(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
28 November 2013 (28.11.2013)

WIPO | PCT

(10) International Publication Number
WO 2013/175352 A1

(51) International Patent Classification: *G06T 11/00* (2006.01)

(21) International Application Number: PCT/IB2013/053965

(22) International Filing Date: 15 May 2013 (15.05.2013)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/649,825 21 May 2012 (21.05.2012) US
61/658,049 11 June 2012 (11.06.2012) US

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

[Continued on next page]

(54) Title: FAST SCATTER ESTIMATION IN PET RECONSTRUCTION.

(57) Abstract: An image processing apparatus includes a scatter simulation processor which processes measured sinograms generated from imaging data acquired for an imaging subject by an imaging apparatus to produce a scatter sinogram that represents a shape of scatter contribution. A scatter scaling processor utilizesa Monte Carlo simulation to determine a scatter fraction and scales the scatter sinogram to generate a scaled scatter sinogram that matches the scatter contribution in the measured sinogram. A reconstruction processor reconstructs the imaging data into an image representation using the scaled scatter sinogram for scatter correction.

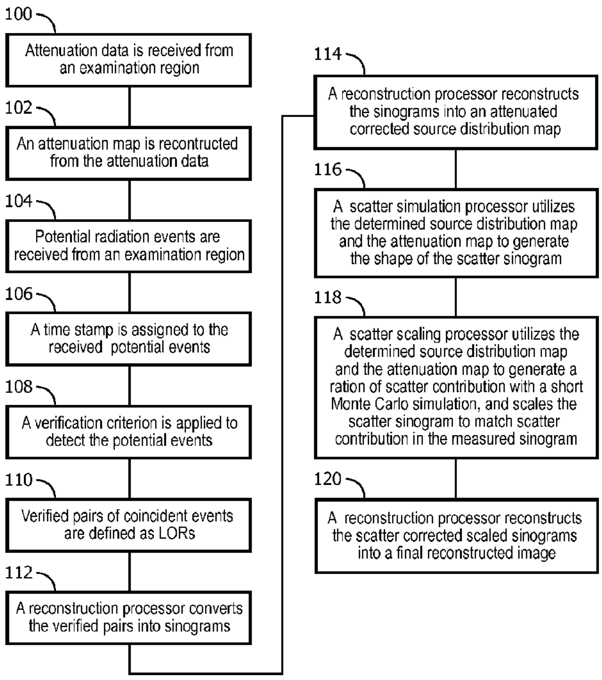


FIG. 5

WO 2013/175352 A1

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

Published:

— *with international search report (Art. 21(3))*

FAST SCATTER ESTIMATION IN PET RECONSTRUCTION

The present application relates to the diagnostic imaging arts. It finds particular application in accelerating the estimation of scatter in a nuclear medicine scanner, and will be described with particular reference thereto. It is to be understood, however, that it also finds application in other usage scenarios, and is not necessarily limited to the aforementioned application.

In nuclear medicine imaging scanners, e.g. positron emission tomography (PET) scanners, typically 30% or more detected coincidence events encounter scattering at least once during imaging. Accurate estimation of the amount of scatter is significant in nuclear medicine image reconstruction. Most commercial PET image reconstruction utilizes a single-scatter simulation (SSS) method to estimate the scatter contribution. The method is accurate when majority of scattered events are of single scattering. However, when a patient is larger, multiple scattering may contribute to large portion of all the scattered events. Therefore, SSS is no longer accurate. However, it has been shown through Monte Carlo simulations that the overall shape of scatter contribution does not change significantly with the addition of multiple scatters. Therefore, the SSS should be scaled to compensate for the contribution from multiple scattering.

In PET image reconstruction, a typical method to estimate the scaling factor for SSS is fitting the "tail" part of a SSS sinogram to the measured sinogram, where tail refers to the portion in the sinogram corresponding to the outside of the imaged object. In the method, it is assumed that the tail part in the measured data includes only contributions from scattered events. This assumption is valid for smaller patients when the tail is available and includes enough counts in it. However, when scanning a larger patient, the tail part decreases in size or disappears (truncated). In the case of the tail part being a smaller size or disappearing, fitting the tail can have significant error. As seen in Figure 1, the resulting image **2** typically suffers from scatter over-subtraction near high concentration areas **4** for a large patient.

Another approach for accurate scatter estimation is to perform a full Monte Carlo simulation to produce shapes of both primary and scatter contributions. It demands significant amount of computations and therefore is too slow for a commercial nuclear medicine imaging system.

The present application provides new and improved methods and systems which overcome the above-referenced problems and others.

In accordance with one aspect, an image processing apparatus is provided. The image processing apparatus a scatter simulation processor which processes measured sinograms generated from imaging data acquired for an imaging subject by an imaging apparatus to produce a scatter sinogram that represents a shape of scatter contribution. A scatter scaling processor utilizes a Monte Carlo simulation to determine a scatter fraction and scales the scatter sinogram to generate a scaled scatter sinogram that matches the scatter contribution in the measured sinogram. A reconstruction processor reconstructs the imaging data into an image representation using the scaled scatter sinogram for scatter correction.

In accordance with another aspect, a method of image processing is provided. The method of image processing including processing measured sinograms generated from imaging data acquired for an imaging subject by an imaging apparatus, producing a scatter sinogram that represents a shape of scatter contribution, determining a scatter fraction and scaling the scatter sinogram to generate a scaled scatter sinogram that matches the scatter contribution in the measured sinogram, and reconstructing the imaging data into an image representation using the scaled scatter sinogram for scatter correction.

In accordance with another aspect, a method of image processing is provided. The method of image processing including with a PET scanner, generating a plurality of events, utilizing SSS and a short Monte Carlo simulation to determine the probability for a detected event pair having encountered scattering, and reconstructing the plurality of generated events into an image representation.

One advantage resides in more accurate estimation of scatter contribution in nuclear medicine scanners.

Another advantage resides in quicker estimation of scatter in nuclear medicine scanners.

Another advantage resides in improved image quality and quantitative accuracy for nuclear medicine scanners.

Another advantage resides in scatter contribution estimation utilizing short Monte Carlo simulations.

Another advantage resides in eliminating tail fitting in scatter contribution estimation.

Another advantage resides in quicker image reconstruction.

Another advantage resides in improved subject throughput.

Still further advantages of the present invention will be appreciated to those of ordinary skill in the art upon reading and understand the following detailed description.

The invention may take form in various components and arrangements of components, and in various steps and arrangements of steps. The drawings are only for purposes of illustrating the preferred embodiments and are not to be construed as limiting the invention.

FIGURE 1 is an exemplary prior art PET image reconstruction with SSS scatter estimation utilizing tail fitting.

FIGURE 2 is an exemplary PET image reconstruction with SSS scatter estimation utilizing Monte Carlo simulation scaling in accordance with the present application.

FIGURE 3 is a diagrammatic illustration of an imaging system in accordance with the present application.

FIGURE 4 is a diagrammatic illustration of the comparison of profiles from measures and simulated data in accordance with the present application.

FIGURE 5 is a flowchart illustration of a method of image processing in accordance with the present application.

The present invention utilizes Monte Carlo simulations to quickly derive the ratio among primary and scattered photon pairs in measured PET data for each specific patient. The Monte Carlo simulation is based on the source distribution and attenuation map. The derived ratio is used to scale the sinogram generated from the single-scatter simulation (SSS) so that the scaled sinogram closely approximates the total scatter in the measured sinogram. As seen in Figure 2, the resulting image **6** reconstructed using SSS with scaling factor derived from a short Monte Carlo simulation eliminates the scanner over-subtraction problem seen in Figure 1. Additionally, since only the ratio is needed, there is no need to simulate large amount of events in the Monte Carlo simulation, and therefore the additional computation time needed is limited. In this way, more accurate scatter correction in PET reconstruction is performed for all different sizes of imaged object without a significant increase in computation time.

With reference to FIGURE 3, a multi-modality system **10** includes a first imaging system, e.g. a functional modality, preferably, a nuclear imaging system **12**, and a second imaging system, e.g. an anatomical modality, such as a computed tomography (CT) scanner **14**. The CT scanner **14** includes a non-rotating gantry **16**. An x-ray tube **18** is mounted to a rotating gantry **20**. A bore **22** defines an examination region **24** of the CT scanner **14**. An array of radiation detectors **26** is disposed on the rotating gantry **20** to receive radiation from the x-ray tube **18** after the x-rays transverse the examination region **24**. Alternatively, the array of detectors **26** may be positioned on the non-rotating gantry **16**. Of course, magnetic resonance and other imaging modalities are also contemplated.

The functional or nuclear imaging system **12**, in the illustrated embodiment, includes a positron emission tomography (PET) scanner **30** which may mounted on tracks **32** to facilitate patient access. Of course, SPECT, CT, nuclear medicine imaging, function magnetic resonance imaging (fMRI), and other imaging modalities are also contemplated. The tracks **32** extend in parallel to a longitudinal axis of a subject support or couch **34**, thus enabling the CT scanner **14** and PET scanner **12** to form a closed system. A motor and drive **36**, is provided to move the PET scanner **12** in and out of the closed position. Detectors **38** are arranged around a bore **40** which defines an examination region **42**. In the illustrated PET system, the detectors **38** are arranged in a stationery ring, although rotatable heads are also contemplated. In the SPECT system, the detectors **38** are typically incorporated into individual heads, which are mounted for rotational and radial movement relative to the patient. A motor and drive **44** or the like, provides a longitudinal movement and vertical adjustment of the subject support **34** in the examination regions **24**, **42**. Mounted CT and PET systems in a single, shared close system with a common examination region is also contemplated.

With continued reference to FIGURE 3, the subject support **34**, which carries a subject, is moved into the examination region **24** of the CT scanner **14**. The CT scanner **14** generates radiation attenuated data which is then used by an attenuation reconstruction processor **60** to reconstruct the radiation attenuated data into an attenuation map that is stored in an attenuation map memory **62**.

The patient support **34** moves the subject into the PET scanner **12** in a position that is geometrically and mechanically predicated as being the same as the imaged position in the CT imaging region **24**. Before the PET scan commences, a subject is injected with a radiopharmaceutical. In PET scanning, a pair of gamma rays is produced by a positron annihilation event in the examination region **42** and travel in opposite directions. When the gamma ray strikes the detectors **38**, the location of the struck detector element and the strike time are recorded. A triggering processor **52** monitors each detector **38** for an energy spike, e.g., integrated area under the pulse, characteristic of the energy of the gamma rays generated by the radiopharmaceutical. From the energy or integrated area, each event is identified as an unscattered or scattered event. The triggering processor **52** checks a clock **54** and time stamps each detected gamma ray with a time of leading edge receipt stamp. In PET imaging, the time stamp, energy estimate and detector position estimation are first used by an event verification processor **56** to determine whether there is a coincident event. Accepted pairs of coincident events define lines of response (LORs). Once an event pair is verified by the event verification processor **56**, the LOR is passed to an event storage buffer **58** with their time stamps and stored in a list in the event storage buffer **58** as event data, i.e. as list-mode data.

A sinogram reconstruction processor **64** reconstructs the verified pairs into an image representation of the subject. In one embodiment, the sinogram reconstruction processor **64** converts the verified pairs into sinograms and accesses the attenuation data stored in the attenuation map memory **62** and reconstructs the sinograms into attenuation corrected source distribution map. The attenuation corrected source distribution map is stored in a source map memory **66**. It is also contemplated that other reconstruction algorithms may be used including algorithms operating directly with the list-mode data such as list-mode ordered subsets expectation maximization (OSEM), and list-mode reconstruction with time-of-flight (TOF) reconstruction, etc.

A scatter simulation processor **68** utilizes the determined source distribution map and the attenuation map to generate the shape of the scatter sinogram. A scatter scaling processor **72** also utilizes the determined source distribution map and the attenuation map to generate a ratio of scatter contribution with a short Monte Carlo simulation. In one embodiment, the Monte Carlo simulation is performed until the calculated ratio stabilizes. Once the ratio is stable, the Monte Carlo simulation can be terminated to reduce processing time. The SSS sinogram is scaled to define a scaled scatter sinogram. A reconstruction processor **74** utilizes scaled scatter sinogram and reconstructs the event pairs into a final reconstructed image with attenuation and scatter correction. The final reconstructed image is stored in an image memory **76** and displayed for a user on a display device **78**, printed, saved for later use, and the like.

Specifically, the measured event data (after random correction) includes primary and scattered coincidence events. The single-scatter simulation (SSS) in scatter simulation processor **68** models single scattering from a given source distribution and the corresponding attenuation map. The scatter scaling processor **72** determines a scale factor with Monte Carlo simulation using the source distribution and the corresponding attenuation map. In the Monte Carlo simulation plurality of photon pairs are generated according to the source distribution. The trajectory of each photon in the attenuation map is traced until the photon escapes from the imaged object. The escaped photon may hit a detector and therefore is detected. A coincidence event is registered if both photons from a positron annihilation are detected. The event is labeled as primary if neither of the photons encountered scattering. The event is labeled as scattered if one or both of the photons have encountered one or more Compton scatterings in the attenuation medium. The ratio of total detected scattered events and total detected events represents the scatter fraction. The scatter fraction changes with number of positron annihilations and eventually stabilizes to a certain value r_{sc}. The scatter fraction obtained from the Monte Carlo simulation is a good approximation of the actual scatter fraction in the measured coincidence events. A scaling factor for SSS sinogram is then obtained by the following formula:

$$k = r_{sc} * T_{measured}/T_{SSS} \quad (1),$$

where $T_{measured}$ is the total counts in the measured sinogram and T_{SSS} is the total counts in the SSS sinogram. The SSS sinogram is scaled by k to produce an estimated scatter sinogram. The reconstruction processor **74** utilizes the scaled SSS sinogram and reconstructs the final reconstructed image.

Illustrated in Figure 4 are the line profiles **80** from the sinograms obtained from the measured data (after random correction), Monte Carlo simulated data, Monte Carlo simulated scattering data, and SSS scattering data after scaled using the scaling factor described above. As shown, (1) the Monte Carlo simulation result matches the measured data and (2) the SSS simulation matches with the total scatter derived from Monte Carlo simulation.

The triggering processor **52,** event verification processor **56,** attenuation reconstruction processor **60**, sinogram reconstruction processor **64**, scatter simulation processor **68**, and scatter scaling processor **72** include a processor, for example a microprocessor or other software controlled device configured to execute software for performing the operations described above. Typically, the software is carried on tangible memory or a computer readable medium for execution by the processor. Types of computer readable media include memory such as a hard disk drive, CD-ROM, DVD-ROM and the like. Other implementations of the processor are also contemplated. Display controllers, Application Specific Integrated Circuits (ASICs), FPGAs, and microcontrollers are illustrative examples of other types of component which may be implemented to provide functions of the processor. Embodiments may be implemented using software for execution by a processor, hardware, or some combination thereof.

FIGURE 5 illustrates a method of image processing. In a step **100**, attenuation data is received from an examination region. An attenuation map is reconstructed from the received attenuation data in a step **102**. In a step **104**, potential radiation events are received from an examination region. A time stamp is assigned to the received events in a step **106**. In a step **108**, a verification criterion is applied to detect the coincident events. In a step **110**, verified pairs of coincident events are defined as LORs. In a step **112**, a reconstruction processor converts the verified pairs into sinograms. In a step

114, a reconstruction processor reconstructs the sinograms into an attenuation corrected source distribution map. A scatter simulation processor utilizes the determined source distribution map and the attenuation map to generate the shape of the scatter sinogram in a step **116**. In a step **118**, a scatter scaling processor utilizes the determined source distribution map and the attenuation map to generate a ratio of scatter contribution with a short Monte Carlo simulation, and scales the scatter sinogram to match scatter contribution in the measured sinogram. In a step **120** a reconstruction processor reconstructs a final reconstructed image utilizing the scaled scatter sinogram and the measured coincidence events or sinograms.

The invention has been described with reference to the preferred embodiments. Modifications and alterations may occur to others upon reading and understanding the preceding detailed description. It is intended that the invention be constructed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.

CLAIMS

Having thus described the preferred embodiments, the invention is now claimed to be:

1. An image processing apparatus comprising:

a scatter simulation processor **(68)** which processes measured sinograms generated from imaging data acquired for an imaging subject by an imaging apparatus **(30)** to produce a scatter sinogram that represents a shape of scatter contribution;

a scatter scaling processor **(72)** utilizing a Monte Carlo simulation to determine a scatter fraction and scales the scatter sinogram to generate a scaled scatter sinogram that matches the scatter contribution in the measured sinogram; and

a reconstruction processor **(74)** which reconstructs the imaging data into an image representation using the scaled scatter sinogram for scatter correction.

2. The image processing apparatus of claim 1, wherein the imaging apparatus **(30)** is a positron emission tomography (PET) scanner and the imaging data acquired from the imaging subject by the PET scanner are coincidence event pairs.

3. The image processing apparatus of claim 1 wherein one of:

the imaging apparatus **(30)** is a positron emission tomography (PET) scanner and the imaging data acquired from the imaging subject by the PET scanner are coincidence event pairs;

the imaging apparatus **(30)** is gamma camera and the imaging data acquired from the imaging subject by the gamma camera are single photon emission computed tomography (SPECT) data; and

the imaging apparatus **(30)** is transmission computed tomography (CT) scanner and the imaging data acquired from the imaging subject by the CT scanner are CT data.

4. The image processing apparatus according to any one of claims 1-3, further including:

a sinogram reconstruction processor **(64)** which converts the coincident event pairs of a subject generated by an imaging apparatus **(30)** to sinograms.

5. The image processing apparatus according to any one of claims 1-4, wherein the Monte Carlo simulation determines a contribution to each sinogram from primary event pairs, single scatter event pairs, and multiple scatter event pairs.

6. The image processing apparatus according to any one of claims 1-5, wherein the scatter scaling processor **(72)** determines a ratio of a total number of scattered event pairs to a total number of event pairs in each sinogram.

7. The image processing apparatus according to any one of claims 1-6, wherein a determined source distribution and the attenuation map are used in the Monte Carlo simulation to the contributions.

8. The image processing apparatus according to any one of claims 1-6, wherein the scatter scaling processor **(72)** uses single-scatter simulation (SSS) to determine the shape of scatter contribution.

9. The image processing apparatus according to any one of claims 1-8, wherein the sinogram reconstruction processor **(64)** generates a source distribution map from the sinograms.

10. The image processing apparatus according to any one of claims 1-9, wherein an attenuation correction reconstruction processor **(60)** generates an attenuation map of the subject from radiation attenuation data.

11. The image processing apparatus according to any one of claims 5-10, wherein the Monte Carlo simulation is performed until the ratio stabilizes.

12. The image processing apparatus according to any one of claims 1-11, further include PET detectors which detect the events stored in event memory **(58)**.

13. The image processing apparatus according to any one of claims 1-12 wherein the reconstruction processor **(74)** operates on list-mode data.

14. The image processing apparatus according to any one of claims 1-12 wherein the reconstruction processor **(74)** operates on measured sinograms.

15. A method of image processing comprising:

processing measured sinograms generated from imaging data acquired for an imaging subject by an imaging apparatus **(30);**

producing a scatter sinogram that represents a shape of scatter contribution;

determining a scatter fraction and scaling the scatter sinogram to generate a scaled scatter sinogram that matches the scatter contribution in the measured sinogram; and

reconstructing the imaging data into an image representation using the scaled scatter sinogram for scatter correction.

16. The method according to claim 15, wherein the imaging apparatus **(30)** is a positron emission tomography (PET) scanner and the imaging data acquired from the imaging subject by the PET scanner are coincidence event pairs.

17. The method according to claim 15, wherein one of:

the imaging apparatus **(30)** is a positron emission tomography (PET) scanner and the imaging data acquired from the imaging subject by the PET scanner are coincidence event pairs;

the imaging apparatus **(30)** is gamma camera and the imaging data acquired from the imaging subject by the gamma camera are single photon emission computed tomography (SPECT) data; and the imaging apparatus **(30)** is transmission computed tomography (CT) scanner and the imaging data acquired from the imaging subject by the CT scanner are CT data.

18. The method according to any one of claims 15-17, further including:

generating the plurality of coincident event pairs of a subject generated by the imaging apparatus **(30)** to be reconstructed; and

converting the coincident event pairs to sinograms.

19. The method of image processing according to any one of claims 15-18, wherein the Monte Carlo simulation determines a contribution to each sinogram from primary event pairs scatter event pairs.

20. The method of image processing according to any one of claims 15-19, wherein the scatter scaling processor **(72)** determines a ratio of a total of scattered event pairs to a total number of event pairs in each sinogram.

21. The method of image processing according to any one of claims 15-20, wherein a determined source distribution and an attenuation map of the subject are used in the Monte Carlo simulation to the contributions.

22. The method of image processing according to any one of claims 15-21, further including:

generating a source distribution map from the sinograms.

23. The method of image processing according to any one of claims 15-22, further including:

generating the attenuation map from radiation attenuation data.

24. The method of image processing according to any one of claims 20-23, wherein the Monte Carlo simulation is performed until the ratio stabilizes.

25. A non-transitory computer readable medium which carries a computer program which controls one or more processors to perform the method of any one of claims 15-24.

26. A method of image processing comprising:

with a PET scanner, generating a plurality of events;

utilizing a Monte Carlo simulation based on the generated events to simulate a scatter contribution;

correcting the plurality of generated events based on the simulation; and

reconstructing the corrected events.

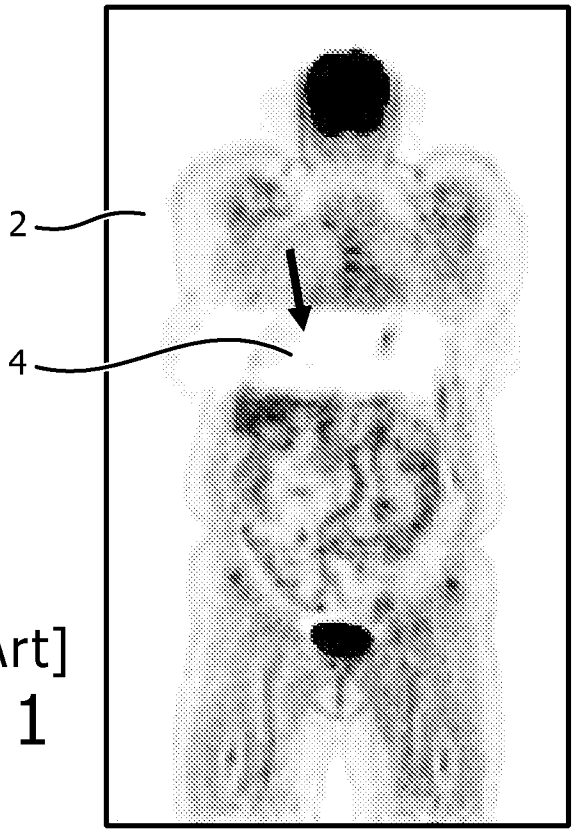
27. The method of image processing according to claim 26, further including:

converting the plurality of events into sinograms; and

estimating scatter contribution to each sinogram using the Monte Carlo simulation.

28. The method image processing according to claim 27, further including:

adjusting each sinogram based on a proportion of each sinogram attributable to scatter.



[Prior Art]
FIG. 1

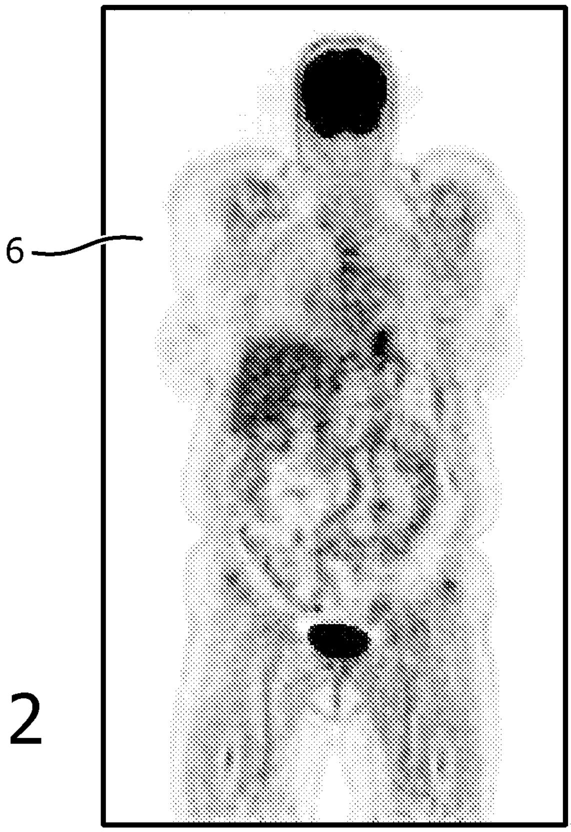


FIG. 2

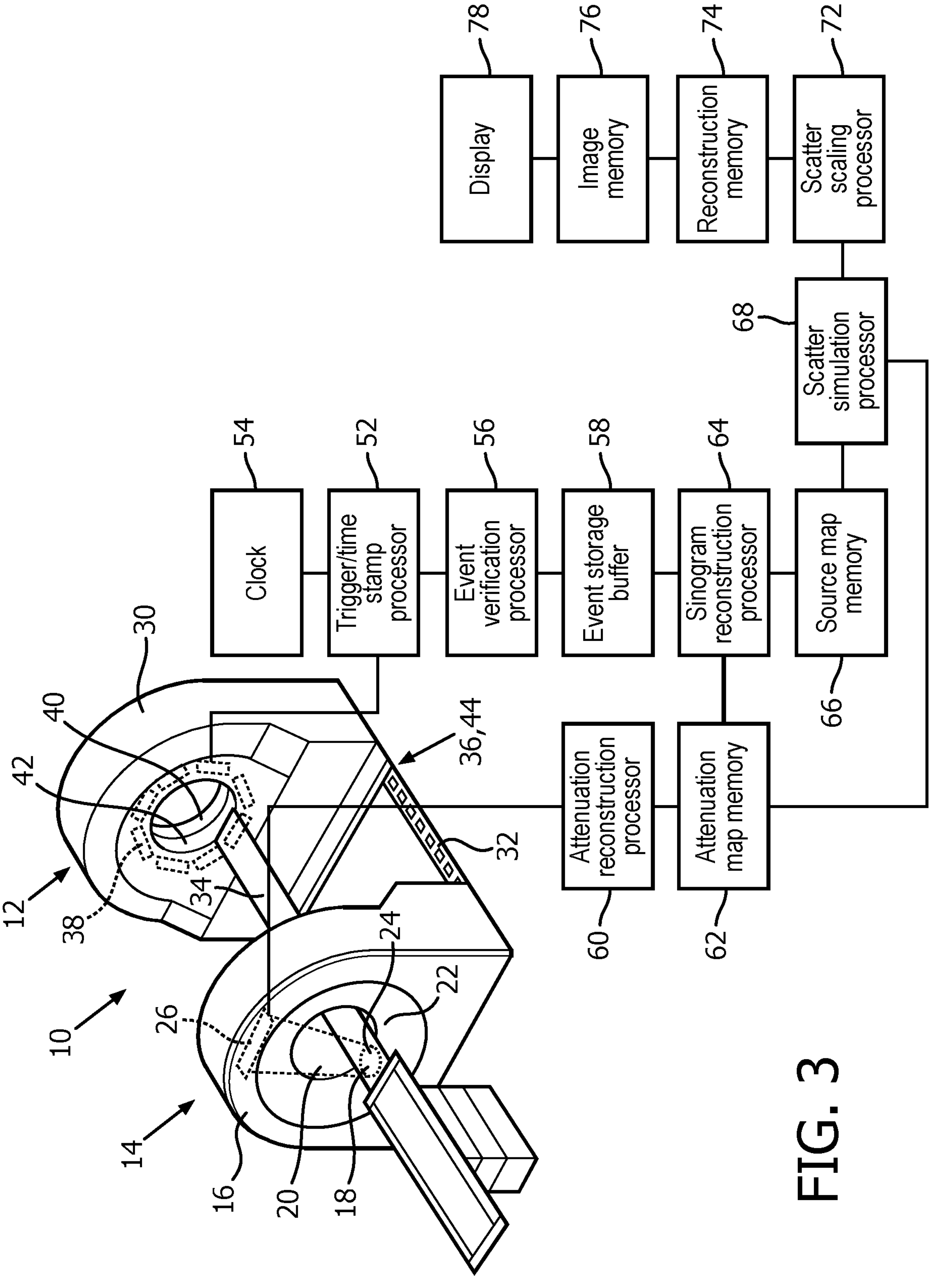

10
12
14
16
18
20
22
24
26
30
32
34
36,44
38
40
42
Clock
54
Trigger/time stamp processor
52
Event verification processor
56
Event storage buffer
58
Sinogram reconstruction processor
64
Source map memory
66
Attenuation reconstruction processor
60
Attenuation map memory
62
Scatter simulation processor
68
Scatter scaling processor
72
Reconstruction memory
74
Image memory
76
Display
78

FIG. 3

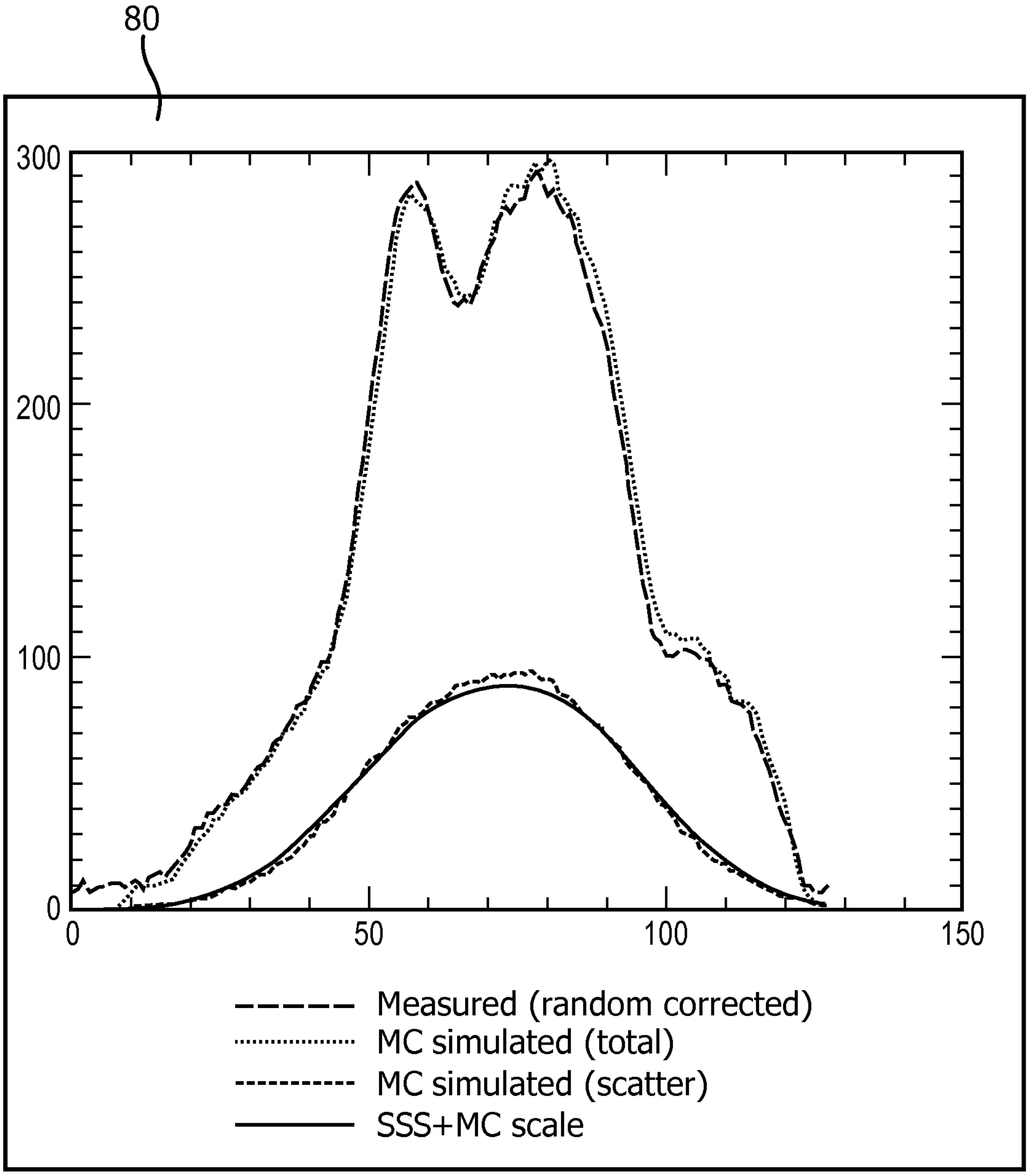

80
300
200
100
0
0
50
100
150
Measured (random corrected)
MC simulated (total)
MC simulated (scatter)
SSS+MC scale

FIG. 4

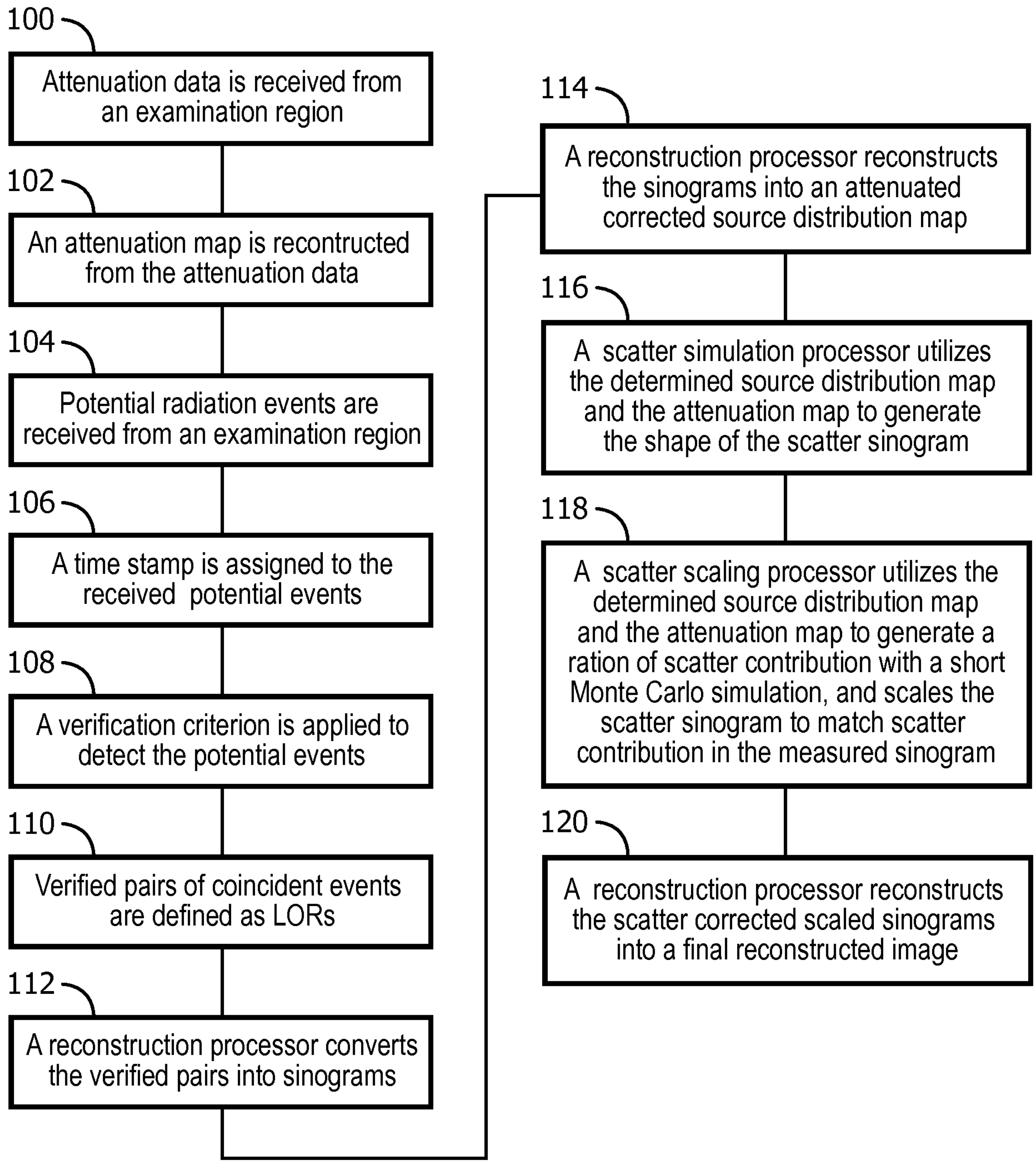

100
Attenuation data is received from an examination region
102
An attenuation map is recontructed from the attenuation data
104
Potential radiation events are received from an examination region
106
A time stamp is assigned to the received potential events
108
A verification criterion is applied to detect the potential events
110
Verified pairs of coincident events are defined as LORs
112
A reconstruction processor converts the verified pairs into sinograms
114
A reconstruction processor reconstructs the sinograms into an attenuated corrected source distribution map
116
A scatter simulation processor utilizes the determined source distribution map and the attenuation map to generate the shape of the scatter sinogram
118
A scatter scaling processor utilizes the determined source distribution map and the attenuation map to generate a ration of scatter contribution with a short Monte Carlo simulation, and scales the scatter sinogram to match scatter contribution in the measured sinogram
120
A reconstruction processor reconstructs the scatter corrected scaled sinograms into a final reconstructed image

FIG. 5

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2013/053965

A. CLASSIFICATION OF SUBJECT MATTER
INV. G06T11/00
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G06T

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

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

EPO-Internal, COMPENDEX, INSPEC, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	KYUNG SANG KIM ET AL: "Ultra-fast hybrid CPU-GPU Monte Carlo simulation for scatter correction in 3D PETs", NUCLEAR SCIENCE SYMPOSIUM AND MEDICAL IMAGING CONFERENCE (NSS/MIC), 2011 IEEE, IEEE, 23 October 2011 (2011-10-23), pages 2749-2752, XP032121241, DOI: 10.1109/NSSMIC.2011.6152961 ISBN: 978-1-4673-0118-3 abstract Section I Section II -----	1-28

-/--

[X] Further documents are listed in the continuation of Box C.

[ ] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
22 August 2013	30/08/2013

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Leclercq, Philippe

1

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2013/053965

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	READER A J ET AL: "Attenuation and scatter correction of list-mode data driven iterative and analytic image reconstruction algorithms for rotating 3D PET systems", IEEE TRANSACTIONS ON NUCLEAR SCIENCE, IEEE SERVICE CENTER, NEW YORK, NY, US, vol. 46, no. 6, 1 December 1999 (1999-12-01), pages 2218-2226, XP011358669, ISSN: 0018-9499, DOI: 10.1109/23.819307 the whole document -----	13
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1