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(54) **SYSTEM AND METHOD FOR ESTIMATING A STATISTICAL NOISE MAP IN X-RAY IMAGING APPLICATIONS**

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See application file for complete search history.

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(57) **ABSTRACT**

Described here are a system and method for producing a statistical noise map that indicates the noise present in data acquired with an x-ray imaging system, such as an x-ray computed tomography system, an x-ray tomosynthesis system, a C-arm x-ray imaging system, and so on. In general, an image is reconstructed from the acquired data using, for example, any standard filtered back projection ("FBP") image reconstruction algorithm. This image is used as a base line to estimate a noise standard distribution map. The raw projection data represents a typical measurement among many repeated measurements under the same experimental conditions; therefore, the measured projection data can be used to numerically generate an ensemble of many (e.g., twenty or more) noisy projection data sets. These noisy projection data sets are then used to reconstruct noisy images and from these noisy images and the original image, the statistical noise map can be computed.
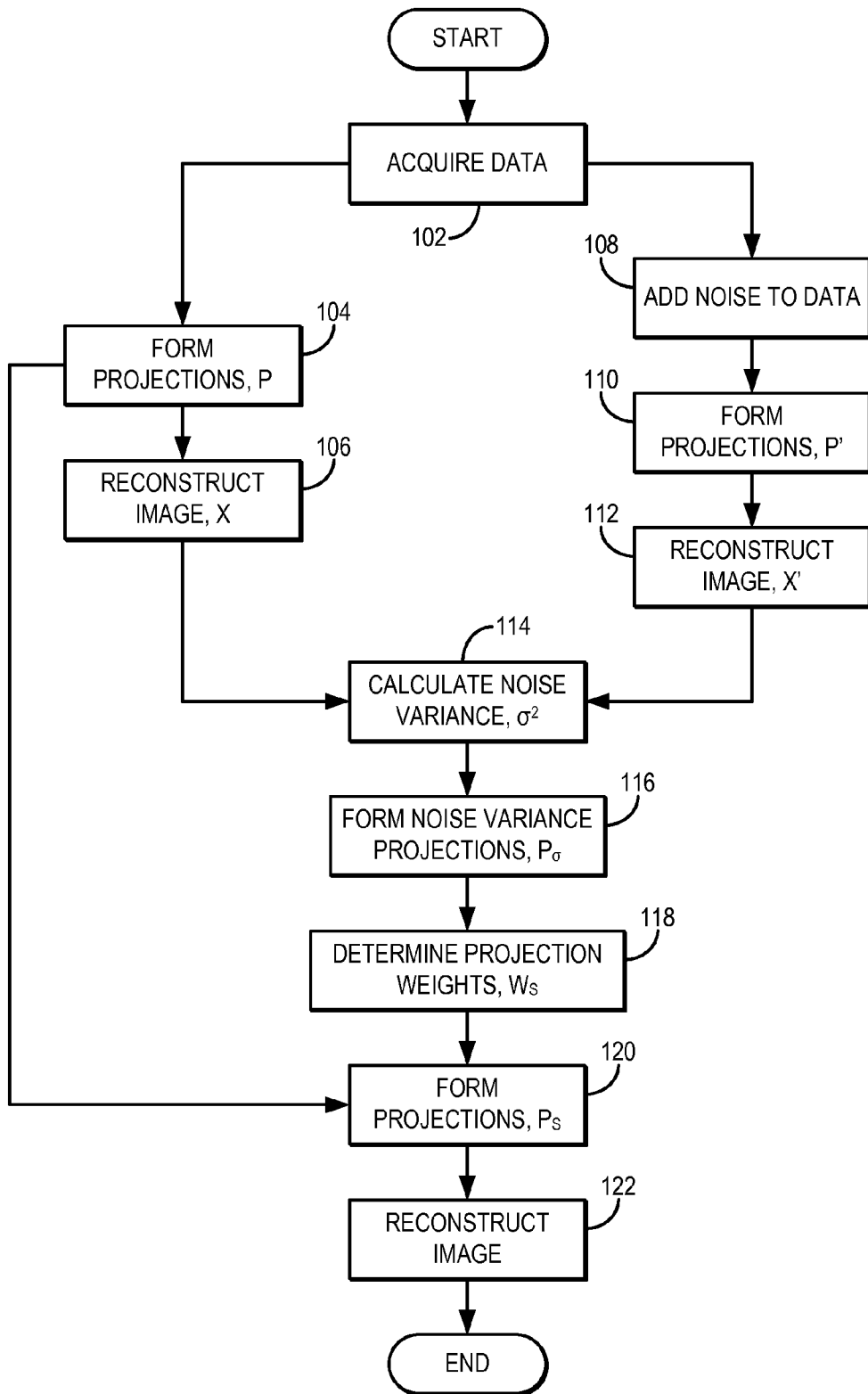
23 Claims, 3 Drawing Sheets
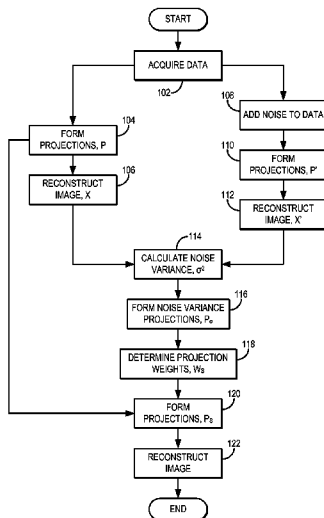
FIG. 1

FIG. 2A

FIG. 2B

FIG. 3A

FIG. 3B

SYSTEM AND METHOD FOR ESTIMATING A STATISTICAL NOISE MAP IN X-RAY IMAGING APPLICATIONS

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

BACKGROUND OF THE INVENTION

The field of the invention is system and methods for x-ray imaging. More particularly, the invention relates to systems and methods for estimating a map of noise statistics in data acquired with an x-ray imaging system such that the noise map can be implemented to account for noise during an iterative image reconstruction.

Iterative image reconstructions, including both algebraic reconstruction and statistical image reconstruction frameworks, have been used for reconstructing high quality tomographic images from severely noise contaminated projection data. It has been known that a statistical weight is critical for great image quality; however, using existing methods for producing noise maps, the data acquisition process must be repeated many times to obtain a good estimate of the statistical noise. This has been a bottleneck for image quality improvement, especially when balanced against the desire to reduce x-ray radiation dose.

It would therefore be desirable to provide a system or method for estimating a statistical noise map that does not require multiple data acquisitions that result in a higher x-ray dose exposure to the imaged subject.

SUMMARY OF THE INVENTION

The present invention overcomes the aforementioned drawbacks by providing a system and method for estimating a statistical noise map from a single x-ray exposure.

It is an aspect of the invention to provide a method for producing a statistical noise map using an x-ray imaging system. Data that indicates a count of photons detected by the x-ray imaging system is acquired, and from this data an image is reconstructed. Noisy data is formed by adding statistical noise to the acquired data. From this noisy data, a noisy image is reconstructed. A statistical noise map is then produced by subtracting the reconstructed image and the noisy image.

It is another aspect of the invention to provide a method for iteratively reconstructing an image of a subject from data acquired with an x-ray imaging system. Data that indicates a count of photons detected by the x-ray imaging system is acquired from a subject, and from this data an image is reconstructed. Noisy data is formed by adding statistical noise to the acquired data. From this noisy data, a noisy image is reconstructed. A statistical noise map is then produced using the reconstructed image and the noisy image. An image of the subject is reconstructed from the acquired data using an iterative image reconstruction that accounts for a physical model of noise in the acquired data by using the produced statistical noise map.

The foregoing and other aspects and advantages of the invention will appear from the following description. In the description, reference is made to the accompanying drawings which form a part hereof, and in which there is shown by way of illustration a preferred embodiment of the invention. Such embodiment does not necessarily represent the full scope of

the invention, however, and reference is made therefore to the claims and herein for interpreting the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a flowchart setting forth the steps of an example of a method for producing a statistical noise map from a single data acquisition and for using that statistical noise map in an iterative image reconstruction;

FIG. 2A is an illustration of an example of an x-ray computed tomography system;

FIG. 2B is a block diagram of the x-ray CT system of FIG. 2A;

FIG. 3A is an illustration of an example of a C-arm x-ray imaging system;

FIG. 3B is a block diagram of the C-arm x-ray imaging system of FIG. 3A.

DETAILED DESCRIPTION OF THE INVENTION

Described here are a system and method for producing a statistical noise map that indicates the noise present in data acquired with an x-ray imaging system, such as an x-ray computed tomography system, an x-ray tomosynthesis system, a C-arm x-ray imaging system, and an on-board imager, such as a cone-beam CT imaging system using in image guided radiation therapy. In general, the method includes reconstructing an image from acquired data using, for example, any standard filtered back projection ("FBP") image reconstruction algorithm. This image is used as a base line to estimate a noise standard distribution map. The raw projection data represents a typical measurement among many repeated measurements under the same experimental conditions; therefore, the measured projection data can be used to numerically generate an ensemble of many (e.g., twenty or more) noisy projection data sets. These noisy projection data sets are then used to reconstruct noisy images, using the same FBP image reconstruction algorithms.

Using these images with added noise, a standard deviation map of the original noise can be generated. This standard deviation map can be generated using a statistical process over the ensemble of noisy images, or can be performed using a statistical process over a spatial region-of-interest using only a single noisy image. After the noise standard deviation map is obtained, a forward projection operation is used to generate the corresponding uncertainty of the projection data.

The system and method of the present invention is capable of producing a statistical noise map from only a single acquisition, thereby reducing the x-ray dose imparted to the subject compared to other noise estimation methods. Using the system and method of the present invention, statistical image reconstruction can also be performed in a new rectified data acquisition geometry that significantly accelerates reconstruction speed.

Referring now to FIG. 1, a flowchart setting forth the steps of an example of a method for producing a statistical noise map from a limited amount of data is illustrated. One advantage of this method is that the subject does not need to be subjected to repeated measurements and thus x-ray exposures in order to obtain the statistical noise map. Rather, only one exposure is necessary. As also illustrated in FIG. 1, this statistical noise map can then advantageously be used in an iterative image reconstruction method.

The method begins with acquiring data with an x-ray system, as indicated at step 102. Preferably, this data is acquired with an x-ray computed tomography system, but may also be acquired using an x-ray tomosynthesis system, a C-arm x-ray

imaging system, or an on-board imaging system in an image guided radiation therapy system. The acquired data is stored as counts of photons impinging on an x-ray detector. As indicated at step **104**, the projections, P, are formed from the acquired data in the traditional sense. From this x-ray projection data, an image, X, is reconstructed, as indicated at step **106**. The image reconstruction performed in step **106** can be performed using any suitable reconstruction technique, such as a simple filtered backprojection.

As indicated at step **108**, the acquired data is also processed by adding noise to the detector counts. By way of example, Poisson noise is added to the acquired data. From the noise-added data, noise-added projections, P', are formed, as indicated at step **110**. From these noise-added projections, a noise-added image, X', is reconstructed, as indicated at step **112**. Like above, this noise-added image can be produced using any suitable image reconstruction method, such as filtered backprojection. Steps **108**-**112** can be repeated to using different Poisson noise statistics in each repetition of step **108** in order to produce a plurality of noise-added images, X'$_i$, with i=1, 2, . . . , N. Alternatively, to reduce the computational burden associated with computing multiple different noise-added images, only one noise-added image, X', can be produced.

The image, X, and the one or more noise-added images, X'$_i$, are then used to estimate the noise variance, σ^2, in the acquired data, as indicated at step **114**. By way of example, a noise distribution map, σ^2 (X, y), can be calculated according to the following equation:

$$\sigma^2(x, y) = \frac{1}{N-1} \sum_{i=1}^{N} (X'_i - X)^2. \tag{1}$$

As another example, the noise distribution map can also be produced by performing a statistical procedure over a spatial region of interest. The latter technique is less computationally burdensome than the averaging process in Eqn. (1), but is also less accurate due to the existence of spatial correlations in the reconstructed images. After the noise distribution map is produced, noise variance projections, P$_\sigma$, can be formed by forward projecting the noise distribution map, as indicated at step **116**. These noise variance projections, P$_\sigma$, indicate the corresponding uncertainty (standard deviation) of the projection data, P, formed in step **104**.

From the generated noise variance projections, P$_\sigma$, projection weights, W$_s$, can be determined, as indicated at step **118**. These projections weights, W$_s$, are defined by a generally monotonically decreasing function that assigns a small weight to data with a high level of uncertainty and a large weight to data with a low level of uncertainty. It is noted that these statistical weights can be obtained for data from any data acquisition geometry, regardless of the specific scanner hardware configuration used to acquire the data in step **102**. This rectification of the data acquisition geometry significantly broadens the applicability of these statistical weights to not only iterative image reconstruction algorithms based on raw projection data, but also to iterative image reconstruction algorithms that are based in the image domain, as will be described below.

One example form of the statistical projection weights is as follows:

$$W_s = W_{s,min} + \left(\frac{P_{\sigma,max} - P_\sigma}{P_{\sigma,max} - P_{\sigma,min}} \right)^2 \cdot (W_{s,max} - W_{s,min}); \tag{2}$$

where W$_{s,min}$ is the value of the weight that corresponds to the smallest uncertainty in the data; W$_{s,max}$ is the value of the weight that corresponds to the highest uncertainty in the data; P$_\sigma$ is a value of the noise variance projection; P$_{\sigma,min}$ is the minimum value of the noise variance projections; and P$_{\sigma,max}$ is the maximum value of the noise variance projections. Another example form of the statistical projection weights is as follows:

$$W_s = e^{-2\left(\frac{P_\sigma - P_{\sigma,min}}{P_{\sigma,max} - P_{\sigma,min}} \right)}. \tag{3}$$

The calculated projection weights, W$_s$, can then be used to form weighted projections by applying the weights to the projections formed in step **104**, as indicated at step **120**. These weighted projections can then be used in an iterative image reconstruction method to reconstruct an image of the subject, as indicated at step **122**. By way of example, the image reconstruction performed in step **122** can be an iterative image reconstruction technique that operates in projection space using the true experimental data pertinent to a specific hardware data acquisition system, or an iterative reconstruction technique that operates in synthetic projection space that is generated from an initially reconstructed image via a forward projection step. The latter scheme does not depend on the original hardware data acquisition scheme. By way of example, the forward projection step can be used to rectify the original data acquisition method into the simplest parallel beam data acquisition geometry in order to simplify the image reconstruction. In those instances, the present invention enables an image denoising process to be incorporated into the image reconstruction process, thereby allowing the preservation of spatial resolution during the denoising process. By way of example, the spatial resolution of the original image can be encoded into the synthetics projection data. The iterative reconstruction can then be designed with an appropriate selection of regularization such that noise is lowered in the reconstructed images while iteratively restoring the spatial resolution of the target image from the high resolution synthetic projection data. An example of such an approach is a prior image constrained compressed sensing method, such as those described in U.S. Pat. Nos. 8,194,937; 8,229,199; and 8,374,413, which are each herein incorporated by reference in their entirety.

With initial reference to FIGS. 2A and 2B, an x-ray computed tomography ("CT") imaging system **200** that may be used when practicing the present invention includes a gantry **202**. The gantry **202** has an x-ray source **204** that projects a fan-beam, or cone-beam, of x-rays **206** toward a detector array **208** on the opposite side of the gantry **202**. The detector array **208** is formed by a number of detector elements **210**, which together sense the projected x-rays **206** that pass through a subject **212**, such as a medical patient or an object undergoing examination. Each detector element **210** produces an electrical signal that represents the intensity of an impinging x-ray beam and, hence, the attenuation of the beam as it passes through the subject **212**. During a scan to acquire x-ray projection data, the gantry **202** and the components mounted thereon rotate about a center of rotation **214** located within the subject **212**.

The rotation of the gantry **202** and the operation of the x-ray source **204** are governed by a control mechanism **216** of the CT system **200**. The control mechanism **216** includes an x-ray controller **218** that provides power and timing signals to the x-ray source **204**, and a gantry controller **220** that controls the rotational speed and position of the gantry **202**. A data acquisition system ("DAS") **222** in the control mechanism **216** samples data from the detector elements **210** and converts the data to digital signals for subsequent processing. An image reconstructor **224**, receives sampled and digitized x-ray data from the DAS **222** and performs image reconstruction thereon. The reconstructed image is applied as an input to a computer **226** which stores the image in a storage device **228**, such as a mass storage device.

The computer **226** also receives commands and scanning parameters from an operator via a console **230** that has a keyboard. An associated display **232** allows the operator to observe the reconstructed image and other data from the computer **226**. The operator supplied commands and parameters are used by the computer **226** to provide control signals and information to the DAS **222**, the x-ray controller **218**, and the gantry controller **220**. In addition, computer **226** operates a table controller **234** that controls a table **236** to position the subject **212** in the gantry **202**.

Referring particularly to FIGS. **3A** and **3B**, an example of a so-called "C-arm" x-ray imaging system **300** is illustrated. Such an imaging system **300** is generally designed for use in connection with interventional procedures. The imaging system **300** is characterized by a gantry having a C-arm **302** that carries an x-ray source assembly **302** on one of its ends and an x-ray detector array assembly **306** at its other end. The gantry enables the x-ray source assembly **303** and detector array assembly **306** to be oriented in different positions and angles around a patient disposed on a table **308**, while enabling a physician access to the patient.

The gantry includes a support base **310**, which may include an L-shaped pedestal that has a horizontal leg **312** that extends beneath the table **308** and a vertical leg **314** that extends upward at the end of the horizontal leg **312** that is spaced from of the table **308**. A support arm **316** is rotatably fastened to the upper end of vertical leg **314** for rotation about a horizontal pivot axis **318**. The pivot axis **318** is aligned with the centerline of the table **308** and the support arm **316** extends radially outward from the pivot axis **318** to support a C-arm drive assembly **320** on its outer end. The C-arm **302** is slidably fastened to the drive assembly **320** and is coupled to a drive motor (not shown) that slides the C-arm **302** to revolve it about a C-axis **322**, as indicated by arrows **324**. The pivot axis **318** and C-axis **322** intersect each other at an isocenter **326** that is located above the table **308** and they are perpendicular to each other.

The x-ray source assembly **304** is mounted to one end of the C-arm **302** and the detector array assembly **306** is mounted to its other end. As will be discussed in more detail below, the x-ray source assembly **304** includes an x-ray source (not shown) that emits a cone beam of x-rays, which are directed at the detector array assembly **306**. Both assemblies **304** and **306** extend radially inward to the pivot axis **318** such that the center ray of this cone beam passes through the system isocenter **326**. The center ray of the cone beam can, thus, be rotated about the system isocenter **326** around either the pivot axis **318**, the C-axis **322**, or both during the acquisition of x-ray attenuation data from a subject placed on the table **308**.

As mentioned above, the x-ray source assembly **304** contains an x-ray source that emits a cone beam of x-rays when energized. The center ray passes through the system isocenter

326 and impinges on a two-dimensional flat panel digital detector housed in the detector assembly **306**. Examples of flat panel detectors include so-called "small flat panel" detectors, in which the detector array panel is around 20×20 centimeters in size. Such a detector panel allows the coverage of a field-of-view of around twelve centimeters. Each detector element produces an electrical signal that represents the intensity of an impinging x-ray and, hence, the attenuation of the x-ray as it passes through the patient. During a scan, the x-ray source and detector array are rotated about the system isocenter **326** to acquire x-ray attenuation projection data from different angles. By way of example, the detector array is able to acquire thirty projections, or views, per second. Generally, the numbers of projections acquired per second is the limiting factor that determines how many views can be acquired for a prescribed scan path and speed.

Referring particularly to FIG. **3B**, the rotation of the assemblies **304** and **306** and the operation of the x-ray source are governed by a control mechanism **328** of the imaging system **300**. The control mechanism **328** includes an x-ray controller **330** that provides power and timing signals to the x-ray source. A data acquisition system ("DAS") **332** in the control mechanism **328** samples data from detector elements in the detector array and passes the data to an image reconstructor **334**. The image reconstructor **334**, receives digitized x-ray data from the DAS **332** and performs image reconstruction. The image reconstructed by the image reconstructor **334** is applied as an input to a computer **336**, which stores the image in a mass storage device **338** or processes the image further.

The control mechanism **328** also includes pivot motor controller **340** and a C-axis motor controller **342**. In response to motion commands from the computer **336**, the motor controllers **340** and **342** provide power to motors in the imaging system **300** that produce the rotations about the pivot axis **318** and C-axis **322**, respectively. A program executed by the computer **336** generates motion commands to the motor controllers **340** and **342** to move the assemblies **304** and **306** in a prescribed scan path.

The computer **336** also receives commands and scanning parameters from an operator via a console **344** that has a keyboard and other manually operable controls. An associated display **346** allows the operator to observe the reconstructed image and other data from the computer **336**. The operator supplied commands are used by the computer **336** under the direction of stored programs to provide control signals and information to the DAS **332**, the x-ray controller **330**, and the motor controllers **340** and **342**. In addition, the computer **336** operates a table motor controller **348**, which controls the patient table **308** to position the patient with respect to the system isocenter **326**.

The present invention has been described in terms of one or more preferred embodiments, and it should be appreciated that many equivalents, alternatives, variations, and modifications, aside from those expressly stated, are possible and within the scope of the invention.

The invention claimed is:

1. A method for producing a statistical noise map using an x-ray imaging system, the steps of the method comprising:
   a) acquiring data with the x-ray imaging system, the acquired data indicating a count of photons detected by the x-ray imaging system;
   b) reconstructing an image from the data acquired in step a);
   c) forming noisy data by adding statistical noise to the data acquired in step a);

d) reconstructing a noisy image from the noisy data formed in step c); and

e) producing a statistical noise map by subtracting the image reconstructed in step b) and the noisy image reconstructed in step d).

2. The method as recited in claim **1** in which the noisy data formed in step c) comprises a plurality of noisy data sets, each noisy data set being formed by adding different statistical noise to the data acquired in step a).

3. The method as recited in claim **2** in which step d) includes reconstructing a plurality of noisy images from the noisy data, each noisy image being reconstructed from a corresponding noisy data set.

4. The method as recited in claim **3** in which step e) includes producing a plurality of statistical noise maps that each depict substantially only noise, each statistical noise map being produced by subtracting one of the plurality of noisy images reconstructed in step d) from the image reconstructed in step b).

5. The method as recited in claim **4** further comprising calculating a noise variance from the plurality of statistical noise maps produced in step e).

6. The method as recited in claim **5** in which the noise variance is calculated by calculating an average of a sum of squares calculated using the image reconstructed in step b) and each of the plurality of noisy images.

7. The method as recited in claim **6** in which the average of a sum of squares is calculated according to:

$$\frac{1}{N-1}\sum_{i=1}^{N}(X_i' - X)^2;$$

wherein N is a number of the plurality of noisy images, X_i' is one of the plurality of noisy images, and X is the image reconstructed in step b).

8. The method as recited in claim **1** further comprising calculating weighting factors from the statistical noise map, the weighting factors indicating weighting values that when applied to the data acquired in step a) reduce contributions of noise in the acquired data.

9. The method as recited in claim **8** in which the weighting factors are calculated by producing noise variance projections by forward projecting the statistical noise map produced in step e) and fitting the noise variance projections to a weighting function.

10. The method as recited in claim **9** in which the weighting function is a monotonically decreasing function that assigns a lower weight to high noise data and a higher weight to lower noise data.

11. The method as recited in claim **1** in which the x-ray imaging system is at least one of an x-ray computed tomography system, an x-ray tomosynthesis system, a C-arm x-ray imaging system, and an on-board imaging system that forms a part of an image guided radiation therapy system.

12. The method as recited in claim **1** further comprising reconstructing an image from the data acquired in step a) using an iterative image reconstruction that accounts for a physical model of noise in the acquired data by using the statistical noise map produced in step e).

13. A method for iteratively reconstructing an image of a subject from data acquired with an x-ray imaging system, the steps of the method comprising:

a) acquiring data form the subject with the x-ray imaging system, the acquired data indicating a count of photons detected by the x-ray imaging system;

b) reconstructing an image from the data acquired in step a);

c) forming noisy data by adding statistical noise to the data acquired in step a);

d) reconstructing a noisy image from the noisy data formed in step c);

e) producing a statistical noise map using the image reconstructed in step b) and the noisy image reconstructed in step d); and

f) reconstructing an image of the subject from the data acquired in step a) using an iterative image reconstruction that accounts for a physical model of noise in the acquired data by using the statistical noise map produced in step e).

14. The method as recited in claim **13** in which the noisy data formed in step c) comprises a plurality of noisy data sets, each noisy data set being formed by adding different statistical noise to the data acquired in step a).

15. The method as recited in claim **14** in which step d) includes reconstructing a plurality of noisy images from the noisy data, each noisy image being reconstructed from a corresponding noisy data set.

16. The method as recited in claim **15** in which step e) includes producing a plurality of statistical noise maps that each depict substantially only noise, each of the plurality of statistical noise maps being produced by subtracting one of the plurality of noisy images reconstructed in step d) from the image reconstructed in step b).

17. The method as recited in claim **16** in which step e) includes producing the statistical noise map by calculating an average of a sum of squares according to:

$$\frac{1}{N-1}\sum_{i=1}^{N}(X_i' - X)^2;$$

wherein N is a number of the plurality of noisy images, X_i' is one of the plurality of noisy images, and X is the image reconstructed in step b).

18. The method as recited in claim **13** further comprising calculating weighting factors from the statistical noise map, the weighting factors that when applied to the data acquired in step a) reduce contributions of noise in the acquired data.

19. The method as recited in claim **18** in which the weighting factors are calculated by producing noise variance projections by forward projecting the statistical noise map produced in step e) and fitting the noise variance projections to a weighting function.

20. The method as recited in claim **19** in which the weighting function is a monotonically decreasing function that assigns a lower weight to high noise data and a higher weight to lower noise data.

21. The method as recited in claim **19** in which the noise variance projections are formed by forward projecting the statistical noise map onto a different acquisition geometry than was used to acquire the data in step a).

22. The method as recited in claim **18** in which step f) includes forming noise-suppressed projections by applying the weighting factors to the data acquired in step a) and reconstructing the image of the subject using the noise-suppressed projections.

23. The method as recited in claim **13** in which the x-ray imaging system is at least one of an x-ray computed tomography system, an x-ray tomosynthesis system, a C-arm x-ray

imaging system, and an on-board imaging system that forms a part of a radiation therapy system.

*   *   *   *   *