der Mittel (a) und (c) zum Erhalten von E_0 und E_1,
Mittel (h) zum Berechnen von ΔH unter Verwendung von:

$$\Delta H = M\Delta\mu^2 + 2\Delta\mu \sum_{\theta} \{p(r(\theta),\theta) - p_0(r(\theta),\theta)\}$$

und Erhalten von ΔE in den Mitteln (d), das das berechnete ΔH als eine Komponente umfasst,
wo, wenn das gegenwärtige geschätzte Querschnittsbild des Objekts durch f(x, y) dargestellt wird und der durch die Mittel (b) geänderte Abschnitt durch $\Delta f(x, y)$ dargestellt wird, $\Delta f(x, y)$ ein Querschnittsbild ist, das einen Wert von $\Delta\mu$ nur an einem Koordinatenpunkt (x_0, y_0) und sonst null aufweist, und $p(r, \theta)$ eine Projektion darstellt, die von dem gegenwärtigen geschätzten Querschnittsbild des Objekts berechnet wird, $p_0(r, \theta)$ eine Röntgenprojektion des Objekts darstellt, r eine Kanalposition eines eindimensionalen Detektors darstellt, der die Projektion

erfasst, θeinen Projektionswinkel darstellt, $r(\theta)=x_0\cos\theta+y_0\sin\theta$ und M die Anzahl der Projektionswinkel darstellt.

4. Bildrekonstruktionsvorrichtung nach Anspruch 2 oder 3, wobei:

das Mittel (h) $\Delta\sigma$ unter Verwendung von

$$\Delta\sigma = \sqrt{\langle f(x_0,y_0)^2\rangle - \frac{f_i^2 - f_j^2}{d^2} - \left\{\langle f(x_0,y_0)\rangle - \frac{f_i - f_j}{d^2}\right\}^2}$$

berechnet und ΔE erhält, das als eine Komponente eine Summe eines Produkts $c\Delta\sigma$ des berechneten $\Delta\sigma$ und eines Koeffizienten c und des ΔH umfasst,
wo σ eine Standardabweichung von Helligkeitswerten von dxd Pixeln um den Koordinatenpunkt (x_0, y_0) herum darstellt und durch

$$\sigma = \sqrt{\langle f(x_0,y_0)^2\rangle - \langle f(x_0,y_0)\rangle^2}$$

berechnet wird und f_i und f_j Werte von $f(x_0, y_0)$ vor und nach der Änderung durch die Mittel (b) darstellen, wo:

[Gleichung 5]

$$\langle f(x_0,y_0)^2\rangle = \frac{1}{d^2}\sum_{i,i=-d/2}^{d/2} f(x_0+i,y_0+j)^2$$

[Gleichung 6]

$$\langle f(x_0,y_0)\rangle = \frac{1}{d^2}\sum_{i,i=-d/2}^{d/2} f(x_0+i,y_0+j)$$

5. Bildrekonstruktionsvorrichtung nach Anspruch 2 oder 3, wobei:

das Mittel (h) ΔS unter Verwendung von $\Delta S = k \ln N_i - k \ln (N_j + 1)$ berechnet und ΔE erhält, das als eine Komponente eine Summe eines Produkts $-T\Delta S$ des berechneten ΔS und des Temperaturparameters T und des ΔH umfasst,
wo S eine Entropie eines Bildes einer lokalen Region von dxd Pixeln um den Koordinatenpunkt (x_0, y_0) herum darstellt und durch Folgendes berechnet wird:

$$S = k \ln \frac{N!}{N_1!\ N_2! \ldots N_i! \ldots N_n!}$$

wo:

N: eine Gesamtanzahl von Pixeln im Bild der lokalen Region,
N_i: eine Gesamtanzahl von Pixeln, deren Pixelwert ein Digitalwert von i ist,
N_j: eine Gesamtanzahl von Pixeln, deren Pixelwert ein Digitalwert von j ist,
k: eine Konstante,
ein Pixelwert von dem Digitalwert i durch die Änderung durch das Mittel (b) in den Digitalwert j geändert wird.

6. Bildrekonstruktionsvorrichtung nach Anspruch 1, die Folgendes umfasst:

anstatt der Mittel (e) und (f),
Mittel (e1), um auf der Grundlage einer Annahmefunktion, die das Differential ΔE und den Temperaturparameter T verwendet, um eine Annahmewahrscheinlichkeit zu steuern, zu bestimmen, ob die Änderung anzunehmen ist oder nicht, und eine Widerspiegelung eines Ergebnisses der Bestimmung auf dem gegenwärtigen geschätzten Querschnittsbild zu reservieren; und
Mittel (f1) zum Widerspiegeln der Reservierung/en in den Mitteln (e1) auf dem gegenwärtigen geschätzten Querschnittsbild und Ändern eines Werts des Temperaturparameters T, jedes Mal, wenn die Anzahl von Iterationen einer Reihe von Prozessen der Mittel (a) bis (d) und (e1) einen vorbestimmten Wert erreicht.

7. Bildrekonstruktionsvorrichtung zum Erhalten eines Querschnittsbildes eines Objekts von Projektionen, die durch Bestrahlen des Objekts mit einem Strahlenbündel erhalten werden, die Folgendes umfasst:

Mittel (m1) zum Berechnen einer Rückprojektion $g_0(x, y)$ einer Röntgenprojektion $p_0(r, \theta)$ des Objekts durch eine Rückprojektionsoperation ohne Filtern;
Mittel (m2) zum Berechnen einer Projektion $p(r, \theta)$ von einem gegenwärtigen geschätzten Querschnittsbild $f(x, y)$ des Objekts und Berechnen einer Rückwärtsprojektion $g(x, y)$ der Projektion $p(r, \theta)$ durch eine Rückprojektionsoperation ohne Filtern;
Mittel (m3) zum Erzeugen eines Bildes $\Delta\mu(x, y)$, dessen Pixelwert ein Änderungswert des gegenwärtigen geschätzten Querschnittsbildes $f(x, y)$ des Objekts ist;
Mittel (m4) zum Erzeugen eines Bildes $\Delta H(x, y)$ durch Anwenden von:

$$\Delta H = M\Delta\mu^2 + 2\Delta\mu\{g(x,y) - g_0(x,y)\}$$

auf jeden Pixelwert
wo:

M: die Anzahl der Projektionswinkel ist;

Mittel (m5) zum Berechnen von $\Delta E(x, y)$ unter Verwendung des $\Delta H(x, y)$,
wo:

$\Delta E(x, y)$ ein Differential zwischen den Bewertungsfunktionen $E_0(x, y)$ und $E_1(x, y)$ darstellt,
$E_0(x, y)$ eine Bewertungsfunktion darstellt, die eine Differenz zwischen der Projektion $p(r, \theta)$, die von dem geschätzten Querschnittsbild $f(x, y)$ berechnet wird, und der Röntgenprojektion $p_0(r, \theta)$ darstellt, und
$E_1(x, y)$ eine Bewertungsfunktion darstellt, die eine Differenz zwischen einer Projektion $p(r, \theta)+\Delta\ p(r, \theta)$, die von einer Summe $f(x, y) + \Delta\mu(x, y)$ des geschätzten Querschnittsbildes $f(x, y)$ und des Bildes $\Delta\mu(x, y)$ berechnet wird, das durch die Mittel (m3) erhalten wird, und der Röntgenprojektion $p_0(r, \theta)$ umfasst;
Mittel (m6) zum Einstellen des $\Delta\mu(x, y)$ auf 0 an einem Koordinatenpunkt (x, y), wo ΔE positiv ist; und
Mittel (m7) zum Einstellen einer Summe des geschätzten Querschnittsbildes $f(x, y)$ und des Bildes $\Delta\mu(x,$

y), das durch die Mittel (m6) erhalten wird, als ein neues geschätztes Querschnittsbild f(x, y) und Wiederholen der Prozesse der Mittel (m2) bis (m6) in Bezug auf das neue geschätzte Querschnittsbild f(x, y).

8. Bildrekonstruktionsvorrichtung zum Erhalten eines Querschnittsbildes eines Objekts von Projektionen, die durch Bestrahlen des Objekts mit einem Strahlenbündel erhalten werden, die Folgendes umfasst:

Mittel (m1) zum Berechnen einer Rückprojektion $g_0(x, y)$ einer Röntgenprojektion $p_0(r, \theta)$ des Objekts unter Verwendung von:

$$g_0(x,y) = \sum_{\theta} p_0(x\,cos\theta + y\sin\theta, \theta)$$

r: eine Kanalposition eines eindimensionalen Detektors, der die Projektion erfasst,
θ: ein Projektionswinkel,

Mittel (m2) zum Berechnen einer Projektion $p(r, \theta)$ von einem gegenwärtigen geschätzten Querschnittsbild f(x, y) des Objekts und Berechnen einer Rückwärtsprojektion g(x, y) der Projektion $p(r, \theta)$ unter Verwendung von:

$$g(x,y) = \sum_{\theta} p(x\,cos\theta + y\sin\theta, \theta)$$

Mittel (m3) zum Erzeugen eines Bildes $\Delta(x, y)$, dessen Pixelwert ein Änderungswert des gegenwärtigen geschätzten Querschnittsbildes f(x, y) des Objekts ist;
Mittel (m4) zum Erzeugen eines Bildes $\Delta H(x, y)$ durch Anwenden von:

$$\Delta H = M\Delta\mu^2 + 2\Delta\mu\{g(x,y) - g_0(x,y)\}$$

auf jeden Pixelwert,
wo:

M: die Anzahl der Projektionswinkel;

Mittel (m5) zum Erzeugen von $\theta\sigma(x, y)$ durch Anwenden von:

$$\Delta\sigma = \sqrt{\langle f(x_0,y_0)^2\rangle - \frac{f_i^2 - f_j^2}{d^2} - \left\{\langle f(x_0,y_0)\rangle - \frac{f_i - f_j}{d^2}\right\}^2}$$

auf jeden Pixelwert,
wo σ eine Standardabweichung von Helligkeitswerten von dxd Pixeln um einen Koordinatenpunkt (x_0, y_0) herum darstellt und durch $\sigma = \sqrt{\langle f(x_0,y_0)^2\rangle - \langle f(x_0,y_0)\rangle^2}$ berechnet wird und f_i und f_j Werte von $f(x_0, y_0)$ vor und nach einer Änderung darstellen,
wo:

$$\langle f(x_0, y_0)^2 \rangle = \frac{1}{d^2} \sum_{i,i=-d/2}^{d/2} f(x_0 + i, y_0 + j)^2$$

$$\langle f(x_0, y_0) \rangle = \frac{1}{d^2} \sum_{i,i=-d/2}^{d/2} f(x_0 + i, y_0 + j)$$

Mittel (m6) zum Erzeugen eines Bildes ΔS durch Anwenden von $\Delta S = k \ln N_i - k \ln(N_j + 1)$ auf jeden Wert, wo S eine Entropie eines Bildes einer lokalen Region der dxd Pixel um den Koordinatenpunkt (x_0, y_0) herum darstellt und durch Folgendes berechnet wird:

$$S = k \ln \frac{N!}{N_1!\ N_2! \ldots N_i! \ldots N_n!}$$

wo:

N: eine Gesamtanzahl von Pixeln im Bild der lokalen Region,
N_i: eine Gesamtanzahl von Pixeln, deren Pixelwert ein Digitalwert von i ist,
N_j: eine Gesamtanzahl von Pixeln, deren Pixelwert ein Digitalwert von j ist,
k: eine Konstante,
ein Pixelwert von dem Digitalwert i durch die Änderung durch das Mittel (b) in den Digitalwert j geändert wird;

Mittel (m7) zum Berechnen von $\Delta E(x, y)$ basierend auf:

$$\Delta E = \Delta H + c\Delta\sigma - T\Delta S,$$

wo:

c: ein Koeffizient,
T: ein Ersatztemperaturparameter,

Mittel (m8) zum Einstellen des $\Delta\mu(x, y)$ auf 0 am Koordinatenpunkt (x, y), wo das ΔE positiv ist;
Mittel (m9) zum Einstellen einer Summe des geschätzten Querschnittsbildes f(x, y) und des Bildes $\Delta\mu(x, y)$, das durch das Mittel (m8) erhalten wird, als ein neues geschätztes Querschnittsbild f(x, y); und
Mittel (m10) zum Multiplizieren des T mit α, $\alpha < 1$, und Wiederholen der Prozesse der Mittel (m2) bis (m9).

9. Verfahren zum Erhalten eines Querschnittsbildes von einem Objekt von Röntgenprojektionen, die durch Bestrahlen des Objekts mit einem Strahlenbündel erhalten werden, das die folgenden Schritte umfasst:

(a) Erhalten einer Energie E_0, die Differenzen zwischen Projektionen, die von einem gegenwärtigen geschätzten Querschnittsbild des Objekts berechnet werden, und den Röntgenprojektionen umfasst, wobei die Energie E_0 gegeben ist durch:

$$E_0 = H_0 + c_0\sigma_0 - TS_0$$

WO:

H_0: Differenzen zwischen Projektionen, die von dem gegenwärtigen geschätzten Querschnittsbild berechnet werden, und den Röntgenprojektionen,
c_0: ein Koeffizient, der eine Stärke eines Glättungsterms darstellt,
σ_0 eine Standardabweichung einer lokalen Region des gegenwärtigen geschätzten Querschnittsbildes, T: ein Ersatztemperaturparameter, und
S_0: eine Entropie einer lokalen Region des gegenwärtigen geschätzten Querschnittsbildes, die auf der Grundlage einer Anzahl von Pixeln berechnet wird, die denselben Pixelwert aufweisen,

(b) Ändern eines Abschnitts des gegenwärtigen geschätzten Querschnittsbildes;
(c) Erhalten einer Energie E_1, die Differenzen zwischen Projektionen, die von dem geänderten geschätzten Querschnittsbild berechnet werden, und den Röntgenprojektionen umfasst, wobei die Energie E_1 gegeben ist durch:

$$E_1 = H + c\sigma - TS$$

WO:

H: Differenzen zwischen Projektionen, die von dem geänderten geschätzten Querschnittsbild berechnet werden, und den Röntgenprojektionen,
c: ein Koeffizient, der eine Stärke eines Glättungsterms darstellt,
σ: eine Standardabweichung einer lokalen Region des geänderten geschätzten Querschnittsbildes,
T: der Ersatztemperaturparameter, und
S: eine Entropie einer lokalen Region des geänderten geschätzten Querschnittsbildes, die auf der Grundlage einer Anzahl von Pixeln berechnet wird, die denselben Pixelwert aufweisen;

(d) Erhalten eines Differentials ΔE zwischen der Energie E_0 und der Energie E_1;
(e) Bestimmen, ob die Änderung anzunehmen ist oder nicht, auf der Grundlage einer Annahmefunktion unter Verwendung des Differentials ΔE und des Temperaturparameters T zum Steuern einer Annahmewahrscheinlichkeit;
(f) Widerspiegeln eines Ergebnisses der Bestimmung auf dem gegenwärtigen geschätzten Querschnittsbild und Zurückkehren zum Schritt (a);
(g) Ändern eines Werts des Temperaturparameters T, jedes Mal, wenn die Anzahl von Iterationen der Schritte (a) bis (f) einen vorbestimmten Wert erreicht; und
(h) Bestimmen, ob das Ergebnis der Bestimmung im Schritt (e) vorbestimmte Haltbedingungen erfüllt, und, wenn das Ergebnis der Bestimmung im Schritt (e) vorbestimmte Haltbedingungen erfüllt, Beenden des Prozesses.

10. Bildrekonstruktionsprogram zum Erhalten eines Querschnittsbildes eines Objekts von Röntgenprojektionen, die durch Bestrahlen des Objekts mit einem Strahlenbündel erhalten werden, wobei
das Programm bewirkt, dass ein Rechner die folgenden Schritte ausführt:

(a) Erhalten einer Energie E_0, die Differenzen zwischen Projektionen, die von einem gegenwärtigen geschätzten Querschnittsbild des Objekts berechnet werden, und den Röntgenprojektionen umfasst, wobei die Energie E_0 gegeben ist durch:

$$E_0 = H_0 + c_0\sigma_0 - TS_0$$

WO:

H_0: Differenzen zwischen Projektionen, die von dem gegenwärtigen geschätzten Querschnittsbild berechnet werden, und den Röntgenprojektionen,

c_0: ein Koeffizient, der eine Stärke eines Glättungsterms darstellt,
σ_0: eine Standardabweichung einer lokalen Region des gegenwärtigen geschätzten Querschnittsbildes,
T: ein Ersatztemperaturparameter, und
S_0: eine Entropie einer lokalen Region des gegenwärtigen geschätzten Querschnittsbildes, die auf der Grundlage einer Anzahl von Pixeln berechnet wird, die denselben Pixelwert aufweisen,

(b) Ändern eines Abschnitts des gegenwärtigen geschätzten Querschnittsbildes;
(c) einer Energie E_1, die Differenzen zwischen Projektionen, die von dem geänderten geschätzten Querschnittsbild berechnet werden, und den Röntgenprojektionen umfasst, wobei die Energie E_1 gegeben ist durch:

$$E_1 = H + c\sigma - TS$$

WO:

H: Differenzen zwischen Projektionen, die von dem geänderten geschätzten Querschnittsbild berechnet werden, und den Röntgenprojektionen,
c: ein Koeffizient, der eine Stärke eines Glättungsterms darstellt,
σ: eine Standardabweichung einer lokalen Region des geänderten geschätzten Querschnittsbildes,
T: der Ersatztemperaturparameter, und
S: eine Entropie einer lokalen Region des geänderten geschätzten Querschnittsbildes, die auf der Grundlage einer Anzahl von Pixeln berechnet wird, die denselben Pixelwert aufweisen;

(d) Erhalten eines Differentials ΔE zwischen der Energie E_0 und der Energie E_1;
(e) Bestimmen, ob die Änderung anzunehmen ist oder nicht, auf der Grundlage einer Annahmefunktion unter Verwendung des Differentials ΔE und des Temperaturparameters T zum Steuern einer Annahmewahrscheinlichkeit;
(f) Widerspiegeln eines Ergebnisses der Bestimmung auf dem gegenwärtigen geschätzten Querschnittsbild und Zurückkehren zum Schritt (a); und
(g) Ändern eines Werts des Temperaturparameters T, jedes Mal, wenn die Anzahl von Iterationen der Schritte (a) bis (f) einen vorbestimmten Wert erreicht.

11. CT-Gerät, das Folgendes umfasst:

Mittel (A) zum Erhalten von Röntgenprojektionen, durch Bestrahlen eines Objekts mit einem Strahlenbündel; und
Mittel (B) zum Erhalten eines Querschnittsbildes des Objekts von den Projektionen;
wobei das Mittel (B) Folgendes umfasst:

Mittel (b1) zum Erhalten einer Energie E_0, die Differenzen zwischen Projektionen, die von einem gegenwärtigen geschätzten Querschnittsbild des Objekts berechnet werden, und den Projektionen, durch Bestrahlen des Objekts mit dem Strahlenbündel (nachfolgend als "Röntgenprojektionen" bezeichnet) umfasst, wobei die Energie E_0 gegeben ist durch:

$$E_0 = H_0 + c_0\sigma_0 - TS_0$$

wo:

H_0: Differenzen zwischen Projektionen, die von dem gegenwärtigen geschätzten Querschnittsbild berechnet werden, und den Röntgenprojektionen,
c_0: ein Koeffizient, der eine Stärke eines Glättungsterms darstellt,
σ_0: eine Standardabweichung einer lokalen Region des gegenwärtigen geschätzten Querschnittsbildes,
T: ein Ersatztemperaturparameter, und

S_0: eine Entropie einer lokalen Region des gegenwärtigen geschätzten Querschnittsbildes, die auf der Grundlage einer Anzahl von Pixeln berechnet wird, die denselben Pixelwert aufweisen,

Mittel (b2) zum Ändern eines Abschnitts des gegenwärtigen geschätzten Querschnittsbildes;
Mittel (b3) zum Erhalten einer Energie E_1, die Differenzen zwischen Projektionen, die von dem geänderten geschätzten Querschnittsbild berechnet werden, und den Röntgenprojektionen umfasst, wobei die Energie E_1 gegeben ist durch:

$$E_1 = H + c\sigma - TS$$

wo:

H: Differenzen zwischen Projektionen, die von dem geänderten geschätzten Querschnittsbild berechnet werden, und den Röntgenprojektionen,
c: ein Koeffizient, der eine Stärke eines Glättungsterms darstellt,
σ: eine Standardabweichung einer lokalen Region des geänderten geschätzten Querschnittsbildes,
T: der Ersatztemperaturparameter, und
S: eine Entropie einer lokalen Region des geänderten geschätzten Querschnittsbildes, die auf der Grundlage einer Anzahl von Pixeln berechnet wird, die denselben Pixelwert aufweisen;

Mittel (b4) zum Erhalten eines Differentials ΔE zwischen der Energie E_0 und der Energie E_1;
Mittel (b5), um auf der Grundlage einer Annahmefunktion, die das Differential ΔE und den Temperaturparameter T verwendet, um eine Annahmewahrscheinlichkeit zu steuern, zu bestimmen, ob die Änderung anzunehmen ist oder nicht, und das Ergebnis der Bestimmung auf dem gegenwärtigen Querschnittsbild widerzuspiegeln; und
Mittel (b6) zum Ändern eines Werts des Temperaturparameters T, jedes Mal, wenn die Anzahl der Iterationen von einer Reihe von Prozessen der Mittel (b1) bis (b5) einen vorbestimmten Wert erreicht.

Revendications

1. Dispositif de reconstruction d'image pour obtenir une image en coupe transversale d'un objet à partir de projections radiographiques obtenues par irradiation de l'objet avec un faisceau de rayonnement, comprenant :

des moyens (a) pour obtenir une énergie E_0 comprenant des différences entre des projections calculées à partir d'une image en coupe transversale estimée actuelle de l'objet et les projections radiographiques, dans lequel l'énergie E_0 est donnée par :

$$E_0 = H_0 + c_0\sigma_0 - TS_0$$

où

H_0 : des différences entre des projections calculées à partir de l'image en coupe transversale estimée actuelle et les projections radiographiques,
c_0 : un coefficient qui représente une force d'un terme de lissage,
σ_0 : un écart-type d'une région locale de l'image en coupe transversale estimée actuelle,
T : un paramètre de température virtuelle, et
S_0 : une entropie, calculée sur la base d'un nombre de pixels ayant la même valeur de pixel, d'une région locale de l'image en coupe transversale estimée actuelle ;

des moyens (b) pour modifier une portion de l'image en coupe transversale estimée actuelle ;
des moyens (c) pour obtenir une énergie E_1 comprenant des différences entre des projections calculées à partir de l'image en coupe transversale estimée modifiée et les projections radiographiques, dans lequel l'énergie E_1

est donnée par :

$$E_1 = H + c\sigma - TS$$

où

H : des différences entre des projections calculées à partir de l'image en coupe transversale estimée modifiée et les projections radiographiques,
c : un coefficient qui représente une force d'un terme de lissage,
σ : un écart-type d'une région locale de l'image en coupe transversale estimée modifiée,
T : le paramètre de température virtuelle, et
S : une entropie, calculée sur la base d'un nombre de pixels ayant la même valeur de pixel, d'une région locale de l'image en coupe transversale estimée modifiée ;

des moyens (d) pour obtenir un différentiel ΔE entre l'énergie E_0 et l'énergie E_1 ;
des moyens (e) pour déterminer si la modification doit être acceptée ou pas, sur la base d'une fonction d'acceptation utilisant le différentiel ΔE et le paramètre de température T pour commander une probabilité d'acceptation, et refléter un résultat de la détermination sur l'image en coupe transversale estimée actuelle ; et
des moyens (f) pour changer une valeur du paramètre de température T chaque fois que le nombre d'itérations d'une série de processus des moyens (a) à (e) atteint une valeur prédéterminée.

2. Dispositif de reconstruction d'image selon la revendication 1, comprenant :

au lieu des moyens (a) et (c) pour obtenir E_0 et E_1,
des moyens (h) pour calculer ΔH en utilisant :

$$\Delta H = \sum_\theta \{\Delta\mu^2 + 2\Delta\mu[p(r(\theta),\theta) - p_0(r(\theta),\theta)]\},$$

et pour obtenir ΔE dans les moyens (d) comprenant le ΔH calculé en tant que composant,
où, lorsque l'image en coupe transversale estimée actuelle de l'objet est représentée par f(x, y) et la portion modifiée par les moyens (b) est représentée par $\Delta f(x, y)$, $\Delta f(x, y)$ est une image en coupe transversale ayant une valeur de $\Delta\mu$ uniquement à un point de coordonnées (x_0, y_0) et zéro ailleurs, et $p(r, \theta)$ représente une projection calculée à partir de l'image en coupe transversale estimée actuelle de l'objet, $p_0(r, \theta)$ représente une projection radiographique de l'objet, r représente une position de canal d'un détecteur unidimensionnel prenant la projection, θ représente un angle de projection, et $r(\theta)=x_0\cos\theta+y_0\sin\theta$.

3. Dispositif de reconstruction d'image selon la revendication 1, comprenant :

au lieu des moyens (a) et (c) pour obtenir E_0 et E_1,
des moyens (h) pour calculer ΔH en utilisant :

$$\Delta H = M\Delta\mu^2 + 2\Delta\mu \sum_\theta \{p(r(\theta),\theta) - p_0(r(\theta),\theta)\},$$

et pour obtenir ΔE dans les moyens (d) comprenant le ΔH calculé en tant que composant,
où, lorsque l'image en coupe transversale estimée actuelle de l'objet est représentée par f(x, y) et la portion modifiée par les moyens (b) est représentée par $\Delta f(x, y)$, $\Delta f(x, y)$ est une image en coupe transversale ayant une valeur de $\Delta\mu$ uniquement à un point de coordonnées (x_0, y_0) et zéro ailleurs, et $p(r, \theta)$ représente une projection calculée à partir de l'image en coupe transversale estimée actuelle de l'objet, $p_0(r, \theta)$ représente une projection radiographique de l'objet, r représente une position de canal d'un détecteur unidimensionnel prenant la projection, θ représente un angle de projection, et $r(\theta) =x_0\cos\theta+y_0\sin\theta$, et représente le nombre d'angles de

projection M.

4. Dispositif de reconstruction d'image selon la revendication 2 ou 3, dans lequel les moyens (h) calculent Δσ en utilisant

$$\Delta\sigma = \sqrt{\langle f(x_0, y_0)^2 \rangle - \frac{f_i^2 - f_j^2}{d^2} - \left\{ \langle f(x_0, y_0) \rangle - \frac{f_i - f_j}{d^2} \right\}^2}$$

et obtient ΔE comprenant, en tant que composant, une somme d'un produit cΔσ du Δσ calculé et un coefficient c, et le ΔH,
où σ représente un écart-type de valeurs de luminance de dxd pixels autour du point de coordonnées (x_0, y_0) et est calculé par

$$\sigma = \sqrt{\langle f(x_0, y_0)^2 \rangle - \langle f(x_0, y_0) \rangle^2}$$

et f_i et f_j représentent des valeurs de $f(x_0, y_0)$ avant et après la modification par le moyen (b),
où

[Expression 5]

$$\langle f(x_0, y_0)^2 \rangle = \frac{1}{d^2} \sum_{i,j=-d/2}^{d/2} f(x_0 + i, y_0 + j)^2$$

[Expression 6]

$$\langle f(x_0, y_0) \rangle = \frac{1}{d^2} \sum_{i,j=-d/2}^{d/2} f(x_0 + i, y_0 + j)\,.$$

5. Dispositif de reconstruction d'image selon la revendication 2 ou 3, dans lequel les moyens (h) calculent ΔS en utilisant

$$\Delta S = k \ln N_i - k \ln(N_j + 1)$$

et obtient ΔE comprenant, en tant que composant, une somme d'un produit -TΔS du ΔS calculé et le paramètre de température T et le ΔH,
où S représente une entropie d'une image de région locale de dxd pixels autour du point de coordonnées (x_0, y_0) et est calculé par :

$$S = k\ln\frac{N!}{N_1!\,N_2!\ldots N_i!\ldots n!}$$

où

N : un nombre total de pixels dans l'image de région locale,
N_i : un nombre total de pixels dont la valeur de pixel est une valeur numérique de i,
N_j : un nombre total de pixels dont la valeur de pixel est une valeur numérique de j,
k : une constante,
une valeur de pixel est changée de la valeur numérique i à la valeur numérique j par la modification par les moyens (b).

6. Dispositif de reconstruction d'image selon la revendication 1, comprenant :

au lieu des moyens (e) et (f),
des moyens (el) pour déterminer si la modification doit être acceptée ou pas, sur la base d'une fonction d'acceptation utilisant le différentiel ΔE et le paramètre de température T pour commander une probabilité d'acceptation, et réserver un reflet d'un résultat de la détermination sur l'image en coupe transversale estimée actuelle ; et
des moyens (f1) pour refléter la ou les réservations dans les moyens (el) sur l'image en coupe transversale estimée actuelle et changer une valeur du paramètre de température T chaque fois que le nombre d'itérations d'une série de processus des moyens (a) à (d) et (el) atteint une valeur prédéterminée.

7. Dispositif de reconstruction d'image pour obtenir une image en coupe transversale d'un objet à partir de projections obtenues par irradiation de l'objet avec un faisceau de rayonnement, comprenant :

des moyens (m1) pour calculer une rétroprojection $g_0(x, y)$ d'une projection radiographique $p_0(r, \theta)$ de l'objet par une opération de rétroprojection sans filtrage ;
des moyens (m2) pour calculer une projection $p(r, \theta)$ à partir d'une image en coupe transversale estimée actuelle $f(x, y)$ de l'objet, et calculer une rétroprojection $g(x, y)$ de la projection $p(r, \theta)$ par une opération de rétroprojection sans filtrage ;
des moyens (m3) pour générer une image $\Delta\mu(x, y)$ dont la valeur de pixel est une valeur de changement de l'image en coupe transversale estimée actuelle $f(x, y)$ de l'objet ;
des moyens (m4) pour générer une image $\Delta H(x, y)$ par l'application de

$$\Delta H = M\Delta\mu^2 + 2\Delta\mu\{g(x,y) - g_0(x,y)\}$$

à chaque valeur de pixel,
où

M : le nombre d'angles de projection ;
des moyens (m5) pour calculer AE(x,y) en utilisant le $\Delta H(x, y)$,

où

$\Delta E(x, y)$ représente un différentiel entre des fonctions d'évaluation $E_0(x, y)$ et $E_1(x, y)$,
$E_0(x, y)$ représente une fonction d'évaluation comprenant une différence entre la projection $p(r, \theta)$ calculée à partir de l'image en coupe transversale estimée $f(x, y)$ et la projection radiographique $p_0(r, \theta)$, et
$E_1(x, y)$ représente une fonction d'évaluation comprenant une différence entre une projection $p(r, \theta)+\Delta\, p(r, \theta)$ calculée à partir d'une somme $f(x, y) + \Delta\mu(x, y)$ de l'image en coupe transversale estimée $f(x, y)$ et l'image $\Delta\mu(x, y)$ obtenue par les moyens (m3), et la projection radiographique $p_0(r, \theta)$;
des moyens (m6) pour régler le $\Delta\mu(x, y)$ à 0 à un point de coordonnées (x, y) où le ΔE est positif ; et
des moyens (m7) pour régler une somme de l'image en coupe transversale estimée $f(x, y)$ et de l'image

$\Delta\mu(x, y)$ obtenue par les moyens (m6) en tant qu'une nouvelle image en coupe transversale estimée f(x, y) et répéter les processus des moyens (m2) à (m6) par rapport à la nouvelle image en coupe transversale estimée f(x, y).

8. Dispositif de reconstruction d'image pour obtenir une image en coupe transversale d'un objet à partir de projections obtenues par irradiation de l'objet avec un faisceau de rayonnement, comprenant :

des moyens (m1) pour calculer une rétroprojection $g_0(x, y)$ d'une projection radiographique $p_0(r, \theta)$ de l'objet en utilisant :

$$g_0(x,y) = \sum_{\theta} p_0(x\cos\theta + y\sin\theta, \theta)$$

r : une position de canal d'un détecteur unidimensionnel prenant la projection,
θ : un angle de projection,

des moyens (m2) pour calculer une projection $p(r, \theta)$ à partir d'une image en coupe transversale estimée actuelle f(x, y) de l'objet, et calculer une rétroprojection g(x, y) de la projection $p(r, \theta)$ en utilisant :

$$g(x,y) = \sum_{\theta} p(x\cos\theta + y\sin\theta, \theta)$$

des moyens (m3) pour générer une image $\Delta\mu(x, y)$ dont la valeur de pixel est une valeur de changement de l'image en coupe transversale estimée actuelle f(x, y) de l'objet ;
des moyens (m4) pour générer une image $\Delta H(x, y)$ par l'application de

$$\Delta H = M\Delta\mu^2 + 2\Delta\mu\{g(x,y) - g_0(x,y)\}$$

à chaque valeur de pixel,
où
M : le nombre d'angles de projection ;
des moyens (m5) pour générer $A\sigma(x, y)$ en appliquant

$$\Delta\sigma = \sqrt{\langle f(x_0,y_0)^2\rangle - \frac{f_i^2 - f_j^2}{d^2} - \left\{\langle f(x_0,y_0)\rangle - \frac{f_i - f_j}{d^2}\right\}^2}$$

à chaque valeur de pixel où σ représente un écart-type de valeurs de luminance de dxd pixels autour d'un point de coordonnées (x_0, y_0) et est calculé par

$$\sigma = \sqrt{\langle f(x_0,y_0)^2\rangle - \langle f(x_0,y_0)\rangle^2}$$

et f_i et f_j représentent des valeurs de $f(x_0, y_0)$ avant et après un changement, où

$$\langle f(x_0,y_0)^2\rangle = \frac{1}{d^2}\sum_{i,j=-d/2}^{d/2} f(x_0+i,y_0+j)^2$$

$$\langle f(x_0,y_0)\rangle = \frac{1}{d^2}\sum_{i,j=-d/2}^{d/2} f(x_0+i,y_0+j)$$

des moyens (m6) pour générer une image ΔS en appliquant :

$$\Delta S = k\ln N_i - k\ln\left(N_j + 1\right)$$

à chaque valeur,
où S représente une entropie d'une image de région locale de dxd pixels autour du point de coordonnées (x_0, y_0) et est calculé par :

$$S = k\ln\frac{N!}{N_1!\,N_2!\,\ldots N_i!\ldots n!}$$

où

N : un nombre total de pixels dans l'image de région locale,
N_i : un nombre total de pixels dont la valeur de pixel est une valeur numérique de i,
N_j : un nombre total de pixels dont la valeur de pixel est une valeur numérique de j,
k : une constante,
une valeur de pixels est changée de la valeur numérique i à la valeur numérique j par la modification par les moyens (b) ;

des moyens (m7) pour calculer $\Delta E(x, y)$ sur la base de :

$$\Delta E = \Delta H + c\Delta\sigma - T\Delta S$$

où

c : un coefficient,
T : un paramètre de température virtuelle,

des moyens (m8) pour régler le $\Delta\mu(x, y)$ à 0 à un point de coordonnées (x, y) où le ΔE est positif ;
des moyens (m9) pour régler une somme de l'image en coupe transversale estimée f(x, y) et de l'image $\Delta\mu(x, y)$ obtenue par les moyens (m8) en tant qu'une nouvelle image en coupe transversale estimée f(x, y) ; et

des moyens (m10) pour multiplier le T par α, $\alpha<1$, et répéter les processus des moyens (m2) à (m9).

9. Procédé pour obtenir une image en coupe transversale d'un objet à partir de projections radiographiques obtenues par irradiation de l'objet avec un faisceau de rayonnement, comprenant les étapes consistant à :

(a) obtenir une énergie E_0 comprenant des différences entre des projections calculées à partir d'une image en coupe transversale estimée actuelle de l'objet et des projections radiographiques, dans lequel l'énergie E_0 est donnée par :

$$E_0 = H_0 + c_0\sigma_0 - TS_0$$

où

H_0 : des différences entre des projections calculées à partir de l'image en coupe transversale estimée actuelle et les projections radiographiques,
c_0 : un coefficient qui représente une force d'un terme de lissage,
σ_0 : un écart-type d'une région locale de l'image en coupe transversale estimée actuelle,
T : un paramètre de température virtuelle, et
S_0 une entropie, calculée sur la base d'un nombre de pixels ayant la même valeur de pixel, d'une région locale de l'image en coupe transversale estimée actuelle ;

(b) modifier une portion de l'image en coupe transversale estimée actuelle ;
(c) obtenir une énergie E_1 comprenant des différences entre des projections calculées à partir de l'image en coupe transversale estimée modifiée et les projections radiographiques, dans lequel l'énergie E_1 est donnée par :

$$E_1 = H + c\sigma - TS$$

où

H : des différences entre des projections calculées à partir de l'image en coupe transversale estimée modifiée et les projections radiographiques,
c : un coefficient qui représente une force d'un terme de lissage,
σ : un écart-type d'une région locale de l'image en coupe transversale estimée modifiée,
T : le paramètre de température virtuelle, et
S : une entropie, calculée sur la base d'un nombre de pixels ayant la même valeur de pixel, d'une région locale de l'image en coupe transversale estimée modifiée ;

(d) obtenir un différentiel ΔE entre l'énergie E_0 et l'énergie E_1 ;
(e) déterminer si la modification doit être acceptée ou pas, sur la base d'une fonction d'acceptation utilisant le différentiel ΔE et le paramètre de température T pour commander une probabilité d'acceptation ;
(f) refléter un résultat de la détermination sur l'image en coupe transversale estimée actuelle, et retourner à l'étape (a) ;
(g) changer une valeur du paramètre de température T chaque fois que le nombre d'itérations des étapes (a) à (f) atteint une valeur prédéterminée ; et
(h) déterminer si le résultat de la détermination à l'étape (e) répond à des conditions d'arrêt prédéterminées, et si le résultat de la détermination à l'étape (e) répond à des conditions d'arrêt prédéterminées, terminer le processus.

10. Programme de reconstruction d'image pour obtenir une image en coupe transversale d'un objet à partir de projections radiographiques obtenues par irradiation de l'objet avec un faisceau de rayonnement, dans lequel
le programme amène un ordinateur à exécuter les étapes consistant à :

(a) obtenir une énergie E_0 comprenant des différences entre des projections calculées à partir d'une image en coupe transversale estimée actuelle de l'objet et des projections radiographiques, dans lequel l'énergie E_0 est donnée par :

$$E_0 = H_0 + c_0\sigma_0 - TS_0$$

où

H_0 : des différences entre des projections calculées à partir de l'image en coupe transversale estimée actuelle et les projections radiographiques,
c_0 : un coefficient qui représente une force d'un terme de lissage,
σ_0 : un écart-type d'une région locale de l'image en coupe transversale estimée actuelle,
T : un paramètre de température virtuelle, et
S_0 :une entropie, calculée sur la base d'un nombre de pixels ayant la même valeur de pixel, d'une région locale de l'image en coupe transversale estimée actuelle ;

(b) modifier une portion de l'image en coupe transversale estimée actuelle ;
(c) obtenir une énergie E_1 comprenant des différences entre des projections calculées à partir de l'image en coupe transversale estimée modifiée et les projections radiographiques, dans lequel l'énergie E_1 est donnée par :

$$E_1 = H + c\sigma - TS$$

où

H : des différences entre des projections calculées à partir de l'image en coupe transversale estimée modifiée et les projections radiographiques,
c : un coefficient qui représente une force d'un terme de lissage,
σ : un écart-type d'une région locale de l'image en coupe transversale estimée modifiée,
T : le paramètre de température virtuelle, et
S : une entropie, calculée sur la base d'un nombre de pixels ayant la même valeur de pixel, d'une région locale de l'image en coupe transversale estimée modifiée ;

(d) obtenir un différentiel ΔE entre l'énergie E_0 et l'énergie E_1 ;
(e) déterminer si la modification doit être acceptée ou pas, sur la base d'une fonction d'acceptation utilisant le différentiel ΔE et le paramètre de température T pour commander une probabilité d'acceptation ;
(f) refléter un résultat de la détermination sur l'image en coupe transversale estimée actuelle, et retourner à l'étape (a) ; et
(g) changer une valeur du paramètre de température T chaque fois que le nombre d'itérations des étapes (a) à (f) atteint une valeur prédéterminée.

11. Appareil de tomodensitométrie comprenant :

des moyens (A) pour obtenir des projections radiographiques par irradiation d'un objet avec un faisceau de rayonnement ; et
des moyens (B) pour obtenir une image en coupe transversale de l'objet à partir des projections,
dans lequel les moyens (B) comprennent :

des moyens (b1) pour obtenir une énergie E_0 comprenant des différences entre des projections calculées à partir d'une image en coupe transversale estimée actuelle de l'objet et les projections par irradiation de l'objet avec le faisceau de rayonnement (les projections radiographiques), dans lequel l'énergie E_0 est donnée par :

$$E_0 = H_0 + c_0\sigma_0 - TS_0$$

où

H_0 : des différences entre des projections calculées à partir de l'image en coupe transversale estimée actuelle et les projections radiographiques,

c_0 : un coefficient qui représente une force d'un terme de lissage,

σ_0 : un écart-type d'une région locale de l'image en coupe transversale estimée actuelle,

T : un paramètre de température virtuelle, et

S_0 : une entropie, calculée sur la base d'un nombre de pixels ayant la même valeur de pixel, d'une région locale de l'image en coupe transversale estimée actuelle ;

des moyens (b2) pour modifier une portion de l'image en coupe transversale estimée actuelle ;

des moyens (b3) pour obtenir une énergie E_1 comprenant des différences entre des projections calculées à partir de l'image en coupe transversale estimée modifiée et les projections radiographiques, dans lequel l'énergie E_1 est donnée par :

$$E_1 = H + c\sigma - TS$$

où

H : des différences entre des projections calculées à partir de l'image en coupe transversale estimée modifiée et les projections radiographiques,

c : un coefficient qui représente une force d'un terme de lissage,

σ : un écart-type d'une région locale de l'image en coupe transversale estimée modifiée,

T : le paramètre de température virtuelle, et

S : une entropie, calculée sur la base d'un nombre de pixels ayant la même valeur de pixel, d'une région locale de l'image en coupe transversale estimée modifiée ;

des moyens (b4) pour obtenir un différentiel ΔE entre l'énergie E_0 et l'énergie E_1 ;

des moyens (b5) pour déterminer si la modification doit être acceptée ou pas, sur la base d'une fonction d'acceptation utilisant le différentiel ΔE et le paramètre de température T pour commander une probabilité d'acceptation, et refléter un résultat de la détermination sur l'image en coupe transversale estimée actuelle ; et

des moyens (b6) pour changer une valeur du paramètre de température T chaque fois que le nombre d'itérations d'une série de processus des moyens (b1) à (b5) atteint une valeur prédéterminée.

FIG.1

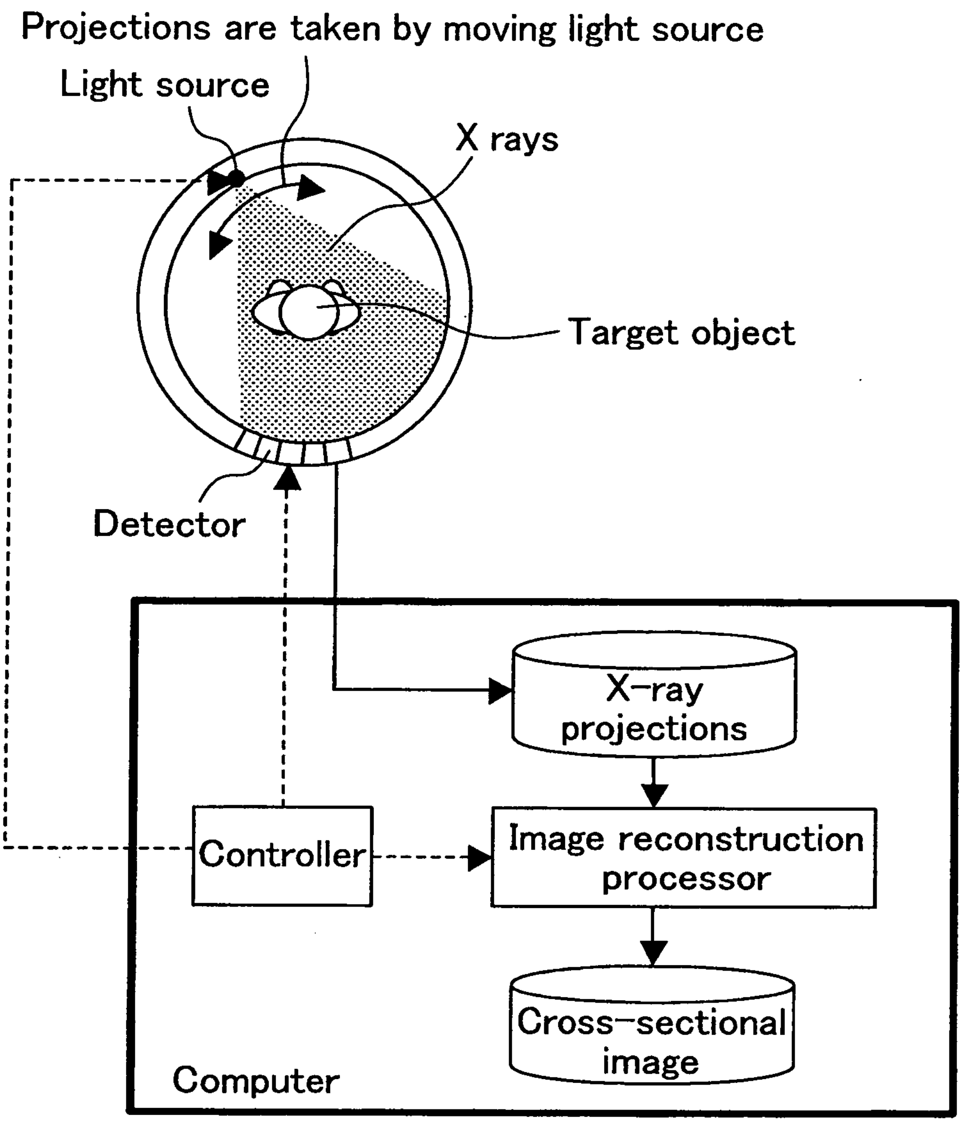

Projections are taken by moving light source
Light source
X rays
Target object
Detector
X-ray projections
Controller
Image reconstruction processor
Cross-sectional image
Computer

FIG.2

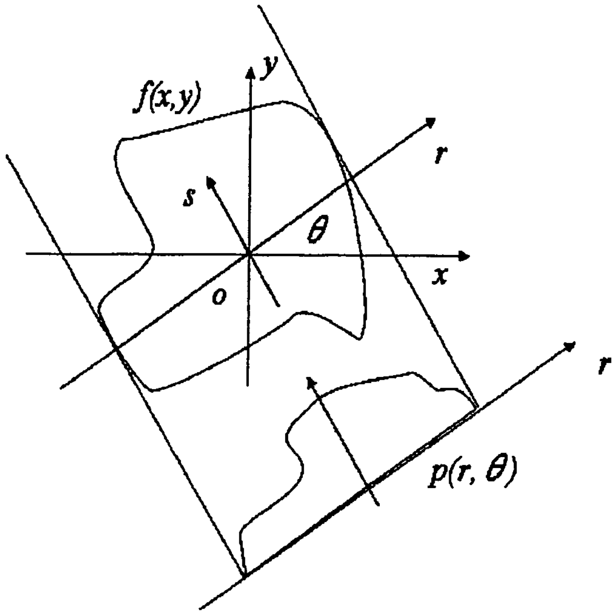


FIG.3

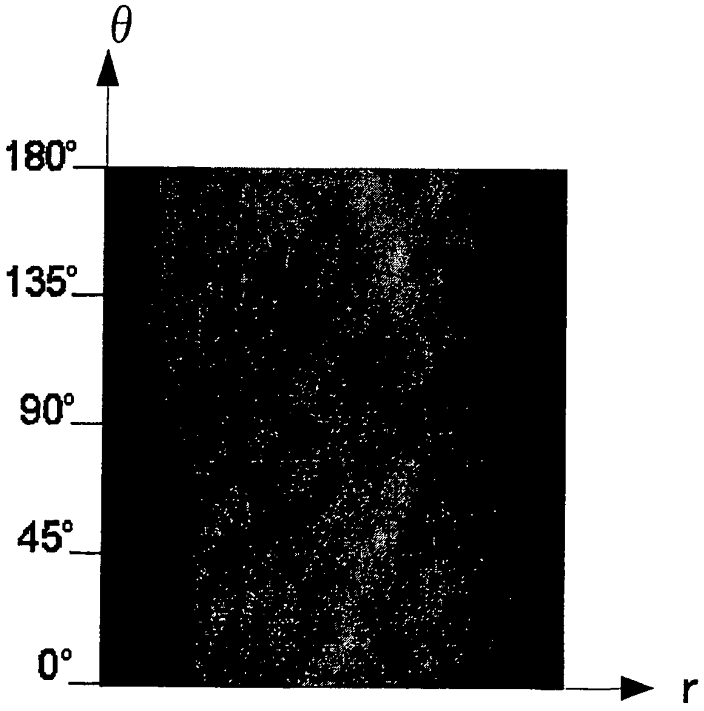
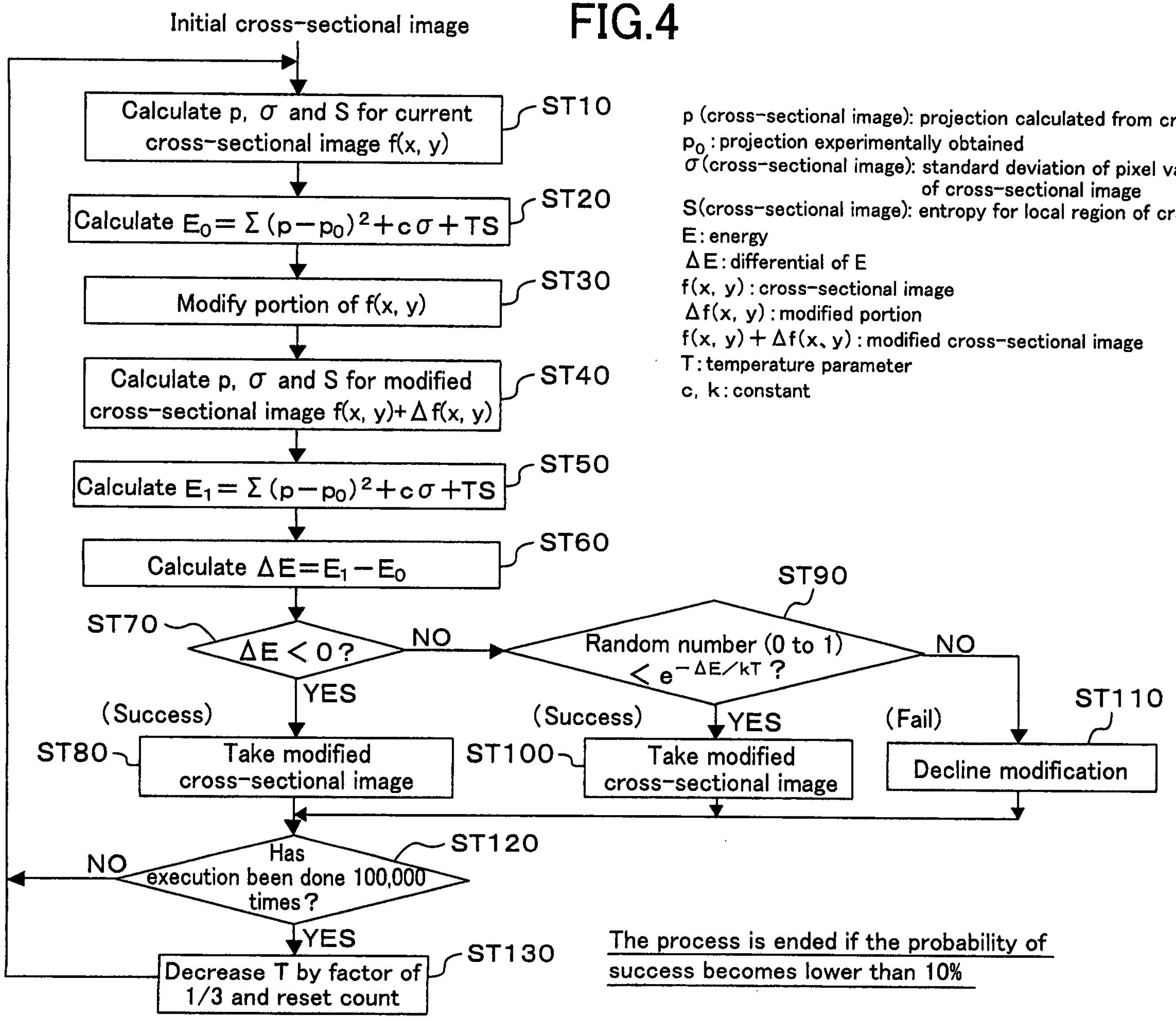


FIG.4



p (cross-sectional image): projection calculated from cross-sectional image
p_0 : projection experimentally obtained
σ(cross-sectional image): standard deviation of pixel values in local region of cross-sectional image
S(cross-sectional image): entropy for local region of cross-sectional image
E : energy
ΔE : differential of E
f(x, y) : cross-sectional image
Δf(x, y) : modified portion
f(x, y) + Δf(x, y) : modified cross-sectional image
T : temperature parameter
c, k : constant

The process is ended if the probability of success becomes lower than 10%

FIG.5

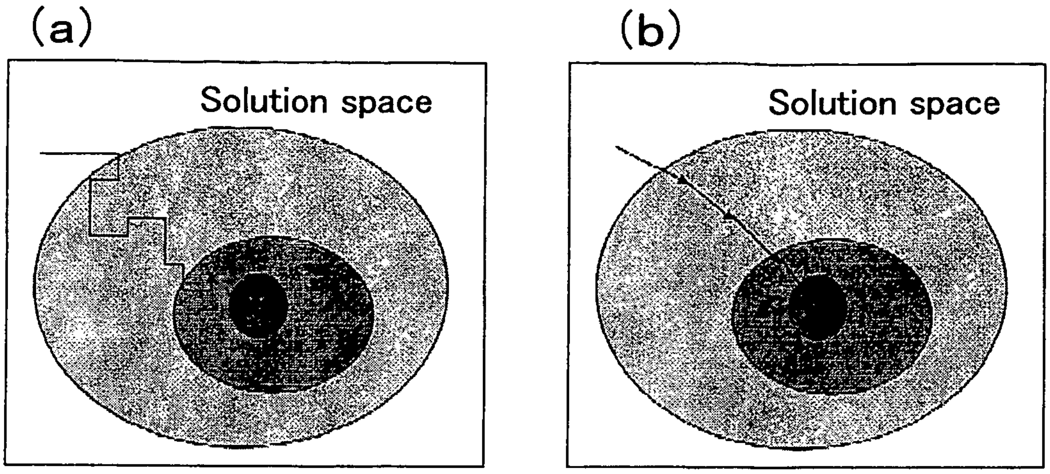


FIG.6

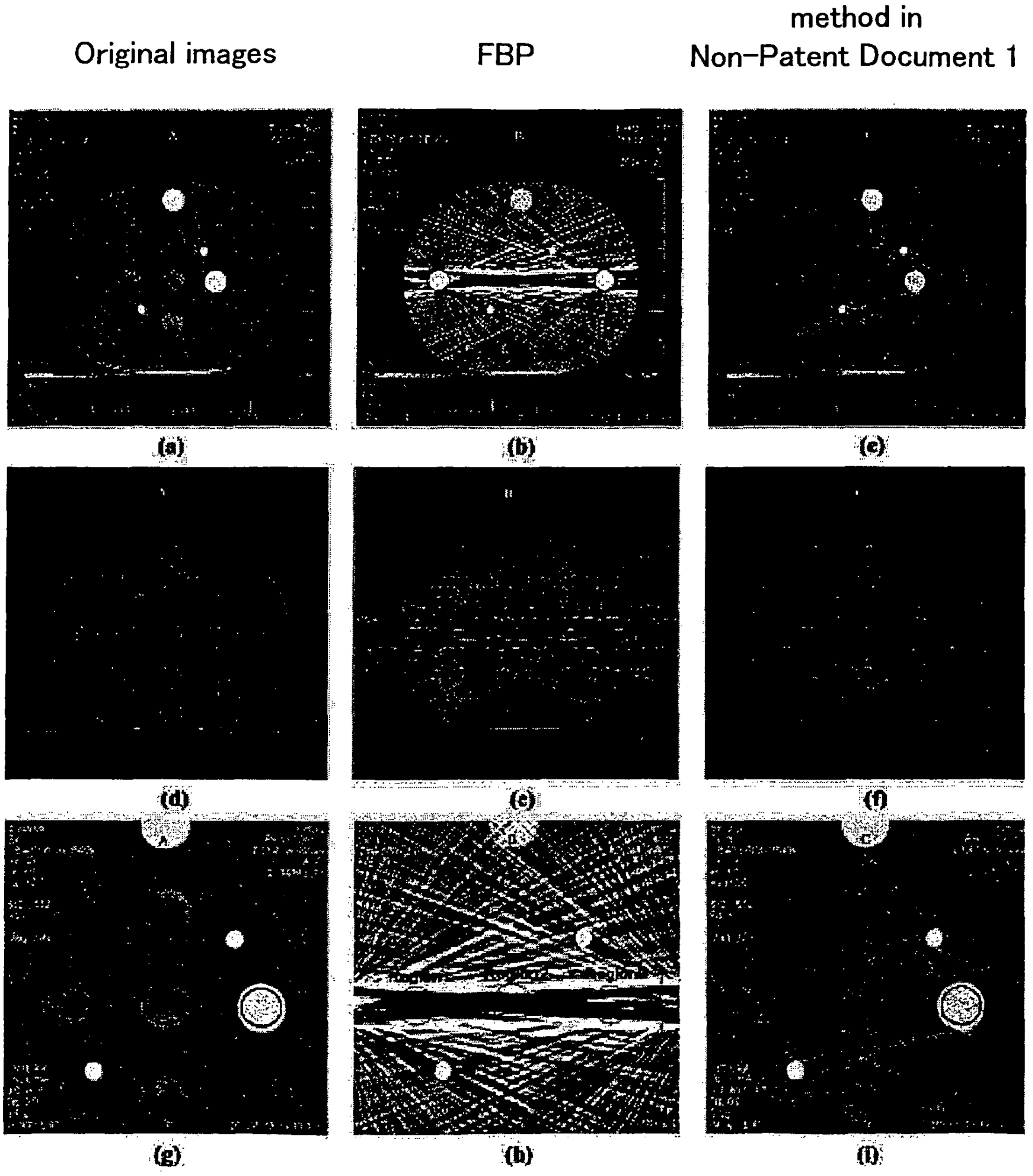


Fig. 5. Phantom test: (a) original phantom image without inserting metallic rods; (b) presence of artifacts because of metallic rods; (c) result of artifact reduction algorithm; (d) result of applying an automatic edge detection algorithm on original phantom image, (e) on phantom image with metallic rods, and (f) on artifact reduction image; (g) computing the mean and SD for three objects in the middle of the phantom in original phantom image, (h) in phantom image with metallic rods, and (i) in artifact reduction image.

FIG.7

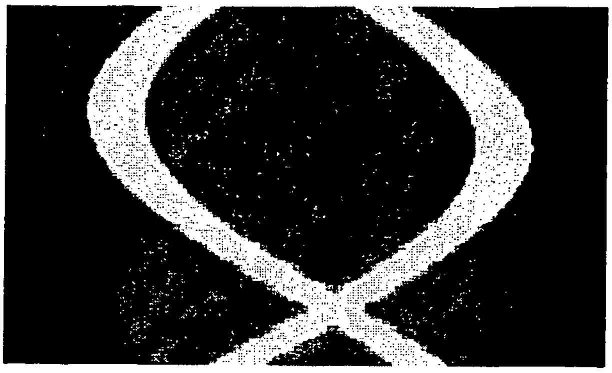
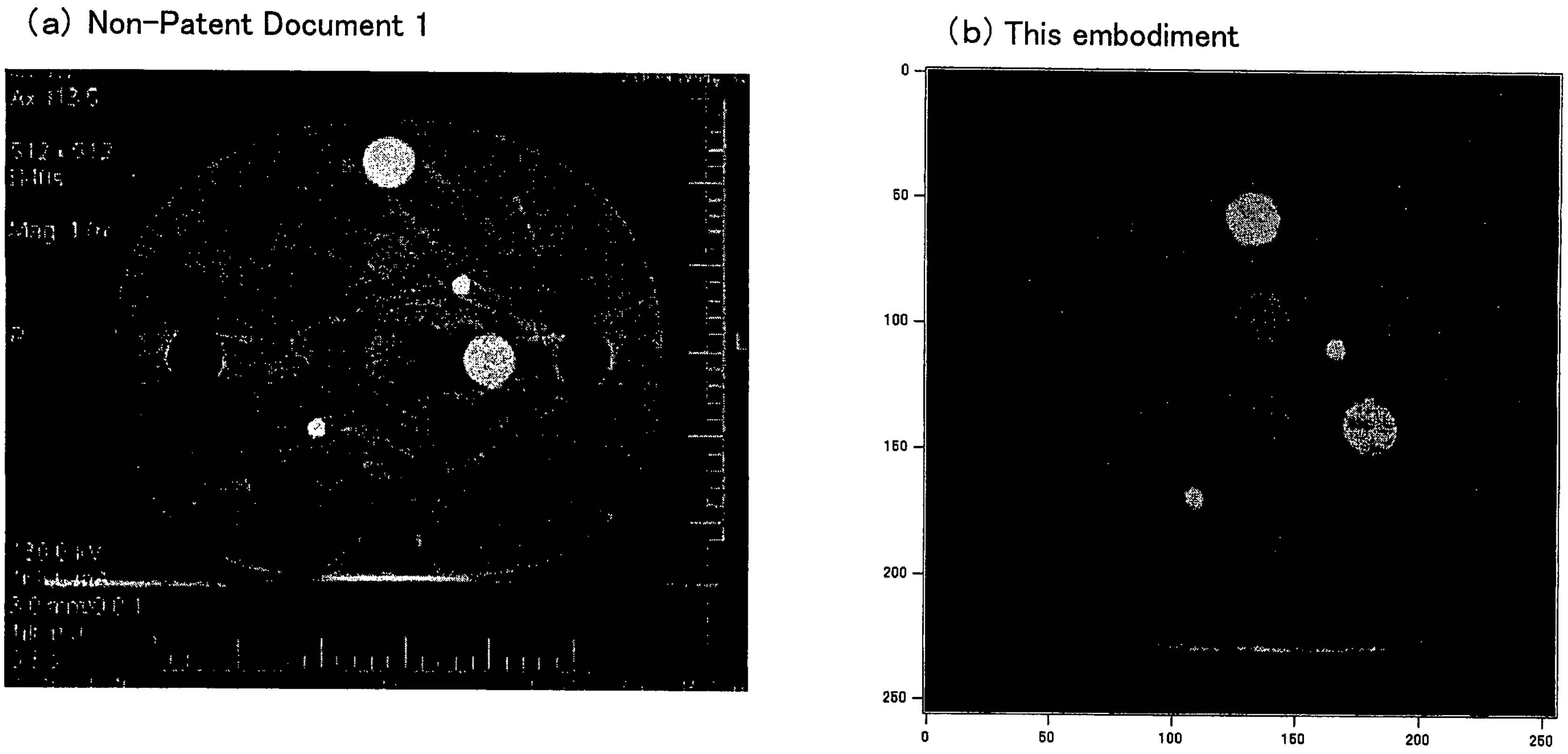
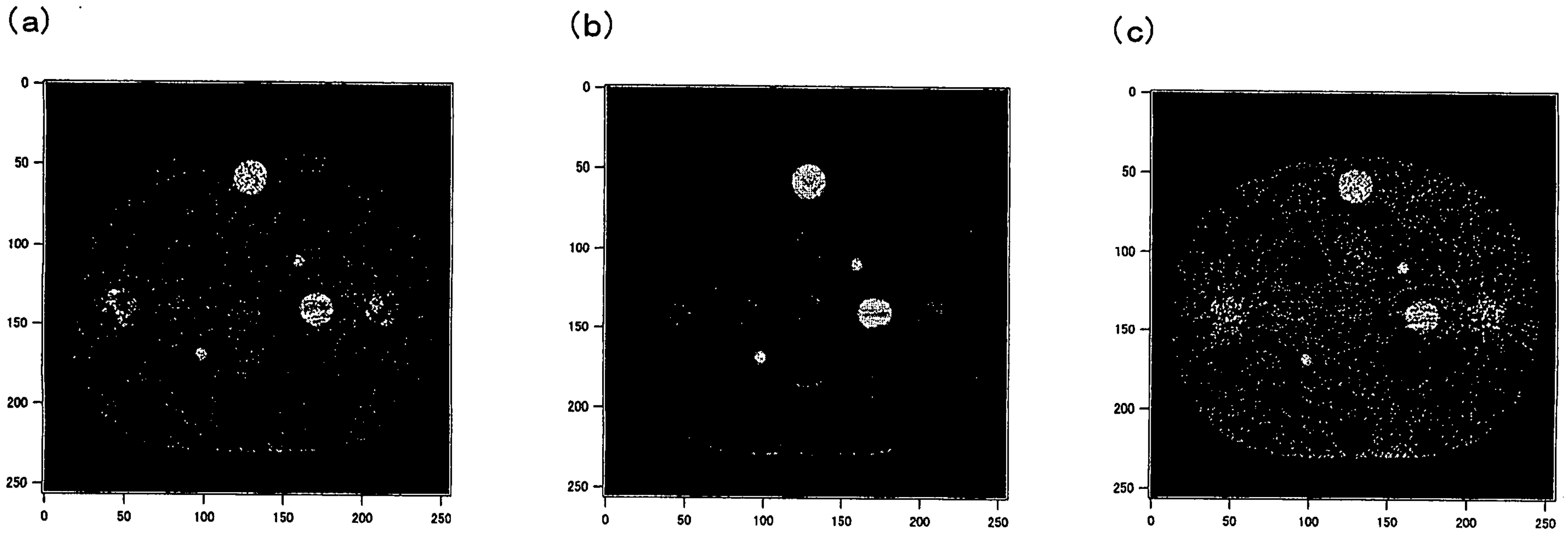


FIG.8


(a) Non-Patent Document 1

(b) This embodiment

FIG.9

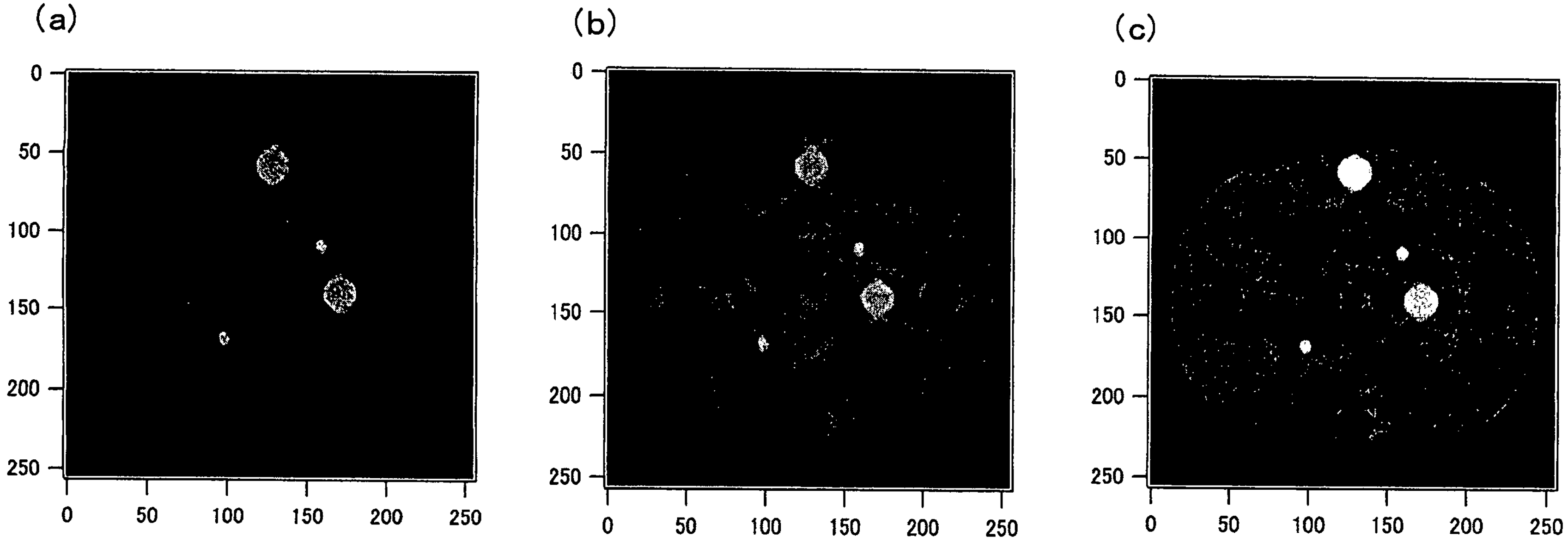


(a) No smoothing term $c\sigma$ (only entropy term TS)

(b) No entropic term TS (only smoothing term $c\sigma$)

(c) No entropic term TS nor smoothing term $c\sigma$

FIG.10



Only FBP (ordinary CT)

ILST applied

This embodiment

REFERENCES CITED IN THE DESCRIPTION

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