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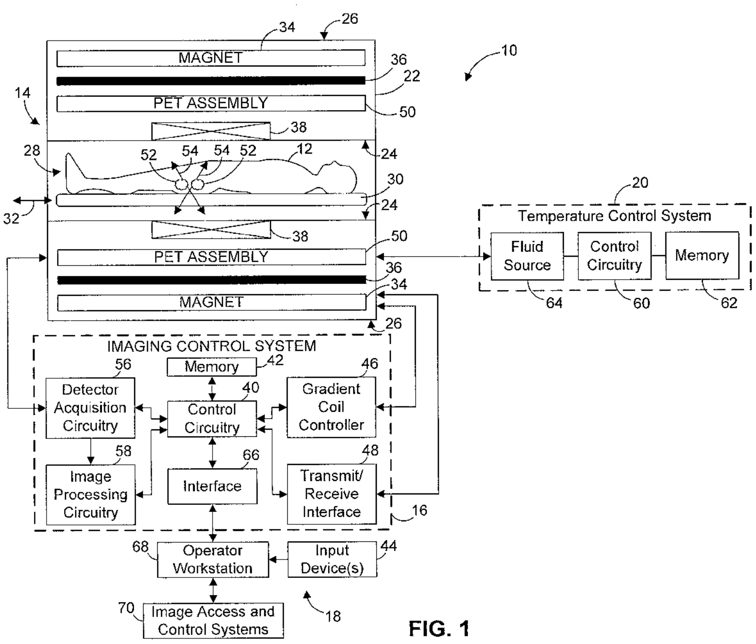

FIG. 1

(57) Abstract: A positron emission tomography (PET) assembly includes an annular housing and an annular scintillator disposed within the annular housing. The annular scintillator includes an annular, substantially continuous crystal scintillator tube configured to absorb ionizing radiation and to emit light energy. A plurality of photo detectors are annularly disposed around the annular scintillator within the annular housing and configured to detect the emitted light energy.

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POSITRON EMISSION TOMOGRAPHY SYSTEMS AND METHODS

DESCRIPTION

Cross-Reference to Related Applications

[001] This application claims the benefit of priority based on U.S. Provisional Patent Application No. 62/258,861, filed November 23, 2015, which is incorporated herein by reference.

Technical Field

[002] The disclosure relates generally to positron emission tomography (PET) imaging systems and, more particularly, to PET devices for use alone or in multi-modality imaging systems.

Background

[003] Imaging instrumentation has improved dramatically over the past couple of decades. Magnetic resonance imaging (MRI) is one modality that provides a wide amount of data, as compared to other imaging techniques. MRI can be used to create images with excellent soft tissue signal and contrast. MRI can also be used to measure motion and flow, metabolites (MR spectroscopy), diffusion of water, temperature, etc. However, compared to other imaging modalities, it is comparatively insensitive as a molecular imaging modality. One modality that is better than MRI for detecting and quantifying exceedingly small amounts of exogenously administered material is positron emission tomography (PET).

[004] Some prior systems have combined MRI and PET imaging together by using serially acquired images on different scanners. However, with such systems, the acquired images have a time delay, during which the patient or the patient's anatomy may shift, introducing imaging errors. Additionally, the spatial resolution of such systems may be lower than desirable for certain applications.

Accordingly, a need exists for PET systems that address one or more of these drawbacks.

SUMMARY

[005] In one embodiment, the PET scanner is based on a single tube made of a scintillator crystal. This feature may eliminate the need for multiple smaller crystals, and effectively remove all edges from the detector. This may also remove the edge distortions and improve the spatial resolution of the detector, as compared to multiple crystal systems. In addition, because there are no gaps between detector elements and between rings of detectors in some embodiments, the sensitivity of the scanner may increase.

[006] In one embodiment, the PET scanner is based on a scintillator tube that includes multiple smaller elements that are joined together to form a pseudo single crystal tube. This embodiment may enable building larger PET scanners based on the edge-less crystal tube design for use in pediatric or adult human scanners.

[007] In one embodiment, a multi-modality imaging system includes a frame having an outer transaxial wall and an inner transaxial wall, the inner wall defining a transaxially extending bore configured to receive a patient. For use in conjunction with a MRI scanner, the inner transaxial space may be occupied by a radiofrequency (RF) coil. The system further includes a positron emission tomography (PET) assembly including an annular scintillator disposed between the inner transaxial wall and the outer transaxial wall. The annular scintillator may include an annular, substantiallycontinuous crystal scintillator tube.

[008] In another embodiment, a positron emission tomography (PET) assembly includes an annular housing and an annular scintillator disposed within the

annular housing. The annular scintillator may include an annular (e.g., tubular), substantially continuous crystal scintillator configured to absorb ionizing radiation and to emit light energy. A plurality of photodetectors are annularly disposed around the annular scintillator within the annular housing and configured to detect the emitted light energy.

[009] In another embodiment, a multi-modality imaging system includes a frame having an outer transaxial wall and an inner transaxial wall defining an axially extending bore configured to receive a patient. A radio frequency (RF) coil is disposed within the inner transaxial wall and the outer transaxial wall and configured to generate radio frequency energy to image the patient. A positron emission tomography (PET) assembly includes an annular scintillator disposed between the inner transaxial wall and the outer transaxial wall about the RF coil. The annular scintillator includes an annular, continuous crystal scintillator tube. A plurality of photomultipliers are disposed on the outer surface of the annular scintillator farther from the transaxially extending bore than an inner surface of the annular scintillator.

[010] It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the invention, as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

[011] The accompanying drawings, which are incorporated in and constitute a part of this disclosure, illustrate exemplary embodiments and, together with the description, serve to explain the disclosed principles.

[012] **FIG. 1** illustrates an embodiment of a multi-modality imaging system having a PET assembly;

[013] **FIG. 2** illustrates an embodiment of a PET system having a continuous crystal scintillator tube;

[014] **FIG. 3** is a perspective view of an embodiment of a PET assembly disposed about an RF coil;

[015] **FIG. 4** is a cross-sectional view of an embodiment of a PET assembly having an annular continuous crystal scintillator tube;

[016] **FIG. 5** is a cross-sectional view of another embodiment of the PET assembly having an annular continuous crystal scintillator tube embedded between two rings of photodetectors;

[017] **FIG. 6** is a schematic illustration of an embodiment of the arrangement between an annular scintillator crystal and an annular plurality of photodetectors; and

[018] **FIG. 7** is a schematic illustration of an embodiment of a crystal scintillator having a coated surface and an etched surface.

DETAILED DESCRIPTION

[019] As discussed in further detail below, various embodiments of a positron emission tomography (PET) assembly are provided. The PET assembly may be configured for use in a standalone PET system or in combination with other imaging modalities, such as magnetic resonance imaging (MRI) and/or X-ray based imaging (e.g., computed tomography (CT)). In some embodiments, the PET assembly may include an annular scintillator having an annular (e.g., tubular), substantially continuous crystal scintillator configured to convert ionizing radiation into light energy detectable by one or more photodetectors. In some implementations, the foregoing feature may enable the PET system utilizing the PET assembly to have improved spatial resolution, as compared to multi-crystal systems.

[020] Further, in some embodiments, by providing a substantially continuous, annular (e.g., tubular) crystal scintillator and containing the light such to avoid light spread throughout the crystal, a PET device having high spatial-resolution

close to the spatial resolution theoretically limited by positron range may be achieved. Additionally, this spatial resolution may be maintained throughout the field of view of the device, as opposed to some conventional systems that experience reduced spatial resolution in certain areas of the field of view. Further, embodiments of the PET systems described herein may have high sensitivity, good energy and timing resolution, and the ability to handle high count rates, as compared to conventional systems including multiple or discontinuous crystal scintillators.

[021] Turning now to the drawings, **FIG. 1** diagrammatically illustrates an imaging system 10 for imaging a patient 12. However, the depiction of a patient is merely an example. The patient 12 may be any target object, any, human, and so forth, in other embodiments. The imaging system 10 includes an imaging device 14, an imaging control system 16, a health care facility system 18, and a temperature control system 20. During operation, the imaging device 14 is configured to image the patient 12 via one or more imaging modalities under control of the control system 16. The control system 16 may receive one or more inputs from the health care facility system 18 regarding operation of the device and output data related to imaging of the patient 12. The temperature control system 20 may coordinate with the control system 16 to facilitate cooling of one or more components of the imaging device 14 during operation.

[022] In the illustrated embodiment, the imaging device 14 includes a frame 22 having an inner transaxial wall 24 and an outer transaxial wall 26. The inner transaxial wall 24 may define a transaxially extending bore 28 configured to receive a patient support 30. The patient support 30 may be configured to position the patient 12 within the transaxially extending bore 28, for example, via movement of

the patient support 30 within, or into and out of, the frame 22, as indicated by arrow 32.

[023] In the illustrated embodiment, the imaging system 10 is a combined PET and MRI imaging system. However, it should be noted that in other embodiments, the imaging system 10 may combine PET with any other suitable imaging modality, such as X-ray CT or ultrasound. Indeed, the depicted MRI/PET system is merely an example.

[024] In the depicted embodiment, the imaging device 14 includes components suitable for performing both MRI and PET. Specifically, the MRI portion of the device 14 may include a magnet 34 configured to generate a primary magnetic field. In some embodiments, the magnet 34 may be driven by a power source (not shown) provided, for example, by control system 16. One or more gradient coils 36 may be configured to generate magnetic gradient fields during imaging. A radio frequency (RF) coil 38 may generate RF pulses for exciting the nuclear spins and/or function as a receiving coil, depending on the given implementation. The arrangement of the magnet 34, the one or more gradient coils 36, and the RF coil 38 is subject to a variety of implementation-specific variations. However, in the illustrated example, the RF coil 38 is nested within the one or more gradient coils 36, which are nested within the magnet 34.

[025] Centralized control circuitry 40 may control both the MRI and PET subsystems of the imaging system 10. With respect to the MRI sub-system, the control circuitry 40 may control the MRI components to generate a desired magnetic field and RF pulses and to process the generated signals. To that end, the control circuitry 40 may include one or more processors communicatively coupled to memory 42. The one or more processors (e.g., microprocessor(s), application-

specific integrated circuit (ASIC), field-programmable gate array (FPGA), etc.) may be configured to execute a control algorithm. By way of example, the control algorithm may be provided as machine-readable encoded instructions stored on a machine-readable medium, such as the memory 42, and may provide control signals for controlling operation of the imaging system 10. The control signals may control the imaging device 14 to selectively acquire MRI and/or PET data.

[026] The memory 42 may be a tangible, non-transitory, machine readable medium. For example, the memory 42 may be volatile or non-volatile memory, such as read only memory (ROM), random access memory (RAM), magnetic storage memory, optical storage memory, or a combination thereof. Furthermore, a variety of control parameters may be stored in the memory 42 along with code configured to provide a specific output (e.g., enable MRI image acquisition, enable PET image acquisition, etc.) to the imaging device 14 during operation. The memory 42 may also store acquired image data, pulse sequences for different modes of operation, or any other parameters defining examination sequences performed by the MRI portion of the device 14. Further, in some embodiments, the processor(s) of the control circuitry 40 may also receive one or more inputs from one or more input devices 44, through which the user may choose a process and/or input desired parameters (e.g., which part of the body should be imaged, whether multiple or single modality operation is desired, etc.).

[027] In some embodiments, a gradient coil controller 46 and a transmit/receive interface 48 may provide interfaces through which the control circuitry 40 may control the one or more gradient coils 36 and RF coil 38. For example, the gradient coil controller 46 may include amplification circuitry configured to drive current for the one or more gradient coils 36 under control of circuitry 40.

For further example, the transmit/receive interface 48 may include amplification circuitry to drive the RF coil 38 during operation. In some embodiments, the RF coil 38 may be configured to both emit RF excitation pulses and receive responsive signals, and the transmit/receive interface 48 may include a switch configured to toggle the RF coil 38 between transmit and receive modes of operation.

[028] In addition to the MRI subsystem, the imaging device 14 also includes one or more components that enable PET imaging. For example, a PET assembly 50 is disposed between the inner transaxial wall 24 and the outer transaxial wall 26 of the frame 22 of the imaging device 14. In the illustrated embodiment, the PET assembly 50 is disposed annularly between the one or more gradient coils 36 and the RF coil 38. However, in other embodiments, the PET assembly 50 may be disposed in any other desired location within the frame 22.

[029] Further, although the PET assembly 50 is illustrated as an integrative part of the frame 22 in the illustrated example, the PET assembly 50 may be configured as a removable insert in other embodiments. For example, the PET assembly 50 may be provided as part of a retrofit kit configured to retrofit an existing imaging system (e.g., MRI system or CT system) to endow the existing system with PET imaging capabilities. Such a retrofit kit may include the PET assembly 50 configured to be inserted into an existing frame 22 and/or software configured to be executed by the control circuitry 40 to enable control of the PET assembly and/or processing of the acquired data.

[030] The PET assembly 50 may include an annular scintillation crystal coupled to one or more photodetectors, as discussed in more detail below, to enable the PET assembly 50 to function as a PET detector. To that end, the patient 12 may be administered a positron-emitting source 52 which will result in the production of a

pair of gammas. In some embodiments, the PET subsystem may generate images illustrating the distributions of positron-emitting nuclides in the patient 12. To that end, the PET assembly 50 may operate on the principle of annihilation coincidence detection (ACD). In such embodiments, a positron is emitted by a nuclear transformation of a radiopharmaceutical (e.g., radiation source 52), and the positron annihilates with an electron to result in photons 54 emitted in opposite directions and detected by PET assembly 50. The single crystal scintillator in the PET assembly 50 may detect the photons 54 and produce visible photons detectable by photodetectors.

[031] Detector acquisition circuitry 56 may be configured to control acquisition of the signals acquired by the PET assembly 50 in coordination with central control circuitry 40. Image processing circuitry 58 may process the acquired data from the detector acquisition circuitry 56. For example, the image processing circuitry 58 may include one or more processors configured to receive the PET image data and the MRI image data, and to overlay the PET data over the MRI data to generate a composite image.

[032] In the illustrated embodiment, the centralized control circuitry 40 controls the PET and MRI subsystems of the imaging system 10. To that end, the control of the subsystems is coordinated to enable acquisition of PET and MRI data while the patient 12 is in the same position. The foregoing feature may offer the advantage of enabling reduction in imaging acquisition time (e.g., because the patient does not have to be moved between imaging modalities) and/or reduction in image artifacts due to patient movement.

[033] In some embodiments, the temperature control system 20 may also be under control of the control circuitry 40 to enable cooling of one or more

components of the imaging device 14. For example, the temperature control system 20 may include control circuitry 60 (e.g., one or more processors) communicatively coupled to control circuitry 40. The control circuitry 60 may access memory 62 (which may include components similar to memory 42 described above) to facilitate control of a fluid source. For example, the control circuitry 60 may control a pump to pump fluid from the fluid source 64 to one or more tubes in the PET assembly 50 to cool one or more components in the PET assembly 50, as described in more detail below.

[034] Further, the imaging control system 16 may include one or more devices that facilitate interaction between a user and the imaging device 14. For example, an interface 66 may communicatively couple the control circuitry 40 to an operator workstation 68. The operator workstation 68 may be a general purpose or special computer including, for example, memory for storing pulse sequences, examination protocols, patient data, raw and/or processed image data, and so forth. The operator workstation 68 may receive one or more operator inputs via the user input devices 44. The user input devices 44 may include, but are not limited to, mobile devices (e.g., smartphones, tablets, laptops, etc.), keyboards, computer mice, etc. The operator workstation 68 may also be coupled to one or more local or remote image access and control systems 70, such as picture archiving and communication systems (PACS), teleradiography systems (TELERAD), etc.

[035] **FIG. 2** illustrates an embodiment of a standalone PET imaging system 72 in accordance with a disclosed embodiment. That is, in this embodiment, the PET assembly 50 may form an integral or removably insertable part of a single modality system 72. As shown, in this embodiment, a radioactive isotope (e.g., radiation source 52) is disposed in the patient 12 (block 74). In some embodiments,

the radioactive isotope may be targeted to a desired location(s) within the patient 12 by chemically binding it to a targeting ligand, such glucose, a peptide, small molecule, etc. Photons are emitted from the radioactive isotope 52 (block 76) and detected by one or more detection elements of the PET assembly 50.

[036] In the illustrated embodiment, the PET assembly 50 includes a substantially continuous scintillator crystal 78. The substantially continuous crystal 78 may be formed in a variety of suitable shapes, such as curved or annular. For example, the substantially continuous crystal 78 may be provided as a tube in some embodiments. The substantially continuous crystal scintillator 78 may include only a single crystal. For example, the substantially continuous crystal scintillator 78 may not be pixelated (i.e., the crystal does not include multiple crystals having gaps or crystal edges there between). The substantially continuous crystal scintillator tube may be continuous in composition such that no discontinuities occur throughout its volume.

[037] PET scanners including the continuous crystal scintillator may offer advantages over PET scanners based on numerous, discrete scintillator elements (e.g., cut into smaller elements (pixels) or remaining uncut (continuous)). Presently disclosed embodiments may overcome problems associated with these types of PET scanners that include multiple crystals elements. For example, presently disclosed embodiments may reduce or eliminate the limitations arising from difficulties in the ability to localize where the high energy gamma ray hits due to the edges of every detector element. By reducing the number of elements, a proportional reduction in the resulting localization artifacts may be achieved. This may enable an increase in the overall spatial resolution of the PET scanner.

[038] In one embodiment, the substantially continuous crystal scintillator 78 may include a plurality of crystals held together by an optical matching glue (e.g., Cargille Meltmount™). In this embodiment, the optical matching glue may have a refractive index approximately equal to the refractive index of the crystals such that light propagates through the edges of the crystals into the optical matching glue without refracting. Thus, in some embodiments, the substantially continuous crystal scintillator 78 may have a continuous refractive index throughout its volume even though it includes more than one crystal. That is, in some embodiments, the substantially continuous crystal scintillator 78 may include multiple smaller elements that are joined together to form a pseudo single crystal tube. This embodiment may enable building larger PET scanners based on the edge-less crystal tube design, for example, for use in pediatric or adult human scanners. As used herein, the term "substantially continuous crystal" refers to both continuous crystals and pseudo single crystals.

[039] The substantially continuous crystal scintillator 78 may be formed via any suitable method. For example, in one embodiment, the substantially continuous crystal scintillator 78 may be made by boring through a boule, sized for the given implementation and then polishing the resulting surfaces. In some embodiments, the material used to make the boule may be tested to meet a minimum threshold value for light output. Any inhomogeneities in light output may be measured, and normalization/efficiency factors may be applied during the calibration of the PET assembly 50.

[040] In another embodiment, a plurality of crystals may be glued together with optical matching glue to form a pseudo single crystal embodiment of the substantially continuous crystal scintillator 78, as discussed above. In another

embodiment, the crystal could be grown to the desired shape and size needed for the desired imaging application.

[041] One of ordinary skill in the art may expect the properties of the substantially continuous crystal scintillator 78 to result in light spread through the volume of the scintillator due to reflection of the light. However, the present inventors have recognized that the light can be contained to avoid spreading through the scintillator volume. Thus, the inventors have recognized that any expected problems with many overlapping detection events (i.e., pileups) and limited spatial position definition of the initial annihilation photon's conversion point in the scintillator are not experienced to a greater degree than multi-crystal designs. Thus, the present inventors have recognized that the substantially continuous crystal scintillator 78 may enable a practical PET system for both preclinical and clinical imaging.

[042] The proposed scanner may remove all scintillator crystal edges from the active volume. This may improve the homogeneity of the scanner response because artifacts that arise at the edges of the modules degrade spatial resolution and sensitivity. Some improvements that may be achieved via the disclosed embodiments are: large field of view (FOV), allowing continuous scanning of an entire target object or body (e.g., whole mouse scanning); high spatial resolution (approximately0.5 mm) that is homogeneous across the entire FOV; high sensitivity (e.g., at least twice that of the Bruker Albira Si); timing (1.5 ns FWHM) and energy resolution that is better than the Albira-Si PET scanner (e.g., by approximately 15-18%).

[043] The substantially continuous crystal scintillator 78 may be formed from any suitable material. For example, the crystal 78 may include, but is not

limited to, LYSO (Cerium-doped Lutetium Yttrium Orthosilicate), $LaBr_3$ (Lanthanum Bromide), NaI(Tl) (Sodium Iodide), BGO (Bismuth Germanate), a combination thereof, or any other suitable scintillator material. The scintillator including the substantially continuous crystal scintillator 78 may be a dense material capable of converting a highly energy gamma ray (e.g., 511 keV in the case of positron emitters), and lower energy in the case of single gamma emitters, such as, but not limited to, ^{99m}Tc, and ^{111}In) into visible light. The visible light may be detected by one or more photodetectors 80. The one or more photodetectors 80, may include, but are not limited to, avalanche photo diodes, silicon photomultipliers (SiPMs), or any other suitable photodetector.

[044] In the PET system 72, the PET assembly 50 is under control of the detector acquisition circuitry 56, as described above. Further, the image processing circuitry 58 is communicatively coupled to the detector acquisition circuitry 56 to receive and process the PET image data, as described in detail above. Likewise, the operator workstation 68 may be included in the PET system 72 to enable operator input. Additionally, an output device 82, such as a display or printer, may be configured to output the PET images generated during operation of the PET imaging system 72.

[045] **FIG. 3** illustrates a perspective view of one embodiment of the PET assembly 50. In this embodiment, the PET assembly 50 is formed as an annular (e.g., tube), substantially continuous crystal scintillator 78. In this embodiment, the annular crystal 78 forms a bore 84 extending therethrough. In the illustrated embodiment, the PET assembly 50 is shown disposed about the RF coil 38, which is received in the bore 84. In this way, the PET assembly 50 may be provided as a

removable insert that may be inserted around an existing RF coil 38 in an MRI system and removed from the MRI system if desired.

[046] Additionally, in this embodiment, the photodetectors 80 include a plurality of photodetectors 80' disposed on an annular shaped printed circuit board 86 adjacent to the annular scintillator crystal 78. In this embodiment, the photodetectors 80' are curved to match the annular profile of the scintillator crystal 78. The photodetectors 80' may also be disposed in a matrix having multiple rows and columns, as depicted, or as a single row of photodetectors 80' disposed annularly around the crystal 78.

[047] In the illustrated PET assembly 50, the photodetectors 80 and the crystal 78 a uniform length 88. However, in other embodiments, the length 88 of the photodetectors 80 may be different than a length of the crystal 78, as discussed in more detail below. Further, the crystal 78 has a wall thickness 90 between an outer wall 92 and an inner wall 94.

[048] **FIGS. 4 and 5** each depict cross-sectional views of embodiments of the PET assembly 50. In the illustrated embodiments, the PET assembly 50 is shown disposed about the RF coil 38 for illustrative purposes only. Indeed, the PET assembly 50 may be provided without the RF coil 38, in a cylindrical bore of an imaging device not having an RF coil, etc.

[049] The PET assembly 50 may include an outer, annular housing 111 configured to enclose one or more components of the PET assembly 50. In the illustrated embodiment, the housing 111 encloses a printed circuit board (PCB) 106. The PCB 106 may be annular to match the curved surface of the crystal 78. Further, in some embodiments, the PCB 106 may be a similar setup that is compatible with the curved surface of the scintillator tube 78. In the illustrated embodiment, the PCB

106 includes a plurality of channels 108 with a plurality of fluid tubes 110 disposed therein at a plurality of radial locations about the circumference of the PCB 106. During operation, the control circuitry 60 may control the fluid source 64 to circulate a cooling fluid through the fluid tubes 110 at a temperature less than a temperature of the PCB 106 to cool the PCB 106.

[050] The PCB 106 may enclose an electronics volume 104, which schematically represents the area provided for the electronics of the PCB 106. The photodetectors 80 are disposed within the electronics volume 104 and are annularly adjacent to the annular, substantially continuous scintillator crystal 78. An annular support 100, such as, but not limited to, a carbon fiber support, provides a frame or housing to complete the PET assembly 50. That is, the housing 111 and the support 100 enclose the components of the PET assembly 50.

[051] In the embodiment of **FIG. 5**, a second set of one or more photodetectors 102 is annularly disposed between the support 100 and the scintillator crystal 78. In some embodiments, by disposing photodetectors 80, 102 on both the inner surface 94 (shown in FIG. 3) and the outer surface 92 (shown in FIG. 3) of the crystal 78, the shape of the light created by the gamma rays may be better visualized, as compared to implementations including only photodetectors 80. The foregoing feature may enable detection of the depth inside the scintillator crystal 78 and the direction from which the high-energy gamma originated. This may enable improved PET images to be generated because of better ability to determine the line of response along which the positron annihilation occurred.

[052] **FIG. 6** is a schematic illustration of one embodiment of the relative configuration between the annular, substantially continuous crystal scintillator tube 78 and the photodetectors 80. In this embodiment, the annular crystal 78 may

extend beyond the length 88 of the photodetectors 80 by a distance 120 on each of a first end 122 and a second end 124 of the PET assembly 50. In one embodiment, the distance 120 on each end may be approximately equal to the thickness 90 of the wall of the crystal 78. This embodiment may be advantageous in certain implementations to reduce or eliminate the quantity of crystal edges present in the portion of the crystal 78 adjacent the photodetectors 80.

[053] **FIG. 7** is a schematic illustration of a cross-section of one embodiment of the PET assembly 50. In this embodiment, the inner surface 94 of the crystal 78 includes a light absorbent coating 126. In some embodiments, the light absorbent coating 126 may include a light absorbing material, such as black paint. However, in other embodiments, the coating 126 may be any coating that absorbs light at a desired wavelength. The light absorbent coating 126 will increase the likelihood that light is absorbed proximate the inner surface 94 of the crystal. By doing so, the light may be contained to reduce or prevent the likelihood that the scintillation light will cascade through the volume of the crystal 78. More specifically, the coating 126 may reduce or prevent the likelihood of scintillation light reflecting throughout the entire crystal 78, thus preventing accurate light detection.

[054] Further, in the illustrated embodiment, an etched surface 128 (e.g., roughened) is provided on the outer wall of the crystal 78. Like the light absorbent coating 126, the etched surface 128 increases the likelihood that the light will exit the crystal 78 and increase the amount of light reaching the photomultipliers. The etched surface also will reduce the likelihood that the scintillation light will reflect back into the crystal 78. However, it should be noted that the etched surface 128 and the coating 126 are merely examples. In order to minimize light reflecting within the crystal 78, a variety of suitable methods may be used. For example, the inner

surface of the crystal 78 and/or the ends 122 and 124 of the crystal may be treated with the light absorbent coating 126. For further example, the exit surface of the crystal 78 may be joined to the photodetectors 80 with a binding agent that matches the refractive index of the crystal 78. In some embodiments, a mechanically roughed surface may transmit up to approximately 25% more light than a smooth surface, and may improve spatial and timing resolution by approximately 15%.

[055] In other embodiments, only one of the coating 126 and the etched surface 128 may be employed, the etched surface may be on the inner wall 94, the coating 126 may be provided in place of the etched surface 128, etc. For further example, the inner and outer surfaces of the crystal 78 may be processed (e.g., polished) in any suitable manner to reduce light reflections, not limited to those disclosed herein. Indeed, any combination or implementation of the light containment devices provided herein may be employed, depending on implementation-specific considerations.

[056] The embodiments of the PET assembly 50 and imaging systems described herein may have one or more advantages over conventional systems. For example, in embodiments using a single crystal 78 that is continuous, mechanical and optical gaps may be reduced or eliminated, thereby maximizing spatial resolution, sensitivity, and uniformity of response. The sampling of the light distribution may be more uniform (e.g., substantially flat and homogeneous), particularly when compared at the edges of current detector modules.

[057] Further, the substantially continuous crystal scintillator tube 78 may enable the tails of light distributions to not be truncated, making it possible to measure depth of interaction (DOI) more accurately. Additionally, because of the large field of view enabled by embodiments of the PET assembly 50, dynamic, multi-

organ imaging may be enabled. Further, the mechanical simplicity of certain embodiments of the PET assembly 50 (e.g., where there is only one scintillator crystal 78 and one SiPM array (readout sampled)) may render the PET assembly 50 easier and less expensive to build than multi-crystal scanners.

[058] It should be noted that the products and/or processes disclosed may be used in combination or separately. Additionally, exemplary embodiments are described with reference to the accompanying drawings. Wherever convenient, the same reference numbers are used throughout the drawings to refer to the same or like parts. While examples and features of disclosed principles are described herein, modifications, adaptations, and other implementations are possible without departing from the spirit and scope of the disclosed embodiments. It is intended that the prior detailed description be considered as exemplary only, with the true scope and spirit being indicated by the following claims.

[059] The examples presented herein are for purposes of illustration, and not limitation. Further, the boundaries of the functional building blocks have been arbitrarily defined herein for the convenience of the description. Alternative boundaries can be defined so long as the specified functions and relationships thereof are appropriately performed. Alternatives (including equivalents, extensions, variations, deviations, etc., of those described herein) will be apparent to persons skilled in the relevant art(s) based on the teachings contained herein. Such alternatives fall within the scope and spirit of the disclosed embodiments. Also, the words “comprising,” “having,” “containing,” and “including,” and other similar forms are intended to be equivalent in meaning and be open ended in that an item or items following any one of these words is not meant to be an exhaustive listing of such item or items, or meant to be limited to only the listed item or items. It must also be

noted that as used herein and in the appended claims, the singular forms “a,” “an,” and “the” include plural references unless the context clearly dictates otherwise.

CLAIMS

What is claimed is:

1. A positron emission tomography (PET) assembly, comprising:

an annular housing;

an annular scintillator disposed within the annular housing, the annular scintillator comprising an annular, substantially continuous crystal configured to absorb ionizing radiation and to emit light energy; and

a plurality of photodetectors annularly disposed around the annular scintillator within the annular housing and configured to detect the emitted light energy.

2. The PET assembly of claim 1, wherein the annular, substantially continuous crystal is a tube.

3. The PET assembly of claim 1, wherein the plurality of photodetectors are disposed on an annular printed circuit board.

4. The PET assembly of claim 3, wherein the photodetectors comprise a plurality of photomultipliers, and a length of the annular scintillator is longer than the coverage of the photomultipliers, and a first end of the annular scintillator extends beyond a first end of the photomultipliers, while a second end of the annular scintillator extends beyond a second end of the photomultipliers.

5. The PET assembly of claim 1, wherein each of the plurality of photodetectors comprises a silicon photomultiplier (SiPM).

6. The PET assembly of claim 1, wherein the annular, continuous scintillator crystal consists essentially of a single crystal.

7. The PET assembly of claim 6, wherein the single crystal is LYSO (Cerium-doped Lutetium Yttrium Orthosilicate).

8. The PET assembly of claim 1, wherein a light-absorbing material is disposed on an inner surface of the annular scintillator.

9. The PET assembly of claim 8, wherein an outer surface of the annular scintillator is etched.

10. A multi-modality imaging system, comprising:

a frame comprising an outer transaxial wall and an inner transaxial wall, the inner transaxial wall defining an transaxially extending bore configured to receive an imaging subject; and

an imaging device disposed within the inner axial wall and the outer axial wall, the imaging device being configured to image the imaging subject; and a positron emission tomography (PET) assembly comprising an annular scintillator disposed between the inner transaxial wall and the outer transaxial wall, wherein the annular scintillator comprises an annular, substantially continuous crystal tube.

11. The multi-modality imaging system of claim 10, wherein the PET assembly comprises a plurality of photomultipliers disposed on an outer surface of the annular scintillator.

12. The multi-modality imaging system of claim 11, wherein photomultipliers are also disposed on the inner surface of the annular scintillator closer to the transaxially extending bore than an outer surface of the annular scintillator.

13. The multi-modality imaging system of claim 10, comprising a plurality of photomultipliers disposed on an inner surface of the annular scintillator closer to the transaxially extending bore than an outer surface of the annular scintillator.

14. The multi-modality imaging system of claim 11, wherein a length of the annular scintillator is longer than a length of the annular photomultipliers, and a first end of the annular scintillator extends beyond a first end of the photomultipliers, while a second end of the annular scintillator extends beyond a second end of the photomultipliers.

15. The multi-modality imaging system of claim 10, wherein the imaging device comprises a radio frequency (RF) coil for magnetic resonance imaging (MRI), and the PET assembly is annularly disposed about the RF coil.

16. The multi-modality imaging system of claim 10, wherein a light-absorbing material is disposed on an inner surface of the annular scintillator closer to the transaxially extending bore than an outer surface of the annular scintillator.

17. The multi-modality imaging system of claim 16, wherein the outer surface of the scintillator is etched.

18. The multi-modality imaging system of claim 10, comprising a cooling system comprising a fluid source and control circuitry configured to control the fluid source to circulate fluid through one or more tubes, wherein the one or more tubes are disposed along a length of the annular scintillator to cool the annular scintillator.

19. The multi-modality imaging system of claim 10, wherein the crystal comprises one or more of LYSO (Cerium-doped Lutetium Yttrium Orthosilicate), LaBr3 (Lanthanum Bromide), NaI(Tl) (Sodium Iodide), and BGO (Bismuth Germanate).

20. The multi-modality imaging system of claim 10, wherein the imaging device comprises an X-ray generation device configured to generate X-ray energy.

21. The multi-modality imaging system of claim 10, wherein the PET assembly comprises a plurality of photodetectors annularly disposed about the annular scintillator, wherein each of the plurality of photodetectors comprise at least one of avalanche photodiodes and silicon photomultipliers (SiPMs).

22. The multi-modality imaging system of claim 10, wherein the annular, substantially continuous crystal tube consists essentially of a single crystal.

23. The multi-modality imaging system of claim 10, wherein the annular, substantially continuous crystal tube comprises a plurality of crystals and optical matching glue disposed between each of the plurality of crystals, wherein a reflective index of each of the plurality of crystals is substantially the same as a refractive index of the optical matching glue.

24. A multi-modality imaging system, comprising:

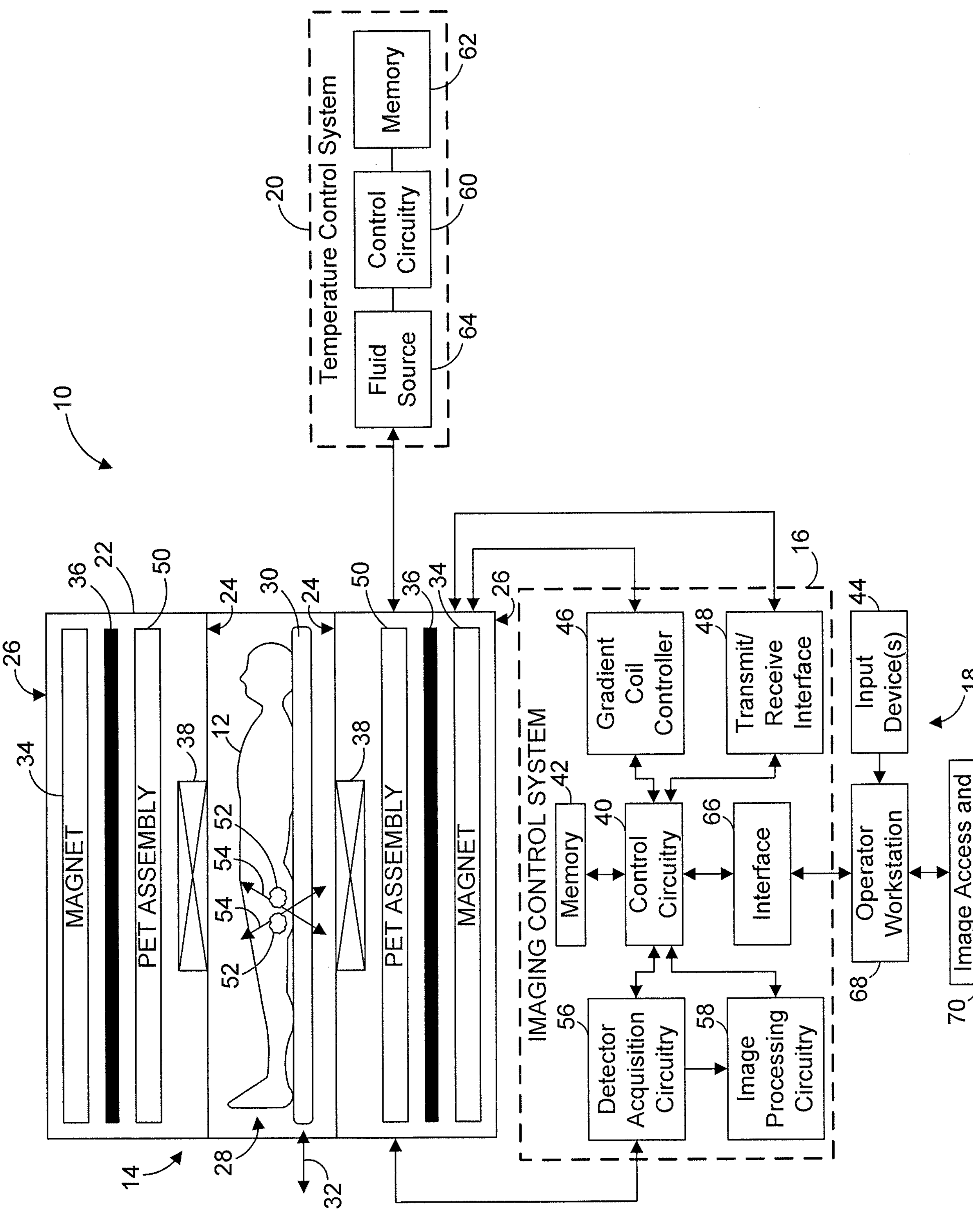
a frame comprising an outer transaxial wall and an inner transaxial wall, the inner transaxial wall defining an transaxially extending bore configured to receive a patient;

radio frequency coil disposed within the inner transaxial wall and the outer transaxial wall, the radio frequency coil being configured to generate radio frequency energy to image the patient; and

a positron emission tomography assembly, comprising:

an annular scintillator disposed between the inner transaxial wall and the outer transaxial wall about the radio frequency coil, wherein the annular scintillator comprises an annular, substantially continuous crystal tube; and

a plurality of photodetectors disposed on the outer surface of the annular scintillator farther from the transaxially extending bore than an inner surface of the annular scintillator.


Temperature Control System
Fluid Source
Control Circuitry
Memory
MAGNET
PET ASSEMBLY
IMAGING CONTROL SYSTEM
Gradient Coil Controller
Transmit/ Receive Interface
Memory
Control Circuitry
Interface
Detector Acquisition Circuitry
Image Processing Circuitry
Input Device(s)
Operator Workstation
Image Access and Control Systems
10
12
14
16
18
20
22
24
26
28
30
32
34
36
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64
66
68
70

FIG. 1

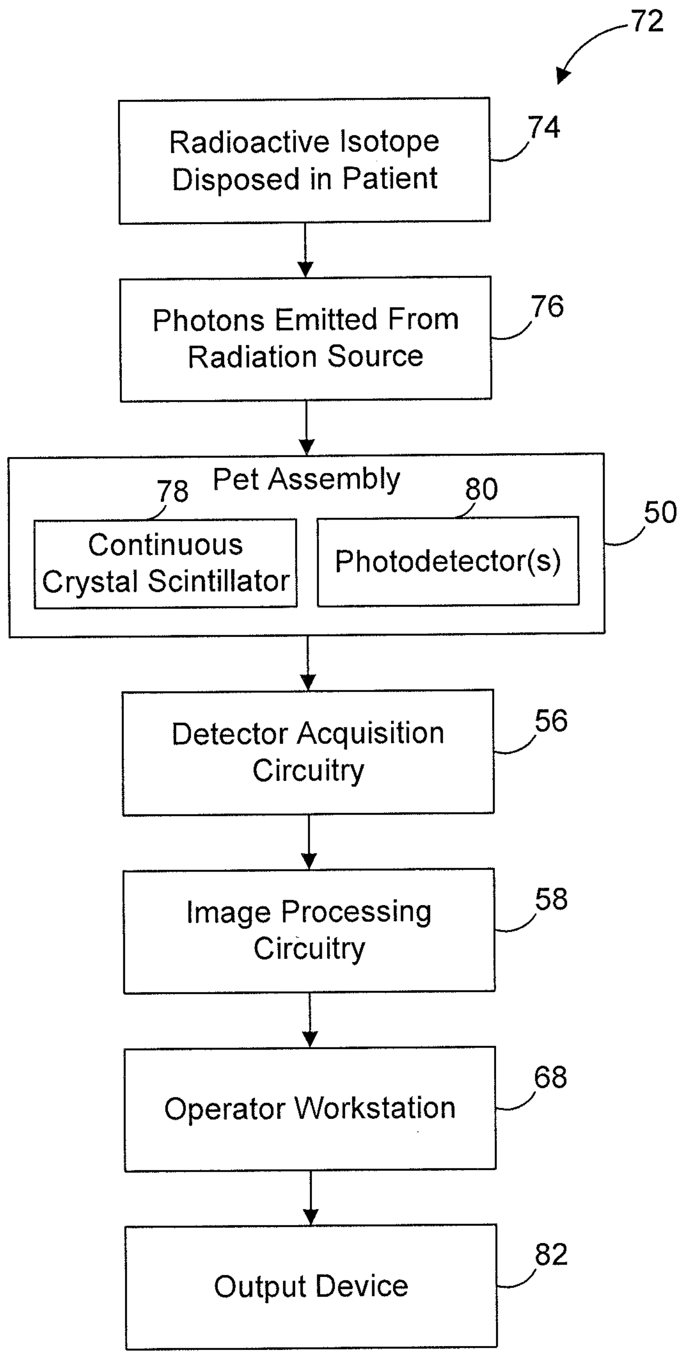

72
Radioactive Isotope Disposed in Patient
74
Photons Emitted From Radiation Source
76
Pet Assembly
78
Continuous Crystal Scintillator
80
Photodetector(s)
50
Detector Acquisition Circuitry
56
Image Processing Circuitry
58
Operator Workstation
68
Output Device
82

FIG. 2

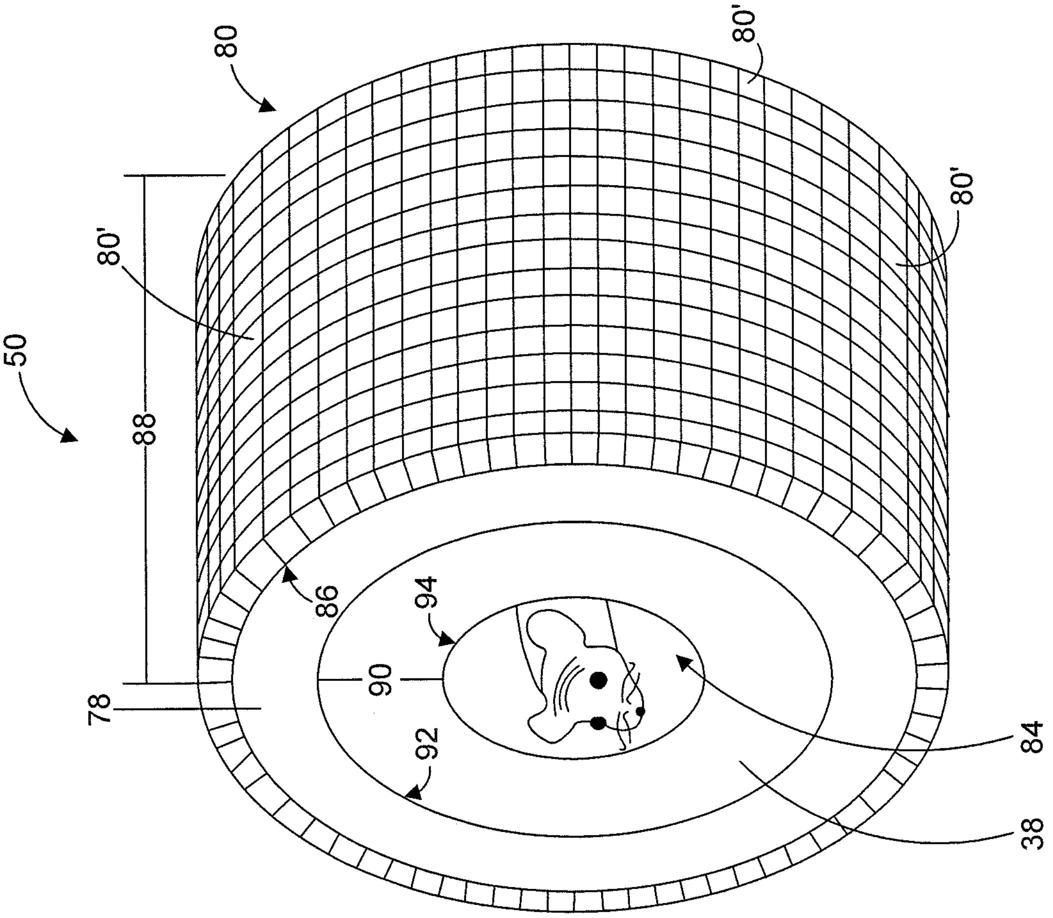
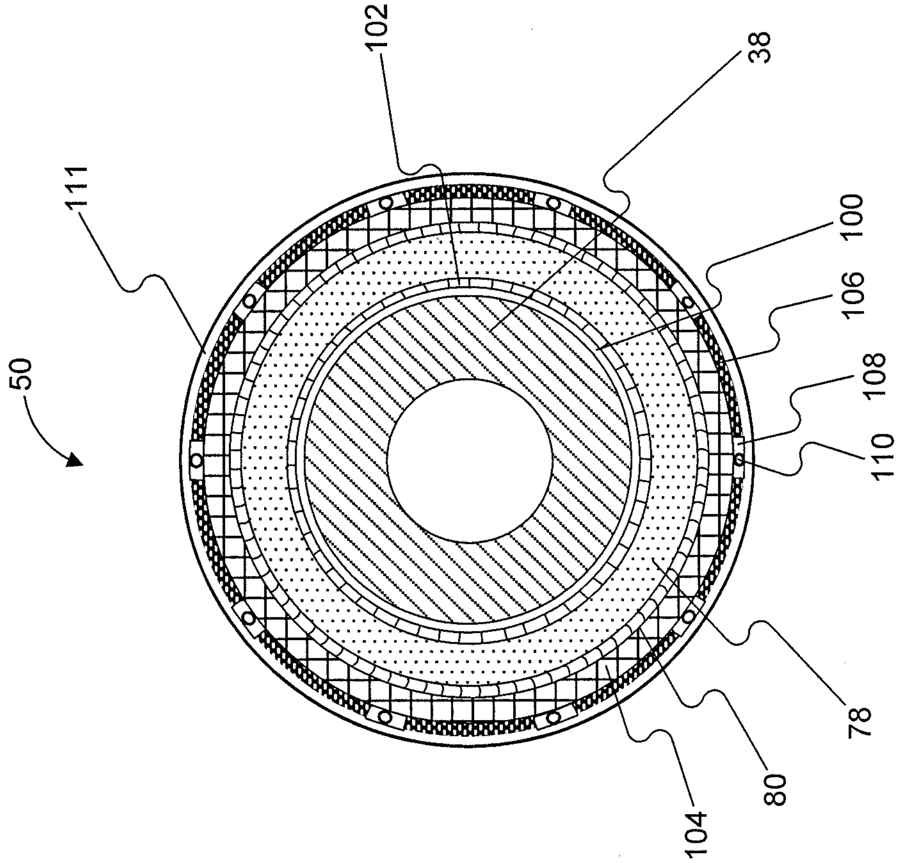


FIG. 3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111
102
38
100
106
108
110
78
80
104

FIG. 5

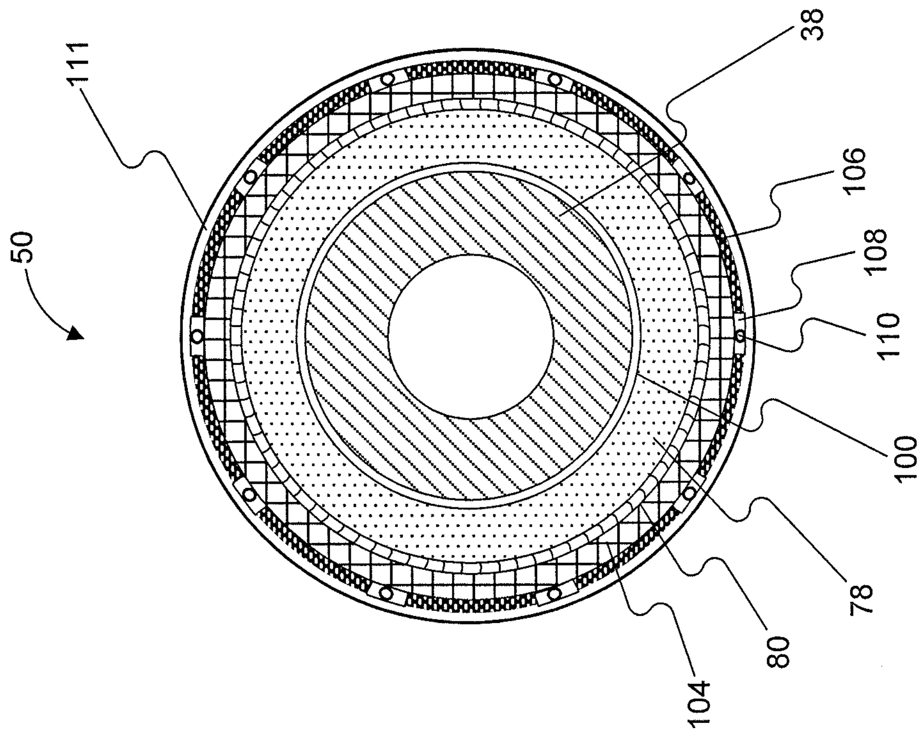
50
111
38
106
108
110
100
78
80
104

FIG. 4

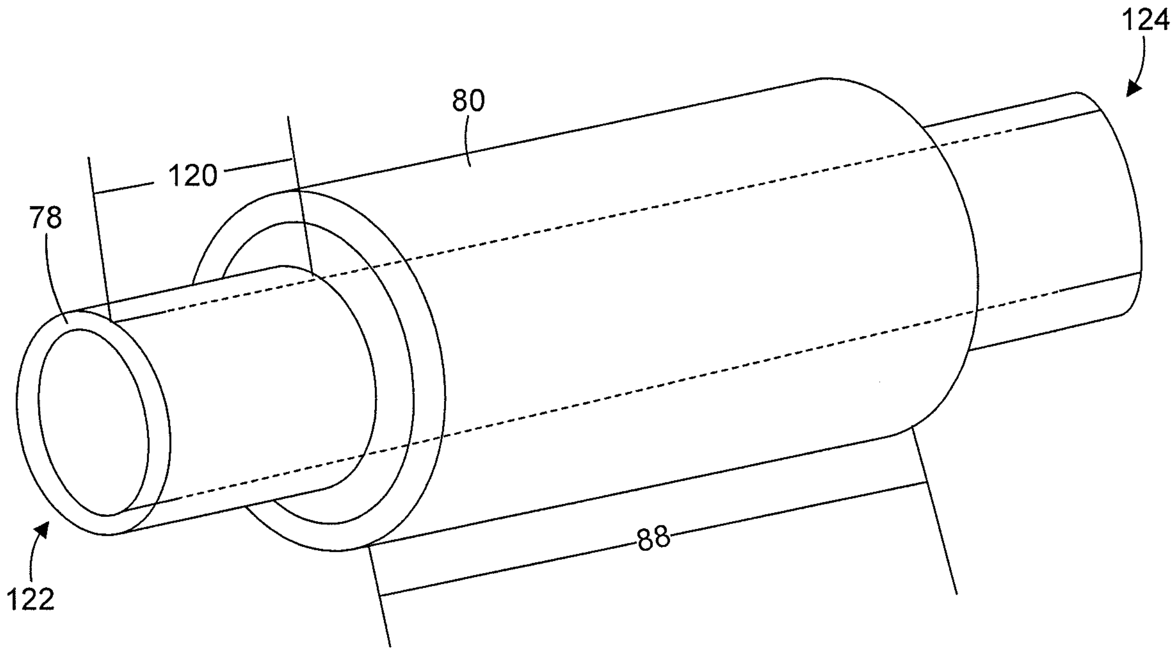

FIG. 6

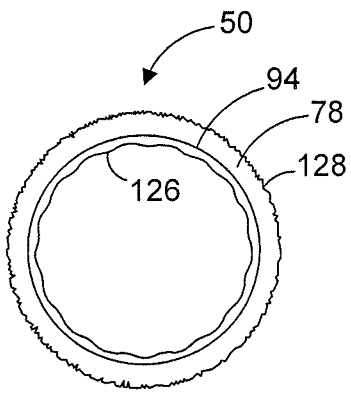

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/063534

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:
See Extra Sheet(s)

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-9

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/063534

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - A61B 6/03; A61K 49/06; A61K 49/08; A61K 49/12; A61K 49/14; G01F 1/66 (2017.01)
CPC - A61B 6/037; A61B 6/032; A61B 6/4035; A61B 6/541; A61K 49/0002; A61K 49/0034; A61K 49/06; A61K 51/06; A61K 51/088; G01R 33/4838; G01R 33/56341; G01T 1/1611; G01T 1/1615; G01T 1/202 (2017.02)

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)
See Search History document

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 4,584,478 A (GENNA et al) 22 April 1986 (22.04.1986) entire document	1, 2, 6 --- 3-5, 7-9
Y	US 2014/0361181 A1 (KONINKLIJKE PHILIPS N.V.) 11 December 2014 (11.12.2014) entire document	3, 4
Y	US 2011/0301918 A1 (HASELMAN et al) 08 December 2011 (08.12.2011) entire document	5
Y	US 2014/0084170 A1 (WIECZOREK et al) 27 March 2014 (27.03.2014) entire document	7, 9
Y	US 5,338,937 A (DAGHIGHIAN et al) 16 August 1994 (16.08.1994) entire document	8, 9

☐ 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
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"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
07 March 2017	04 APR 2017

Name and mailing address of the ISA/US	Authorized officer
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, VA 22313-1450 Facsimile No. 571-273-8300	Blaine R. Copenheaver PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/063534

Continued from Box No. III Observations where unity of invention is lacking

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fees must be paid.

Group I, claims 1-9, drawn to a positron emission tomography (PET) assembly, comprising: an annular housing.
Group II, claims 10-24, drawn to a multi-modality imaging system, comprising: a frame comprising an outer transaxial wall and an inner transaxial wall.

The inventions listed as Groups I-II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features for the following reasons: the special technical feature of the Group I invention: "a positron emission tomography (PET) assembly, comprising: an annular housing; an annular scintillator disposed within the annular housing" as claimed therein is not present in the invention of Group II. The special technical feature of the Group II invention: "a positron emission tomography assembly, comprising: an annular scintillator disposed between the inner transaxial wall and the outer transaxial wall about the radio frequency coil" as claimed therein is not present in the invention of Group I.

Groups I and II lack unity of invention because even though the inventions of these groups require the technical feature of a positron emission tomography (PET) assembly comprising the annular scintillator comprising an annular, substantially continuous crystal, and a plurality of photodetectors because this technical feature is not a special technical feature as it does not make a contribution over the prior art.

Specifically, US 2011/0301918 A1 Haselman et al., December 08 2011, teaches a positron emission tomography (PET) assembly (positron emission tomography, para. 0025) comprising the annular scintillator comprising an annular, substantially continuous crystal, and a plurality of photodetectors (a plurality of detectors arranged in an annular array, each detector comprising at least one scintillator. See claim 25. The scintillator crystal 93, para. 0054. Also see Fig.1).
Since none of the special technical features of the Group I or II inventions are found in more than one of the inventions, unity of invention is lacking.