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(54) MRI METHOD FOR ASSIGNING INDIVIDUAL PIXELS OR VOXELS TISSUE - SPECIFIC PET ATTENUATION VALUES

MRI-VERFAHREN ZUR ZUWEISUNG VON INDIVIDUELLEN GEWEBESPEZIFISCHEN PET-DÄMPFUNGSWERTEN FÜR PIXEL ODER VOXEL

PROCÉDÉ D'IRM POUR ATTRIBUER À DES PIXELS OU VOXELS INDIVIDUELS DES VALEURS D'ATTÉNUATION TEP SPÉCIFIQUES DE TISSU

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Description

[0001] The present application relates generally to medical imaging. It finds application in conjunction with magnetic resonance (MR) systems, and will be described with particular reference thereto.

[0002] In the past, computed tomography (CT) has been utilized for attenuation correction (AC) in diagnostic positron emission tomography (PET) and tissue density in simulation sessions for radiation therapy (RT) planning. Namely, CT typically measures radiodensity of tissue in Hounsfield units, which correlate with radiation attenuation and tissue density. Advances in medical imaging have led to the development of hybrid PET/MR and MR/RT systems, as well as MR-based simulation. However, unlike CT, MR signal intensity does not correlate directly with radiation attenuation (e.g., mu-values) or tissue densities and presents a technical challenge for the generation of attenuation or density maps.

[0003] To date, most research has focused on methods to differentiate or "segment" tissues from MR images into different classes, such as soft-tissue, bone and air, using "normal" anatomy or atlases or model-based approaches (i.e., shape-finding). However, such methodologies perform poorly for patients with abnormal anatomy, which is more frequent in some patient populations due to inherent disease processes or medical intervention, such as surgery and irradiation. Further, such methodologies fail to address that multiple tissue types can be located within a single image pixel or voxel. These limitations potentially lead to clinically significant inaccuracies, especially in the context of RT planning where patient dosimetry is calculated quantitatively on a pixel-to-pixel basis. Moreover, segmentation techniques are also time intensive to perform, often incorporating manual review and adjustment steps, which reduce patient throughput.

[0004] A document "MRI-Based Attenuation Correction for whole-body PET/MRI"; Quantitative Evaluation of Segmentation- and Atlas-Based Methods, The Journal of Nuclear Medicine, V. 52, No. 9, 1 September 2011 pp 1392 - 1399 by M. Hofmann et al, discloses an assessment of two algorithms for whole-body MRI-based attenuation correction.

[0005] The present application provides new and improved methods and systems which overcome the above-referenced challenges.

[0006] In accordance with one aspect, a magnetic resonance (MR) system is provided as defined in claim 1.

[0007] In accordance with another aspect, a method is provided as defined in claim 6.

[0008] One advantage resides in generating tissue-specific and/or material-specific attenuation or density values for each pixel or voxel of a target image.

[0009] Another advantage resides in a plurality of tissue-specific and/or material-specific attenuation or density values for each pixel or voxel of a target image, the plurality of values weighted according to their contribution to overall signal intensity.

[0010] Another advantage resides in improved patient throughput.

[0011] Another advantage resides in greater accuracy.

[0012] Another advantage resides in classifying tissue types utilizing magnetic resonance (MR) signal phase and/or magnitude, or the real and/or imaginary MR signal parts.

[0013] Still further advantages of the present invention will be appreciated by those of ordinary skill in the art upon reading and understand the following detailed description.

[0014] 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 illustrates a magnetic resonance (MR) system for determining tissue-specific and/or material-specific attenuation or density values for each pixel or voxel of an MR image.

FIGURE 2 illustrates a schematic diagram of a bore-type MR scanner.

FIGURE 3A illustrates a sagittal plane of an MR phase image.

FIGURE 3B illustrates data points captured during generation of the MR phase image of FIGURE 3A.

FIGURE 4 illustrates a therapy system employing an attenuation or density map.

FIGURE 5 illustrates a positron emission tomography (PET)/single-photon emission computed tomography (SPECT) system employing an attenuation or density map.

FIGURE 6 illustrates a method for generating an attenuation or density map.

[0015] With reference to FIGURE 1, a magnetic resonance (MR) system **10** utilizes magnetic resonance to form two- or three-dimensional images of a subject **12.** The system **10** includes a main magnet **14** that creates a strong, static B_0 magnetic field extending through an examination volume **16.** The examination volume **16** is sized to accommodate the subject **12.** The strength of the static B_0 magnetic field is commonly one of 0.23 Tesla, 0.5 Tesla, 1.5 Tesla, 3 Tesla, 7 Tesla, and so on in the examination region **16,** but other strengths are contemplated.

[0016] A gradient controller **18** controls a plurality of magnetic field gradient coils **20, 22, 24** to selectively superimpose magnetic field gradients, such as x, y and z gradients, on the static B_0 magnetic field in the examination volume **16.** Further, a transmitter **26** transmits B_1 resonance excitation and manipulation radio frequency (RF) pulses into the examination volume **16** with one or more transmit coils **28,** such as a whole body coil. The B_1 pulses are typically of short duration and, when taken together with the magnetic field gradients, achieve a se-

lected manipulation of magnetic resonance. For example, the B_1 pulses excite the hydrogen dipoles to resonance and the magnetic field gradients encode spatial information in the frequency and phase of the resonance signal. By adjusting the RF frequencies, resonance can be excited in other dipoles, such as phosphorous, which tend to concentrate in known tissues, such as bones. A sequence controller **30** controls the transmitter **26** and/or the gradient controller **18** to implement a selected imaging sequence within the examination volume **16,** the imaging sequence defining a sequence of B_1 pulses and/or magnetic field gradients.

[0017] In response to an imaging sequence, spatially encoded magnetic resonance signals corresponding to a map or image of the subject **12** are produced from the examination volume **16.** These spatially encoded magnetic resonance signals are received by a plurality of receive coils **32, 34, 36,** such as a whole body receive coil or local receive-only coils. A receiver **38** demodulates the received signals to an MR data set corresponding to, for example, k-space data trajectories and stores the MR data set in a data buffer (e.g., a memory) **40.** The MR data set can be employed for reconstruction of a map or image by a reconstruction processor **42.** The reconstruction processor **42** spatially decodes the spatial encoding by the magnetic field gradients to ascertain a property of the resonance signal from each spatial region, such as a pixel or voxel. The intensity or magnitude of the signal is commonly ascertained, but other properties related to phase, relaxation time, magnetization transfer, and the like can also be ascertained. Further, the real and the imaginary parts of the signal can be used to determine phase and/or magnitude. The converse also holds. Reconstructed maps or images of various properties are then stored in map and image memories **44** and, optionally, displayed on a display device **46.**

[0018] With reference to FIGURE 2, the MR system **10** includes a scanner **48** and, optionally, a support **50.** The scanner **48** defines the examination volume **16** and includes the main magnet **14,** the receive coils **32, 34, 36,** the gradient coils **20, 22, 24,** and the transmit coils **28** positioned around the examination volume **16.** The scanner **48** can also, but need not, include one or more of the transmitter **26,** the receiver **38,** the gradient controller **18,** and the sequence controller **30.** The support **50** supports the subject **12** and facilitates positioning the subject **12** in the examination volume **16** during imaging. As illustrated, the scanner **48** is bore-type, but C-type, open-type, or the like are contemplated.

[0019] Referring back to FIGURE 1, during imaging, the subject **12** is arranged in the examination volume **16.** The main magnet **14** generates the static B_0 magnetic field with which hydrogen or other nuclear dipoles in the subject **12** preferentially align. Further, a main controller **52** controls the sequence controller **30** and the receiver **38** to generate a plurality of MR data sets of the subject **12.** The main controller **52** does so by way of a processor **54** executing computer executable instructions on a memory **56.**

[0020] A sequence memory **58** stores a plurality of magnetic resonance sequences that are known in the art. The various sequences have been developed to optimize various functional, physiological and anatomical examinations. Sequences have been developed for differentiating lipids and soft tissue, for differentiating between soft tissue and scar tissue, for differentiating between cancerous and non-cancerous tissue, for differentiating various organ or tissue types, for measuring perfusion, for imaging or identifying bone, for imaging or locating metal, and many more. The main controller 52 can access a patient records database **60** to retrieve information about one or more of the patient to be examined, the nature of the examination(s) to be conducted, and the like. This patient information can be used to help select among the sequences stored in the sequence memory **58.** For example, if the patient has had surgery in which metal clips, screws, stents or the like have been implanted, the sequence for identify metal is selected. A sequence for identifying scar tissues is also retrieved if the nature of the patient treatment calls for differentiating between the radiation attenuation of soft tissue and scar tissue. The sequence controller **30** is controlled according to the selected imaging sequences, and the receiver **38** is controlled to generate an MR data set corresponding to each of the imaging sequences. When the imaging sequences include a plurality of imaging sequences, the main controller **52** iterates through the imaging sequences to control the sequence controller **30** and the receiver **38.**

[0021] The imaging sequences selected include, for example, one or more of multi-echo sequences with ultrashort echo times (TEs), slice encoding for metal artifact correction (SEMAC) sequences, and DIXON sequences. Typically, the TE values of the echos of the multi-echo UTE sequences vary. Each of the imaging sequences leads to the generation of one of the MR data sets, which can be reconstructed into a map or image and allow identification of at least one tissue and/or material type within a volume of the subject **12.** Hence, each of the imaging sequences yields MR data which differentiates between two or more tissue and/or material types, or identifies a tissue and/or material type in each pixel or voxel volume of the subject **12.** Tissue and/or material types include one or more of air, bone, lung, metal, fat, water, plastic and the like. The imaging sequences are selected, typically by the main controller **52,** based on one or a combination of selections schemes, such as the selection schemes discussed hereafter.

[0022] According to one selection scheme, a user of the MR system **10** manually selects the imaging sequences, or tissue and/or material types, within the examination volume **16** using a user input device **62** of the MR system **10.** As to the latter, the imaging sequences are then automatically selected based on the selected tissue and/or material types. Optionally, a display device, such as the display device **46,** can present the user with

a listing of available sequences and information about the use of each sequence to allow the user to select the imaging sequences, or the tissue and/or material types, using the user input device **62.** For example, the user can manually select the imaging sequences to acquire MR data sets allowing identification of tissues and/or materials of interest.

[0023] According to another selection scheme, the imaging sequences are selected based on the expected tissue and/or material types. Expected tissue and/or material types can be determined automatically from the patient records database **60.** For example, if a patient medical record indicates a patient includes metal screws from a past surgery within the volume, an imaging sequence for acquiring an MR data set allowing identification of metal is selected.

[0024] According to another selection scheme, the imaging sequences are selected on an as-needed basis. That is to say, an imaging sequence is selected and an MR data set generated in response to the selected imaging sequence is analyzed. If there are unidentified tissue and/or material types within the examination volume **16,** another imaging sequence is selected and analyzed. This repeats until the tissue and/or material types in all of the voxels within the examination volume **16** are identified. An AC processor **64** suitably performs analysis of each voxel of the various maps and images or other information from the MR data set to determine whether additional MR data sets are needed. In which case, the main controller **52** coordinates with the AC processor **64** when employing this selection scheme.

[0025] During imaging and/or after imaging, the AC processor **64** analyzes the MR data sets and the maps and images to quantitatively assess the tissue and/or material types(s) contained within each voxel, the tissue and/or material types(s) each having known radiation attenuation and/or density values. The value of each pixel or voxel is analyzed to determine one or more tissue and/or material types each pixel or voxel can and cannot be or a probability that each voxel contains each of two or more tissue and/or material types. As to the latter, some of the pixels or voxels can overlay an interface between two or more tissue and/or material types, whereby pixels or voxels can represent two or more tissue and/or material types. The possible, probable, improbable, eliminated tissue and/or material types in the corresponding pixel or voxel of all the images or maps are used to determine which tissue and/or material type(s) are in the examination volume **16** within a preselected certainty. Optionally, the display device **46** can present the user with an image depicting the tissue and/or material type in each voxel or pixel.

[0026] The value of each pixel or voxel is typically the relative MR signal intensity of the pixel or voxel relative to other pixels or voxels of the map or image generated by the same sequence. The relative signal strengths can be used to estimate a relative proportion or probability of each tissue and/or material type. The value of each pixel or voxel can alternatively correspond to phase or other magnetic resonance properties. Typically, the value of each pixel or voxel is dependent upon the nature of the sequence used to generate the image or map.

[0027] The specific approach to quantification depends upon the imaging sequence employed for generation of the MR data set. For example, where an MR data set is generated using a multi-echo UTE sequence, such as a UTE mDIXON sequence, signal intensities of a plurality of echo times can be used to identify T2* decay properties of the tissue and/or material corresponding to the pixel or voxel. The specific decay of each pixel or voxel can be used to address a lookup table **66** which maps the decay time to one or more tissue-specific and/or material-specific attenuation or density values. Alternatively, the decay can be mapped to a tissue and/or material type, which has a known attenuation or density value. More generally, additional tissue and/or material properties may be defined and the properties used to determine the tissue and/or material type.

[0028] While the foregoing focused on MR signal intensity imaging, MR phase imaging is used according to the invention to generate identifying information about the tissue and/or material corresponding to each pixel or voxel. MR signal intensity imaging can be suboptimal due to the lack of quantification, the non-linear fit of signal contrast over time, and low signal to noise ratio (SNR). These limitations deter quantitative measurement of tissue properties over the time course of patient-care leading to inaccuracies in standardized uptake values (SUV) in positron emission tomography (PET) and present a barrier to the development of adaptive patient-specific dosimetry and treatment plans in radiation therapy (RT) planning.

[0029] In contrast to MR signal intensity imaging, MR phase imaging has superior SNR, leading to improved image contrast in low signal tissues, such as cortical bone. In addition, MR phase imaging has a linear fit of tissue-dependent phase accumulation over time, making quantification practical and technically feasible. Such an approach provides a reliable means to monitor the same patient over time allowing assessment of tumor response to treatment with SUVs in PET and MR-based RT planning.

[0030] With reference to FIGURES 3A and 3B, the linearity of MR phase is illustrated. FIGURE 3A illustrates a sagittal plane of an MR phase image. The vertical axis corresponds to rows, and the horizontal axis corresponds to columns, in the MR phase image. FIGURE 3B illustrates data points captured during generation of the MR phase image for row 81, column 61 of the MR phase image. The vertical axis corresponds to signal intensity, and the horizontal axis corresponds to echo times in microseconds. A first line is fit to the data points to show the linearity. A second line is fit to data points (not visible) for signal intensity to show the nonlinearity of signal intensity.

[0031] While MR phase imaging has certain advantag-

es over MR signal intensity imaging, MR phase imaging is primarily used for quantification (e.g., T1, T2, T2* and diffusion mapping) despite MR phase imaging being capable of quantification. MR phase imaging is more difficult to use because of phase wrap and less direct anatomical information. Accordingly, MR phase imaging is generally limited to: (1) "susceptibility weighted imaging," and is typically only semi-quantitative and depends on information from the MR magnitude signal; and (2) quantification of certain contrast agents for certain geometries.

[0032] To overcome the foregoing challenges, a series of ultra-short TE acquisition sequences of MR phase data are used. Suitably, inphase TEs are chosen. Ultra short TEs (e.g., 0 to 1500 microseconds) are preferable to acquire signal from very short T2* species, such as cortical bone. For post-processing, the reconstruction processor **42** analyzes the MR phase data to: (1) unwrap the phase; and (2) then map the intensity of the series of images as a function of time, thus producing a series of phase accumulation maps. Phase unwrapping can, for example, be performed in accordance with the algorithm disclosed in Jenkinson M. Fast, Automated, N-dimensional Phase-Unwrapping Algorithm. Magn Reson Med 2003; 49:193-197. Each phase accumulation map corresponds to a different TE and is generated by accumulating the different intensities measured during the corresponding acquisition sequence for each pixel.

[0033] The change in phase over time (i.e., over the different TEs) is known to be linearly correlated to tissue type. Unlike known uses of MR phase, the MR phase is used by the AC processor **64** to allow generation of a quantitative map for all tissue types. The change in phase over time for each pixel or voxel is used to lookup the known tissue type for the change in phase over time. The quantitative map, in turn, can be used to generate AC maps (e.g., for PET-MR) and/or density maps (e.g., for MR RT planning and simulation) by mapping the different tissue types in the quantitative map to known AC values and/or density values of the tissue types in the quantitative map. The quantitative map can also be used to acquire sets of ultra-short TEs that can characterize additional tissues with very short T2*.

[0034] Once the MR data sets are analyzed to identify tissue-specific and/or material-specific radiation attenuation or density values, the tissue-specific and/or material-specific attenuation or density values are normalized and combined to create a patient specific attenuation or density map. To determine radiation attenuation of radiation traversing a given beam or ray through the subject **12,** a corresponding beam or trajectory is identified in the attenuation map. The attenuation values of the voxels falling in or partially in the beam or ray are summed by a percent contribution or inclusion within the beam or ray.

[0035] One challenge with combining the tissue-specific and/or material-specific attenuation or density values of the MR data sets into the attenuation or density map is that the coordinate frames of the MR data sets and the target image may not align. Further, the spatial resolutions of the MR data sets and the target image may not be the same. Hence, the voxels or pixels of the MR data sets and the target image need to be correlated. Because the MR data sets and the target image overlap spatially, one approach is image registration. Using image registration, a registration map from a first image to a second image can be generated, which can be used to map a pixel or voxel in the first image to the corresponding pixel(s) or voxel in the second image.

[0036] Typically the resolutions of the images are the same, but the resolutions need not be the same. Where the resolutions of the first image and the second image differ, the pixels of the two images may not include a 1:1 correspondence. If the resolution of the second image is greater than the resolution of the first image, a pixel in the first image can map to a plurality of pixels in the second image. If the resolution of the second image is less than the resolution of the first image, a plurality of pixels in the first image can map to a single pixel in the second image. More generally, image-processing operations may be used to obtain images at the desired resolution. To combine the tissue-specific and/or material-specific attenuation or density values for a plurality of pixels in the first image, any approach can be employed. However, one approach is, for each tissue and/or material type, to average the attenuation or density values of the pixels.

[0037] Once the attenuation or density map is generated, it is stored in an attenuation or density memory **68.** Further, it can be used for attenuation correction in PET/MR systems. Additionally, the attenuation or density map can be employed in hybrid MR/radiation therapy (RT) systems for treatment planning and monitoring. For example, the attenuation or density map can be employed for density correction in MR guided high intensity focused ultrasound (HIFU). As another example, the attenuation or density map can be employed for pixel- and/or voxel-based dosimetry in MR simulation. Additionally, the attenuation or density map can be employed for identifying iron in the liver or bone delineation for digitally reconstructed radiograph (DRR) generation.

[0038] With reference to FIGURE 4, a therapy system **70** (e.g., for MR RT planning and/or simulation) receives a planning image **72,** such as three- or four-dimensional image, of the subject **12** from an imaging modality, such as the MR scanner **48.** The image includes a target and, commonly, one or more organs at risk (OARs), the target being an organ or other tissue region which contains a lesion, such as a tumor, to be treated. Other imaging modalities from which the planning image **72** can be received include a computed tomography (CT) scanner, a positron emission tomography (PET) scanner, a single photon emission computed tomography (SPECT) scanner, a cone-beam computed tomography (CBCT) scanner, and the like. The therapy system **70** further receives an attenuation or density map **74** of tissue-specific and/or material-specific densities generated by the MR system **10.** Suitably, the attenuation or density map **74** is registered to the planning image **72.**

[0039] A therapy planning system **76** of the therapy system **70** receives delineates between tissue regions, such as the target and/or the organs at risk, in the planning image **72** typically using contours surrounding the regions. Further, using the attenuation or density map **74** and the contours of the target and/or the OARs, the therapy planning system **76** generates a treatment plan. The generated treatment plan takes in to account the tissue-specific and/or material-specific densities of the attenuation or density map **74** when generating the treatment plan, and suitably includes a plurality of fractions and a planned treatment volume (PTV) to be irradiated. The treatment plan is suitably stored in a therapy memory **78.**

[0040] At a scheduled day and time for a therapy session of the subject **12,** a therapy delivery apparatus **80** of the therapy system **70** delivers therapy to the subject **12.** The therapy, such as ablation therapy and/or brachytherapy, can include radiation involving one or more of x-rays, gamma rays, protons, HIFU, focused ultrasound, and the like. Suitably, the therapy delivery apparatus **80** is controlled by a therapy control system **82** in accordance with the treatment plan.

[0041] With reference to FIGURE 5, a PET/SPECT system **84** includes a plurality of detector modules **86, 88, 90, 92, 94, 96, 98, 100** arranged, typically in a circle or a polygon approximating a circle, around an examination volume **102** into which a patient volume **104** is positioned. Further, the PET/SPECT system **84** can include a patient support (not shown), such as a patient bed, to support the patient and/or position the patient volume **104** in the examination volume **102.** Examples of the imaged patient volume **104** include, but are not limited to, hearts, brains, thyroids, bones, joints, ligaments, tendons, muscles, nerves, kidneys, lungs, tumors, lesions, and so on.

[0042] Before imaging, the patient volume **104** is injected with one or more radioisotopes. Examples of such radioisotopes include, but are not limited to, F-18 C-11, Rb-82, N-13, O-15, Cu-64 for PET and Tc-99m, 1-131, Ga-67, and In-lll for SPECT. The radioisotopes can be in the form of radioligands or material generally called a radiopharmaceutical that binds to specific types of tissue and/or material, is preferentially absorbed by specific types of tissue and/or material, is normally excluded from certain spaces, or exhibits some other desired biodistribution. The patient volume **104** is then positioned in the examination volume **102.** For example, the patient is positioned on the patient support and the patient support moves the patient volume **104** into the examination volume **102.**

[0043] The detector modules **86, 88, 90, 92, 94, 96, 98, 100** receive gamma photons emitted by the radioisotopes injected into the patient volume **104** during imaging. The received gamma photons penetrate into, deposit energy within, and are detected by the detector modules **86, 88, 90, 92, 94, 96, 98, 100.** For example, in PET and as illustrated, a pair of gamma photons are emitted from the patient volume **104** and strike a first detector module **86** and a second detector module **94** nearly simultaneously. The detector modules **86, 88, 90, 92, 94, 96, 98, 100** digitize detected events and send the digitized events with corresponding time stamps to a processing system **106** of the PET/SPECT system **84.** The digitized events suitably identify the location of the corresponding gamma photon interaction in the detector, energy of the event and the time stamp.

[0044] During imaging, the processing system **106** acquires event data from the detector modules **86, 88, 90, 92, 94, 96, 98, 100** over a selected period of time, such as ten minutes. For each detection event, the detection event data typically includes a location of the detection event and information of the detector, energy of each event, and a time stamp. The event data is stored in a memory and reconstructed into a three-dimensional image representation. For PET, this includes filtering invalid events, pairing events based on the time stamps to define line of responses (LORs), and reconstructing the LORs into an image respresentation. For time of flight (TOF) PET, the time stamps associated with each LOR are used to localize the annihilation event which caused the gamma photon pair along the LOR. For SPECT, the reconstruction is similar except that the processing does not include pairing. Reconstruction is suitably performed using an attenuation or density map **108** generated by the MR system **10** for attenuation correction.

[0045] With reference to FIGURE 6, a method **150** for generating an attenuation or density map is provided. The method **150** is performed by the MR system **10.** The method **150** includes applying **152** a plurality of imaging sequences to the examination volume **16.** Suitably, the imaging sequences include sequences which differentiate between different combinations of tissue and/or material types. In response to the imaging sequences, a plurality of MR data sets of a patient volume are received and registered **154.** Each of the MR data sets is then analyzed **156** to identify different tissue and/or material types in the MR data set. For example, the data sets can be reconstructed into maps or images. The properties of the corresponding voxels in the maps or images can be employed to identify the tissue and/or material type(s) in the patient. Based on the tissue and/or material types, tissue-specific and/or material-specific attenuation or density values are assigned **158** to the corresponding pixels or voxels of the attenuation density image or map.

[0046] The method **150** can be further enhanced to iteratively acquire the MR data sets. Namely, the method **150** can include selecting one of the imaging sequences. For example, the initial selected imaging sequence can be a multi-echo UTE sequence with varying TEs. The selected imaging sequence is then applied to the examination volume **16** and, in response to the selected imaging sequence, at least one of the MR data sets are received. The first MR data set is then analyzed to determine the characteristics of tissue and/or material within of each pixel or voxel. In response to unidentified tissue and/or material, or artifacts, another one of the imaging

sequences is selected and the foregoing steps are repeated. This process may be iterated with additional acquisitions and analyses. For example, metal cannot be identified with the multi-echo UTE sequence. Hence, if there are unidentified tissue and/or material types after the multi-echo UTE sequence, an imaging sequence for identifying metal, such as SEMAC can be selected.

[0047] It is to be appreciated that utilizing a pixel or voxel-based approach bypasses pitfalls associated with anatomy or atlas approaches to attenuation correction or density determination since it does not require normal anatomy or shape-finding. Further, by quantitatively assessing the resonance data corresponding to each voxel, more than one attenuation value for different tissue and/or material types can be assigned to each pixel or voxel and weighted according to their percent contribution to the overall signal intensity.

[0048] As used herein, a memory includes one or more of a non-transient computer readable medium; a magnetic disk or other magnetic storage medium; an optical disk or other optical storage medium; a random access memory (RAM), read-only memory (ROM), or other electronic memory device or chip or set of operatively interconnected chips; an Internet/Intranet server from which the stored instructions may be retrieved via the Internet/Intranet or a local area network; or so forth. Further, as used herein, a processor includes one or more of a microprocessor, a microcontroller, a graphic processing unit (GPU), an application-specific integrated circuit (ASIC), an FPGA, and the like; a controller includes: (1) a processor and a memory, the processor executing computer executable instructions on the memory embodying the functionality of the controller; or (2) analog and/or digital hardware; a user input device includes one or more of a mouse, a keyboard, a touch screen display, one or more buttons, one or more switches, one or more toggles, voice recognition engines, and the like; a database includes one or more memories; and a display device includes one or more of a LCD display, an LED display, a plasma display, a projection display, a touch screen display, and the like.

[0049] 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 construed as including all such modifications and alterations insofar as they come within the scope of the appended claims.

Claims

1. A system **(10)** comprising:

a magnetic resonance (MR) scanner **(48)** defining an examination volume **(16);** and
at least one processor **(54)** programmed to:
control the MR scanner **(48)** to apply imaging sequences to a subject (12) arranged in the examination volume **(16);**
in response to the imaging sequences, acquire a series of MR data sets of the subject (12) at a plurality of mutually different echo times (TEs);
reconstruct an MR phase image from each MR data set, thereby generating a series of MR phase images;
phase unwrap the series of MR phase images;
map the intensity of the series of MR phase images as a function of time, thereby producing a series of phase accumulation maps; and to
use the change in phase over time from the series of phase accumulation maps to identify the tissue and/or material type of each pixel or voxel of interest within a volume of the subject (12).

2. The system (10) according to claim 1, wherein the at least one processor (54) is further programmed to:
assign one or more tissue-specific and/or material-specific values to each pixel or voxel of the volume of the subject based on the identified tissue and/or material type(s).

3. The system **(10)** according to claim 2, wherein tissue-specific and/or material-specific values assigned to a pixel or voxel are weighted based on a percent contribution of the corresponding tissue or material.

4. The system **(10)** according to either one of claims 1-3, wherein the at least one processor (54) is further programmed to select the TEs of the series of TE acquisitions to be inphase and ultra-short.

5. The system **(10)** according to any one of claims 1-4, wherein the at least one processor **(54)** is further programmed to:
generate a positron emission tomography (PET) image using known attenuation correction values associated with the different tissue and/or material types found in the examination volume **(16).**

6. A method comprising the steps of:

controlling a MR scanner **(48)** to apply imaging sequences to a subject (12) arranged in an examination volume **(16)** defined by an MR scanner **(48);**
in response to the imaging sequences, acquiring a series of of MR data sets of the subject (12) at a plurality of mutually different echo times (TEs); reconstructing an MR phase image from

each MR data set, thereby generating a series of MR phase images;
phase unwrapping the series of MR phase images;
mapping the intensity of the series of MR phase images as a function of time, thereby producing a series of phase accumulation maps; and
using the change in phase over time from the series of phase accumulation maps to identify the tissue and/or material type of each pixel or voxel of interest within a volume of the subject (12).

7. The method (10) according to claim 6, further including the steps of:
assigning one or more tissue-specific and/or material-specific values to each pixel or voxel of the volume of the subject based on the identified tissue and/or material type(s).

8. The method according to any one of claims 6 and 7, wherein the TEs of the series of TE acquisitions are inphase and ultra-short.

9. The method according to any one of claims 6-8, further including the step of:
generating a positron emission tomography (PET) image using known attenuation correction values associated with the different tissue and/or material types found in the examination volume **(16).**

10. A non-transitory computer readable medium **(56)** carrying software configured to control or more processors **(54)** of a magnetic resonance scanner to perform the method **(150)** according to any one of claims 6-9.

Patentansprüche

1. System **(10)** umfassend:

einen Magnetresonanz(MR)-Scanner **(48),** der ein Untersuchungsvolumen **(16)** definiert, und
mindestens einem Prozessor **(54),** der programmiert ist zum:

Steuern des MR-Scanners **(48),** um Bildgebungssequenzen auf ein Subjekt (12) anzuwenden, das in dem Untersuchungsvolumen **(16)** angeordnet ist;
Ermitteln einer Reihe von MR-Datensätzen des Subjekts (12) zu einer
Mehrzahl von voneinander verschiedenen Nachhallzeiten (TE) als Reaktion auf die Bildgebungssequenzen;
Rekonstruieren eines MR-Phasenbilds aus jedem MR-Datensatz, wodurch eine Reihe von MR-Phasenbildern erzeugt wird;
Phasenentpacken der Reihe von MR-Phasenbildern;
Abbilden der Intensität der Reihe von MR-Phasenbildern als Funktion der Zeit, wodurch eine Reihe von Phasenakkumulationsabbildungen produziert wird, und
Verwenden der Phasenänderung im Zeitverlauf aus der Reihe von Phasenakkumulationsabbildungen, um den Gewebe- und/oder Materialtyp jedes Pixels oder Voxels von Interesse innerhalb eines Volumens des Subjekts (12) zu identifizieren.

2. System **(10)** nach Anspruch 1, wobei der mindestens eine Prozessor **(54)** ferner programmiert ist zum:
Zuweisen eines oder mehrerer gewebespezifischen und/oder materialspezifischen Werte zu jedem Pixel oder Voxel des Volumens des Subjekts auf Basis des (mindestens einen) identifizierten Gewebe- und/oder Materialtyps.

3. System **(10)** nach Anspruch 2, wobei gewebespezifische und/oder materialspezifische Werte, die einem Pixel oder Voxel zugewiesen werden,
auf Basis eines prozentualen Beitrags des entsprechenden Gewebes oder Materials gewichtet werden.

4. System **(10)** nach einem der Ansprüche 1-3, wobei der mindestens eine Prozessor (54) ferner dafür programmiert ist, die TE der
Reihe von ermittelten TE so auszuwählen, dass diese phasengleich und ultrakurz sind.

5. System **(10)** nach einem der Ansprüche 1-4, wobei der mindestens eine Prozessor **(54)** ferner programmiert ist zum:
Erzeugen eines Positronemissionstomographie(PET)-Bildes unter Verwendung bekannter Attenuationskorrekturwerte, die mit den verschiedenen Gewebe- und/oder Materialtypen assoziiert sind, die in dem Untersuchungsvolumen **(16)** vorkommen.

6. Verfahren, die folgenden Schritte umfassend:

Steuern eines MR-Scanners **(48),** um Bildgebungssequenzen auf ein Subjekt (12) anzuwenden,
das in einem Untersuchungsvolumen **(16)** angeordnet ist, das von einem MR-Scanner **(48)** definiert wird;
Ermitteln einer Reihe von MR-Datensätzen des Subjekts (12) zu einer
Mehrzahl von voneinander verschiedenen Nachhallzeiten (TE) als Reaktion auf die Bildgebungssequenzen;

Rekonstruieren eines MR-Phasenbilds aus jedem MR-Datensatz, wodurch eine Reihe von MR-Phasenbildern erzeugt wird;
Phasenentpacken der Reihe von MR-Phasenbildern;
Abbilden der Intensität der Reihe von MR-Phasenbildern als Funktion der Zeit, wodurch eine Reihe von Phasenakkumulationsabbildungen produziert wird; und
Verwenden der Phasenänderung im Zeitverlauf aus der Reihe von Phasenakkumulationsabbildungen, um den Gewebe- und/oder Materialtyp jedes Pixels oder Voxels von Interesse innerhalb eines Volumens des Subjekts (12) zu identifizieren.

7. Verfahren **(10)** nach Anspruch 6, ferner die folgenden Schritte umfassend:
Zuweisen eines oder mehrerer gewebespezifischen und/oder materialspezifischen Werte zu jedem Pixel oder Voxel des Volumens des Subjekts
auf Basis des (mindestens einen) identifizierten Gewebe- und/oder Materialtyps.

8. Verfahren nach einem der Ansprüche 6 und 7, wobei die TE der Reihen von ermittelten TE phasengleich und ultrakurz sind.

9. Verfahren nach einem der Ansprüche 6-8, ferner die folgenden Schritte umfassend:
Erzeugen eines Positronemissionstomographie(PET)-Bildes unter Verwendung bekannter Attenuationskorrekturwerte, die mit den verschiedenen Gewebe- und/oder Materialtypen assoziiert sind, die in dem Untersuchungsvolumen **(16)** vorkommen.

10. Nicht-flüchtiges computerlesbares Medium **(56),** das Software trägt, die dafür ausgelegt ist,
einen oder mehrere Prozessoren **(54)** eines Magnetresonanzscanners so zu steuern,
dass dieser das Verfahren **(150)** nach einem der Ansprüche 6-9 durchführt.

Revendications

1. Système **(10)** comprenant :

un balayeur à résonance magnétique (RM) **(48)** définissant un volume d'examen **(16)** ; et
au moins un processeur **(54)** programmé :

pour commander le balayeur RM **(48)** pour appliquer des séquences d'imagerie à un sujet (12) disposé dans le volume d'examen **(16)** ;
pour acquérir, en réponse aux séquences d'imagerie, une série d'ensembles de données RM du sujet (12) à une
pluralité de temps d'écho (TE) mutuellement différents ;
pour reconstruire une image de phase RM à partir de chaque ensemble de données RM, générant ainsi une série d'images de phase RM ;
pour effectuer le déroulement de phase de la série d'images de phase RM ;
pour cartographier l'intensité de la série d'images de phase RM en fonction du temps, générant ainsi une série de cartes d'accumulation de phase ; et pour utiliser le changement de phase dans le temps à partir de la série de cartes d'accumulation de phase pour identifier le type de tissu et/ou de matière de chaque pixel ou chaque voxel d'intérêt dans un volume du sujet (12) .

2. Système **(10)** selon la revendication 1, dans lequel l'au moins un processeur **(54)** est en outre programmé :
pour attribuer au moins une valeur spécifique au tissu et/ou à la matière à chaque pixel ou chaque voxel du volume du sujet en fonction du type de tissu et/ou de matière identifié.

3. Système **(10)** selon la revendication 2, dans lequel les valeurs spécifiques au tissu et/ou spécifiques à la matière attribuées à un pixel ou à un voxel sont pondérées en fonction d'une contribution en pourcentage du tissu ou de la matière correspondant.

4. Système **(10)** selon l'une quelconque des revendications 1 à 3, dans lequel l'au moins un processeur (54) est en outre programmé pour sélectionner les TE de la
série d'acquisitions TE pour être en phase et ultracourts.

5. Système **(10)** selon l'une quelconque des revendications 1 à 4, dans lequel l'au moins un processeur **(54)** est en outre programmé :
pour générer une image de tomographie par émission de positons (TEP) à l'aide des valeurs de correction d'atténuation connues associées aux différents types de tissu et/ou de matière trouvés dans le volume d'examen **(16) .**

6. Procédé comprenant les étapes suivantes :

la commande d'un balayeur RM **(48)** pour appliquer des séquences d'imagerie à un sujet (12) disposé dans un volume
d'examen **(16)** défini par un balayeur RM **(48)** ;
l'acquisition, en réponse aux séquences d'imagerie, d'une série d'ensembles de données RM

du sujet (12) à une
pluralité de temps d'écho mutuellement différents (TE) ; la reconstruction d'une image de phase MR à partir de chaque ensemble de données RM, générant ainsi une série d'images de phase RM ;
le déroulement de phase de la série d'images de phase RM ;
la cartographie de l'intensité de la série d'images de phase RM en fonction du temps, générant ainsi d'une série de cartes d'accumulation de phase ; et
l'utilisation du changement de phase dans le temps à partir de la série de cartes d'accumulation de phase pour identifier le type de tissu et/ou de matière de chaque pixel ou de chaque voxel d'intérêt dans un volume du sujet (12).

7. Procédé **(10)** selon la revendication 6, comprenant en outre les étapes suivantes :
l'attribution d'au moins une valeur spécifique au tissu et/ou à la matière à chaque pixel ou à chaque voxel du volume du sujet
en fonction du type de tissu et/ou de matière identifié.

8. Procédé selon l'une quelconque des revendications 6 et 7, dans lequel les TE de la série d'acquisitions TE sont en phase et ultra-courts.

9. Procédé selon l'une quelconque des revendications 6 à 8, comprenant en outre l'étape suivante :
la génération d'une image de tomographie par émission de positons (TEP) à l'aide des valeurs de correction d'atténuation associées aux différents types de tissu et/ou de matière trouvés dans le volume d'examen **(16)** .

10. Support lisible par ordinateur non transitoire **(56)** portant un logiciel configuré pour commander au moins un processeur **(54)** d'un balayeur à résonance magnétique pour mettre en œuvre le procédé **(150)** selon l'une quelconque des
revendications 6 à 9.

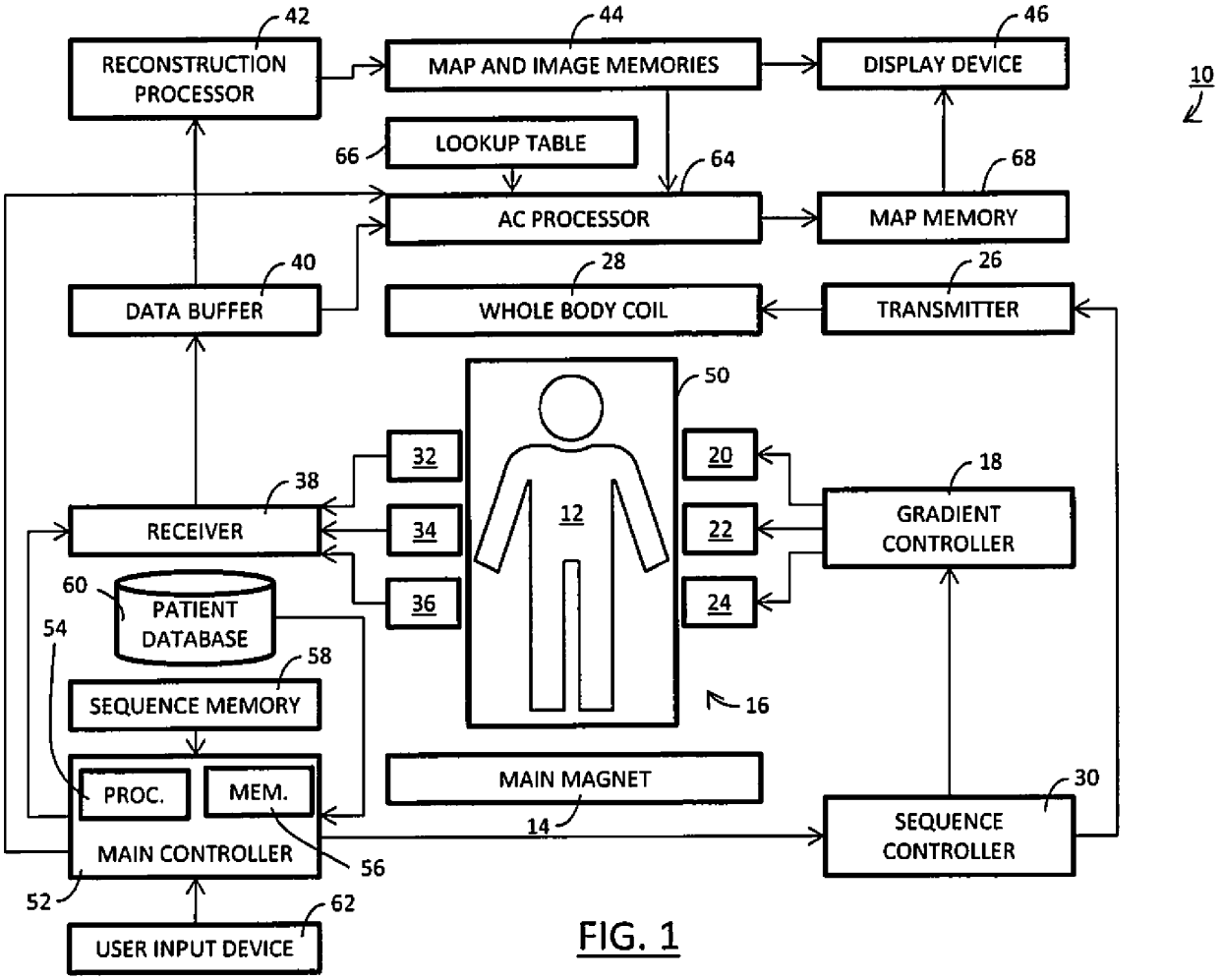

FIG. 1

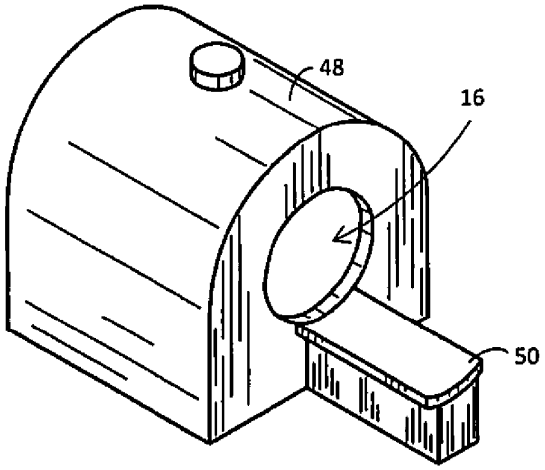

FIG. 2
(PRIOR ART)

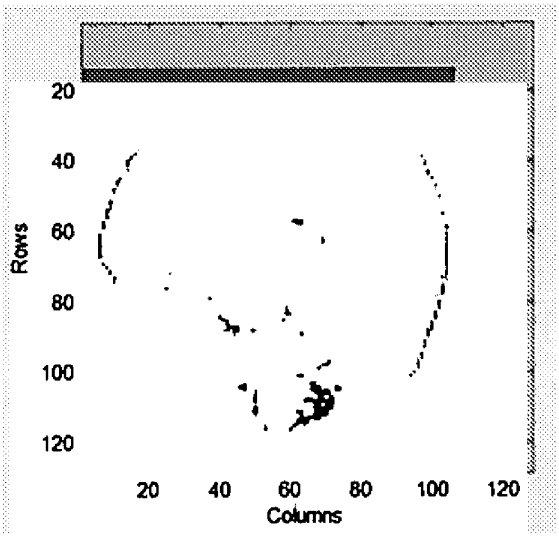

FIG. 3A

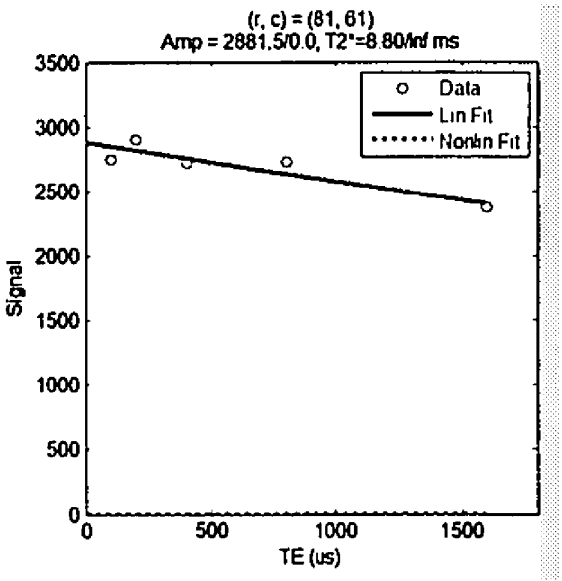

FIG. 3B

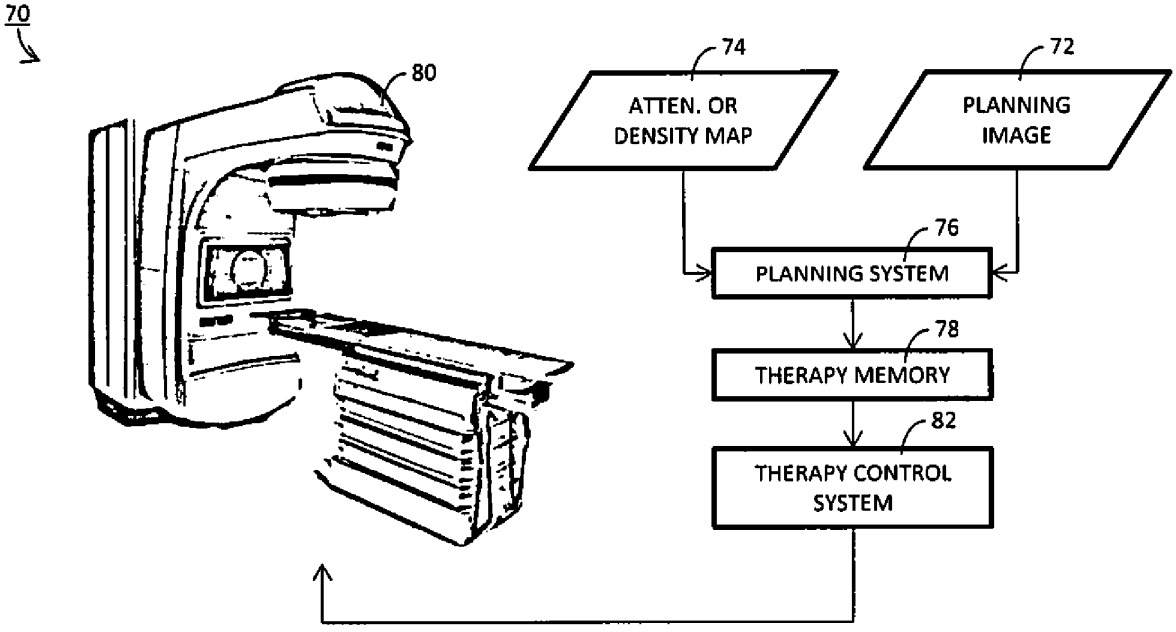

FIG. 4

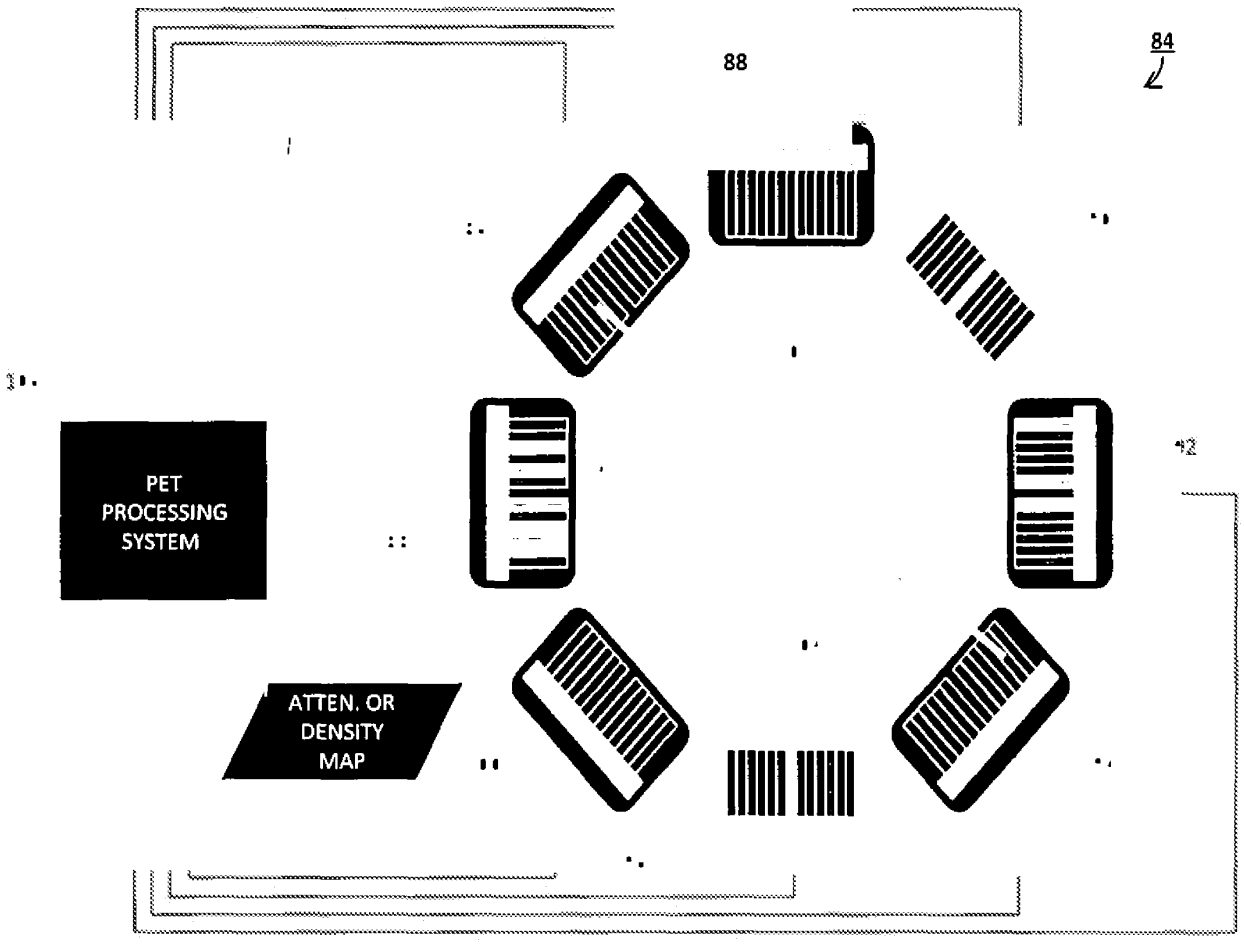
88
84
PET PROCESSING SYSTEM
ATTEN. OR DENSITY MAP

FIG. 5

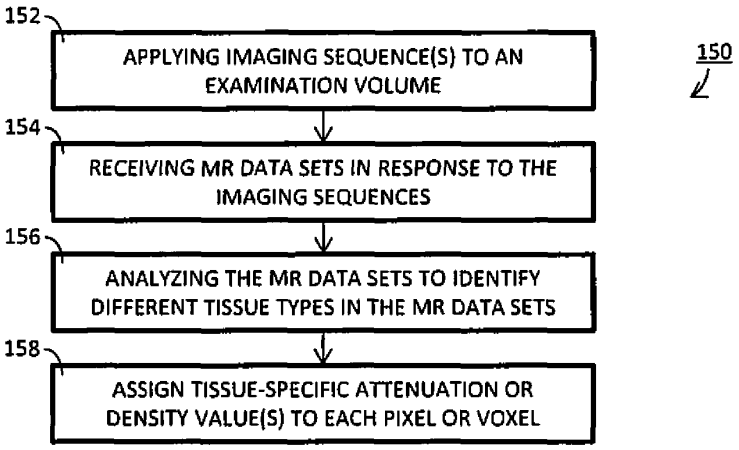
152
APPLYING IMAGING SEQUENCE(S) TO AN EXAMINATION VOLUME
154
RECEIVING MR DATA SETS IN RESPONSE TO THE IMAGING SEQUENCES
156
ANALYZING THE MR DATA SETS TO IDENTIFY DIFFERENT TISSUE TYPES IN THE MR DATA SETS
158
ASSIGN TISSUE-SPECIFIC ATTENUATION OR DENSITY VALUE(S) TO EACH PIXEL OR VOXEL
150

FIG. 6

REFERENCES CITED IN THE DESCRIPTION

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Non-patent literature cited in the description

- **M. HOFMANN.** MRI-Based Attenuation Correction for whole-body PET/MRI''; Quantitative Evaluation of Segmentation- and Atlas-Based Methods. *The Journal of Nuclear Medicine,* 01 September 2011, vol. 52 (9), 1392-1399 **[0004]**
- **JENKINSON M.** Fast, Automated, N-dimensional Phase-Unwrapping Algorithm. *Magn Reson Med,* 2003, vol. 49, 193-197 **[0032]**