(19) Europäisches
Patentamt
European
Patent Office
Office européen
des brevets

(11) **EP 3 039 453 B1**

(12) **EUROPEAN PATENT SPECIFICATION**

(45) Date of publication and mention
of the grant of the patent:
**29.04.2020 Bulletin 2020/18**

(21) Application number: **14784189.4**

(22) Date of filing: **29.08.2014**

(51) Int Cl.:
***G01T 1/16*** $^{(2006.01)}$ ***G01T 1/29*** $^{(2006.01)}$

(86) International application number:
**PCT/EP2014/068374**

(87) International publication number:
**WO 2015/028604 (05.03.2015 Gazette 2015/09)**

# (54) A TOF-PET TOMOGRAPH AND A METHOD OF IMAGING USING A TOF-PET TOMOGRAPH, BASED ON A PROBABILITY OF PRODUCTION AND LIFETIME OF A POSITRONIUM

EIN TOF-PET TOMOGRAPH UND EIN VERFAHREN DER BILDFORMUNG ANHAND EINES TOF-PET TOMOGRAPHEN, AUF BASIS EINER WAHRSCHEINLICHKEIT DER PRODUKTION UND LEBENSDAUER EINES POSITRONIUMS

TOF-PET TOMOGRAPHE ET METODE DE FORMATION D’IMAGE UTILISANT UN TOF-PET TOMOGRAPH, SUR LA BASE D’UNE PROBABILITE DE PRODUCTION ET DURÉE DE VIE D’UN POSITRONIUM

(84) Designated Contracting States:
**AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR**

(30) Priority: **30.08.2013 PL 40518513**

(43) Date of publication of application:
**06.07.2016 Bulletin 2016/27**

(73) Proprietor: **Uniwersytet Jagiellonski**
**31-007 Krakow (PL)**

(72) Inventors:
- **MOSKAL, Pawel**
  **32-061 Czulowek (PL)**
- **MOSKAL, Ines**
  **32-061 Czulowek (PL)**
- **MOSKAL, Gabriel**
  **32-061 Czulowek (PL)**

(74) Representative: **Kancelaria Eupatent.pl Sp. z.o.o**
**Ul. Kilinskiego 185**
**90-348 Lodz (PL)**

(56) References cited:
**WO-A2-2007/117801 WO-A2-2012/135725**
**US-A- 4 864 131 US-A- 4 939 464**
**US-A1- 2005 104 001**

- **PAWEL MOSKAL: "TOF-PET detector concept based on organic scintillators", NUCLEAR MEDICINE REVIEW 2012, [Online] vol. 15, no. C, 31 December 2012 (2012-12-31), pages C81-C84, XP002733765,**
- **C.P.SWANN, V.K.RASMUSSEN,F.R.METZGER: "Lifetime of the First Excited State of N-14", PHYSICAL REVIEW, vol. 121, no. 1, 1 January 1961 (1961-01-01), pages 242-245, XP002733766,**
- **DANIEL W RICKEY ET AL: "ON LIFTING THE INHERENT LIMITATIONS OF POSITRON EMISSION TOMOGRAPHY BY USING MAGNETIC FIELDS (MagPET)", AUTOMEDICA, GORDON AND BREACH SCIENCE PUBLISHERS, LONDON, GB, vol. 14, 10 January 1992 (1992-01-10), pages 355-369, XP007922936, ISSN: 0095-0963**

Note: Within nine months of the publication of the mention of the grant of the European patent in the European Patent Bulletin, any person may give notice to the European Patent Office of opposition to that patent, in accordance with the Implementing Regulations. Notice of opposition shall not be deemed to have been filed until the opposition fee has been paid. (Art. 99(1) European Patent Convention).

Printed by Jouve, 75001 PARIS (FR)

## Description

### TECHNICAL FIELD

**[0001]** The present disclosure relates to a TOF-PET tomograph and a method of imaging using a TOF-PET tomograph, based on a probability of production and lifetime of a positronium.

### BACKGROUND

**[0002]** Images of the interiors of bodies may be acquired using various types of tomographic techniques, which involve recording and measuring radiation from tissues and processing acquired data into images.

**[0003]** One of these tomographic techniques is positron emission tomography (PET), which involves determining spatial distribution of a selected substance throughout the body and facilitates detection of changes in the concentration of that substance over time, thus allowing to determine the metabolic rates in tissue cells.

**[0004]** The selected substance is a radiopharmaceutical administered to the examined object (e.g. a patient) before the PET scan. The radiopharmaceutical, also referred to as an isotopic tracer, is a chemical substance having at least one atom replaced by a radioactive isotope, e.g. $^{11}C$, $^{15}O$, $^{13}N$, $^{18}F$, selected so that it undergoes radioactive decay including the emission of a positron (antielectron). The positron is emitted from the atom nucleus and penetrates into the object's tissue, where it is annihilated in reaction with an electron present within the object's body.

**[0005]** The phenomenon of positron and electron annihilation, constituting the principle of PET imaging, consists in converting the masses of both particles into energy emitted as annihilation photons, each having the energy of 511 keV. A single annihilation event usually leads to formation of two photons that diverge in opposite directions at the angle of 180° in accordance with the law of conservation of the momentum within the electron-positron pair's rest frame, with the straight line of photon emission being referred to as the line of response (LOR). The stream of photons generated in the above process is referred to as gamma radiation and each photon is referred to as gamma quantum to highlight the nuclear origin of this radiation. The gamma quanta are capable of penetrating matter, including tissues of living organisms, facilitating their detection at certain distance from object's body. The process of annihilation of the positron-electron pair usually occurs at a distance of several millimetres from the place of the radioactive decay of the isotopic tracer. This distance constitutes a natural limitation of the spatial resolution of PET images to a few millimetres.

**[0006]** In addition to the direct annihilation, also annihilation via electron-positron bound state may exist. Annihilation in the bound state occurs along with creation of the quasi-stable state with the so-called positronium (Ps). Dimensions of positronium are close to the size of the hydrogen atom; however positronium energy structure is significantly different from the energy structure of the hydrogen atom. Positronium, similarly to the hydrogen atom, may be formed in a singlet state of the anti-parallel spins orientation, the so-called para-positronium (p-Ps), with the average lifetime in a vacuum of $\tau_{p\text{-}Ps} = 0.125$ ns, or in a triplet state of parallel spin orientation, the so-called ortho-positronium (oPs) with the average lifetime in a vacuum of $\tau_{o\text{-}Ps} = 142$ ns. The lifetime of ortho-positronium $\tau_{o\text{-}Ps}$ decreases to a few nanoseconds in the spaces between cells, while in the case of materials of high electron density, such as metals, o-Ps is not formed at all. Due to the symmetry of charge conjugation, p-Ps undergoes annihilation with emission of an even number of gamma quanta (most often, two quanta), while o-Ps undergoes annihilation with emission of an odd number of gamma quanta (most often, three quanta). The probability of o-Ps creation is three times greater than the probability of p-Ps, creation, whereas the multiple interaction of positronium with environment electrons cause that at the moment of the annihilation, the o-Ps to p-Ps ratio may differ from three. Processes leading to changes in this ratio are called positronium quenching processes. One of the quenching processes is the so-called "pick-off' process, which consists in the fact that the positron bound with electron in positronium annihilates with another electron from the environment. This process involves a quick break of positron-electron "bond" in positronium and immediate annihilation of positron with an electron from the environment. Another example of the process leading to shortening the lifetime of o-Ps is the o-Ps transition into the state of p-Ps. The probability of the positronium quenching processes depends on the size of electron-free volumes, wherein the larger the free volumes in the material, the less the probability of occurrence of the quenching processes and the longer the lifetime of o-Ps.

**[0007]** For free positrons, the direct annihilation with electrons into two gamma quanta is about 370 times more likely than annihilation into 3 gamma quanta, and almost a million times more likely than annihilation into four gamma quanta. Such drastic differences are mainly due to the small value of the electromagnetic coupling constant of 1/137. This means that annihilation usually takes place into two gamma quanta. Annihilations that occurred with creation, in an intermediate state, of ortho-positronium also occur, in the vast majority, into two gamma quanta because they are the result of either conversion of ortho-positronium into para-positronium or interaction of the positron with the electron not bound to it.

**[0008]** Currently, in the PET technique, the phenomenon of producing positronium is neither recorded nor used for imaging. Using conventional PET tomographs gives information on the distribution of a radiopharmaceutical in the body of the object. The detection system of conventional PET tomographs is programmed to record data on annihilation into two gamma quanta of energy of 511 keV.

**[0009]** A PET scanner comprises detection devices used to detect gamma radiation as well as electronic hardware and software allowing to determine the position of the positron-electron pair annihilation on the basis of the position and time of detection of a particular pair of the gamma quanta. The radiation detectors are usually arranged in layers forming a ring around object's body and are mainly made of an inorganic scintillation material. A gamma quantum enters the scintillator, which absorbs its energy to re-emit it in the form of light (a stream of photons). The mechanism of gamma quantum energy absorption within the scintillator may be of dual nature, occurring either by means of the Compton's effect or by means of the photoelectric phenomenon, with only the photoelectric phenomenon being taken into account in calculations carried out by current PET scanners. Thus, it is assumed that the number of photons generated in the scintillator material is proportional to the energy of gamma quanta deposited within the scintillator.

**[0010]** When two annihilation gamma quanta are detected by a pair of detectors at a time interval not larger than several nanoseconds, i.e. in coincidence, the position of annihilation point along the line of response may be determined, i.e. along the line connecting the detector centres or the points within the scintillator strips where the energy of the gamma quanta was deposited. The coordinates of annihilation place are obtained from the difference in times of arrival of two gamma quanta to the detectors located at both ends of the LOR. In the prior art literature, this technique is referred to as the time of flight (TOF) technique, and the PET scanners utilizing time measurements are referred to as TOF-PET scanners. This technique requires that the scintillator has time resolution of a few hundred picoseconds.

**[0011]** Light pulses reaching the scintillator can be converted into electric pulses by means of photomultipliers or photodiodes. Electric signals from the converters carry information on positions and times of the annihilation quanta subjected to detection, as well as on the energy deposited by these quanta.

**[0012]** The standard detection systems of PET tomographs comprises a scintillator layer surrounding the detection chamber, which absorb gamma quanta, being a product of radiopharmaceutical decay, and emits scintillation photons. The most commonly used scintillators are inorganic crystals. In addition, there are known polymer scintillators for use in PET tomographs, as disclosed by patent applications WO2011/008119 and WO2011008118; they enable achieving much better time resolution of the detection system - at the level of 100 ps.

**[0013]** Document WO2012135725 further discloses a PET scanner with imaging detectors capable of detecting annihilation gamma rays and including prompt gamma-ray detectors. A time-window for triple coincidences made up of two annihilation gamma hits and one de-excitation gamma hit is defined between positron emission and prompt gamma emission.

**[0014]** Also hybrid tomographs are known in which the PET technique is combined with other known imaging techniques such as magnetic resonance imaging (MRI) or computed tomography (CT). Using these devices, hybrid images are obtained, for example, PET/CT or PET/MRI, which provide complementary information: anatomical, functional and morphological. CT tomography provides anatomical image, PET provides metabolic image, while the MR tomography provides morphological image; the PET imaging is particularly advantageous for early detection of metabolic changes - before occurrence of morphological changes detectable via CT or MR imaging. Combination of metabolic (PET) and anatomical (CT) images, or combination of PET image with the morphological (MR) image, is particularly advantageous because it allows precise localization of metabolic changes in individual body parts and determination of degree of these changes.

**[0015]** The parameter determining the degree of metabolic changes recorded by PET is SUV index *(Standardised Uptake Value),* which expresses the value of the uptake of the radiopharmaceutical in a volume unit (voxel) of the organism in relation to the average value of the uptake of the radiopharmaceutical throughout the body. The higher the SUV the greater the probability of occurrence of cells with disturbed metabolism in a given region of tissue.

**[0016]** The measurement of the lifetime of positrons is used to study the structure of matter at the atomic level. The Positron annihilation lifetime spectroscopy (PALS) allows collect data in the form of positron lifetime spectra, based on which a degree of defect of material of the test sample can be determined. PALS spectroscopes, similarly as PET tomographs, include the scintillators detection system which is connected to the computer. PALS spectrometer measurement consists in introduction of a sample of material with an isotope tracer between detectors and registration of gamma quanta. Positron lifetime information contained in the PALS spectrum is read, for example, by means of a computer program as a result of a numerical analysis consisting in matching the theoretical function to the experimental time spectrum. Such analysis enables determination of the several components of positron lifetime, including ortho-positronium lifetime.

**[0017]** Literature includes numerous publications concerning measurement of lifetime of positrons using the PALS technique.

**[0018]** The article "Badanie zmian wolnych objętości w strukturze polimerowych dwuogniskowych soczewek kontaktowych metodą anihilacji pozytonów" [*Study of changes in free volume in the polymer structure of bifocal contact lenses using the positron annihilation method"* (J. Filipecki et al., Polimery w Medycynie 2010 [*Polymers in Medicine*

*2010*], Vol. 40, No. 4, pp. 27 - 33) published results of research on positron lifetime value in the polymer material used for production of contact lenses. As a source of positrons, the radioactive $^{22}$Na isotope was used. Positron lifetime values were calculated using a computer program taking into account the time resolution of the detection system of 270ps. The best match between the theoretical function and the points constituting the time spectrum was obtained by dividing positron lifetime spectra into three components. The first and the second component were introduced to the program as the following constant values: $\tau_{p\text{-}Ps}$=0.125ns and $\tau_b$=0.36ns (average lifetime of positrons with free annihilation). For all samples measured using the spectrometer, the third component $\tau_{o\text{-}Ps}$ responsible for the process of annihilation of ortho-positronium related with the process of ortho-positronium "pick-off' by free volume in the polymer matrix was calculated. The study showed that the lifetime of ortho-positronium $\tau_{o\text{-}Ps}$ reflects the average size of free volume present in the polymer matrix.

**[0019]** The article "Influence of neoplastic therapy on the investigated blood using positron annihilation lifetime spectroscopy" (R. Pietrzak et al. NUKLEONIKA 2013, 58 (1): pp. 199-202) describes an experiment in which the PALS spectrometer was used to measure lifetime of positrons in blood samples taken from healthy examined objects and examined objects with cancer. As a source of gamma radiation, $^{22}$Na isotope was used. The spectrometer used was characterized by the time resolution of 226ps. Using a computer program, the average lifetime of ortho-positronium in blood samples of normal and disturbed metabolism was calculated. The results showed that the average radius of the volumes between cells is reduced from about 0.25 nm in blood cells of normal metabolism to about 0.12 nm in blood cells with a disturbed metabolism.

**[0020]** Thus, the larger the ratio of the atom-free volume to the volume of high electron density, the greater the probability that a positron emitted from the radiopharmaceutical creates a bounded state with the electron. The probability of creation and lifetime of positronium depends on the electromagnetic environment (density and momentum distribution of electrons), in which the positron interacts with an electron, which in turn depends on the size of the space between cells; these, in turn, depend on the type of tissue and, in particular, on the stage of development of metabolic disorders (age of ill cells).

**[0021]** It would be desirable to develop a method for measuring the lifetime of positrons in living organisms without the need for invasive sampling, and the development of a tomograph which would enable imaging of positron lifetime distributions as a function of position in the body, providing information about the structure of tissue at the atomic level and allowing for estimating the degree of cell metabolism disorder.

## SUMMARY

**[0022]** The invention provides a tomograph for imaging an interior of an examined object according to claim 1 and a method of imaging according to claim 6. Further embodiments are detailed in the dependent claims.

## BRIEF DESCRIPTION OF FIGURES

**[0023]** Example embodiments are presented on a drawing wherein:

Fig. 1 is a block diagram of the process of reconstruction of images of distribution of lifetime of ortho-positronium in the first embodiment in an example of TOF-PET tomograph;
Fig. 2 is a block diagram of the process of reconstruction of images of distribution of lifetime of ortho-positronium in the second embodiment in an example of hybrid TOF-PET/CT tomograph;
Fig. 3 is a block diagram of the process of reconstruction of images of distribution of lifetime of ortho-positronium in the third embodiment in an example of hybrid TOF-PET/MRI tomograph;
Fig. 4 presents structure of the TOF-PET tomograph for the process depicted in Figure 1;
Fig. 5 presents structure of the hybrid TOF-PET/CT tomograph for realisation of the process depicted in Figure 2;
Fig. 6 presents structure of the hybrid TOF-PET/MRI tomograph for realisation of the process depicted in Figure 3.

## DETAILED DESCRIPTION

**[0024]** For registration of gamma quanta by the presented means, polymer TOF-PET detectors described in patent applications WO2011/008118 or WO2011/008119 can be used.

**[0025]** Fig. 1 is a block diagram of the process of obtaining images of distribution of lifetime of ortho-positronium as a function of position in an examined object (e.g. a living organism) based on an example of TOF-PET tomograph; TOF-PET tomograph comprises a detector system 110 which may include multiple detector modules and a scintillation chamber, into which the examined object after application of the radiopharmaceutical is introduced for registration of gamma radiation.

**[0026]** A single detector module is constructed of a scintillator coupled to at least one photomultiplier, or to a photomultiplier system, wherein any detection system registering gamma radiation allowing for tomograph time resolution below 100ps may be used. For example, in the presented method, images of the positron lifetime can be prepared using a tomograph with polymer scintillation strips, wherein each detection module comprises polymer scintillators to achieve a time resolution of less than 100 ps. Before scanning with the TOF-PET tomograph, a radiopharmaceutical with a radioactive tracer is administered to an examined object, the tracer is selected from radioactive isotopes whose atomic nuclei undergo $\beta^+$ decay and upon emission of positrons change into daughter nuclei remaining in an excited state for some time, then deexcitating through emission of one or several gamma quanta, while the lifetime of the daughter nucleus in an excited state must not exceed 100 ps. An example of a radiotracer meeting the above criteria is the isotope of oxygen: $^{14}O$, which by emitting a positron changes into nitrogen isotope: $^{14}N$ in the excited state with energy of about 2.3 MeV and average lifetime of about 0.07 ps.

**[0027]** The procedure begins with starting the detection system in step 110, which records the gamma quanta from annihilation into two gamma quanta of energy 511keV, analogously to the known TOF-PET tomograph, and registers gamma quanta from annihilation into three gamma quanta, as well as deexcitation gamma quanta resulting from deexcitation of daughter nucleus of radiotracer.

**[0028]** Gamma quanta created as result of annihilation and deexcitation of daughter nucleus of radiotracer are changed into electrical signals by photomultipliers and sent in step 111 via cables to electronic units constituting the data acquisition system *(DAQ).*

**[0029]** The data acquisition system, with respect to the trigger signal, determines the amplitude and time of creation of signals and sends them in step 112 as digital data to a recorder, where they can be saved to disk; the trigger signal is a result of logical operations performed by the electronic system in step 111 in order to make a decision to save or reject the signal. In the next step, 113, by means of a computer an identification and selection of such signals is performed which were registered in step 110 in at least two detection modules within a predetermined time interval (a few nanoseconds).

**[0030]** Further analysis and processing by a computer program will be carried out only for those signals for which within one time interval:

- two gamma quanta were registered: $\mu$ = 2, and both gamma quanta meet the criteria for identification of quanta from annihilation of electron with positron into two gamma quanta;
- three gamma quanta were registered: $\mu$ = 3, and two of the three gamma quanta meet the criteria for identification of quanta from annihilation of electron with positron into two gamma quanta and the third gamma quantum meets the criterion for identification of gamma quanta from deexcitation of daughter nucleus;
- four gamma quanta were registered: $\mu$ = 4, and at least one gamma quantum meets the criterion for identification of gamma quanta from deexcitation of daughter nucleus;
- where $\mu$ is a multiplicity of an event, i.e., the number of registered gamma quanta within a single time interval, resulting from decay of radioactive radiotracer atom.

**[0031]** Data obtained from detection modules, which registered event multiplicity of $\mu$ = 2 and $\mu$ = 3 can be used to reconstruct the images of density distribution of the radiopharmaceutical in examined object's body: M (x, y, z), based on known image reconstruction methods of PET 120, 121, 122, 123, for example by means of TOF-PET technique, wherein for events with the multiplicity of $\mu$ = 2 what is used is the data obtained from both detection modules 110, and for events of multiplicity of $\mu$ = 3, in the first step the modules that registered annihilation quanta are identified, since only this data is used to reconstruct a metabolic image M (x, y, z) 122. In step 120 reconstruction of the following data is carried out: LOR (Line of Response) and TOF (Time of Flight), which is obtained in step 121 and on this basis image reconstruction is performed in step 122, thereby obtaining a metabolic image in step 123.

**[0032]** For events with multiplicity of $\mu$ = 3 and $\mu$ = 4 with annihilation into two gamma quanta, data 113 and 117 from detection modules is used to reconstruct 118 of additional two images:

a) image of distribution of lifetime of ortho-positronium as a function of position in an examined object $\tau_{p\text{-}Ps}$ (x, y, z) 119 and

b) image of distribution of probability of creation of positronium as a function of position in an examined object $P_{poz}$(x, y, z) 119,

wherein x, y and z coordinates indicate the centre of a given voxel in the body of the examined object.

**[0033]** In addition for events with $\mu$ = 4 with annihilation into three gamma quanta, data 117 obtained from the detection modules 110 is used to reconstruct the additional image 119 of distribution of lifetime of ortho-positronium ($\tau_{o\text{-}Ps}$) wherein the image is obtained for larger areas of the body, due to low statistics of events (low probability of annihilation into three gamma quanta).

**[0034]** Detectors 110 that registered annihilation quanta and deexcitation quanta are identified in such a way that:

- the maximum value of energy that an annihilation gamma quantum can deposit in the scintillator is calculated,
- the maximum value of energy that an deexcitation gamma quantum can deposit in the scintillator is calculated,
- the energy criterion of identification of annihilation and deexcitation gamma quanta ($E_{min}$) is determined, whose value is characteristic for a given PET tomograph.

**[0035]** The maximum energy that an annihilation and deexcitation gamma quantum can deposit in the scintillator material - $E_{max}$ is determined taking into account the fact that distribution of energy deposited in the scintillator is continuous in the range from 0 to $E_{max}$, for example, using the formula:

$$E_{max}= ( E_{\gamma} / (m_e/2E_{\gamma} + 1) ) \qquad \text{(Formula I)}$$

where:

$E_{\gamma}$ - energy of emitted gamma quantum (annihilation or deexcitation)
$m_e$- electron mass

**[0036]** Formula I may be used to calculate $E_{max}$ in scintillators for which the photoelectric effect does not occur for absorbed gamma quanta of energy in the order of 1 MeV, such as polymer scintillators.

**[0037]** For example, for TOF-PET tomograph with polymer scintillation strips, the value $E_{max}$ for annihilation quanta, calculated according to the Formula I, is about 340 keV, while for deexcitation quantum from nucleus $^{14}N$ deexcitation, which is a daughter nucleus in the case of the use of radiopharmaceutical traced with oxygen $^{14}O$ isotope, the value of $E_{max}$ is about 2070 keV. This high difference in values of $E_{max}$ of annihilation and deexcitation quanta deposited in scintillators allows them to be identified.

**[0038]** The energy criterion $E_{min}$ can be, for example, determined by maximizing the probability product of correct identification and efficiency of selection as a function of value of $E_{min}$, while $E_{min}$ is to be optimized for a given energy resolution of detection modules and energy value of deexcitation quantum.

**[0039]** For example, for polymer scintillator strips read out by two photomultipliers, whose energy resolution is about ten percent, the energetic criterion for annihilation quanta of $E_{max}$ = 340 keV is $E_{min}$ = 400keV. This means that every registered signal resulting from depositing energy $\leq E_{min}$ is identified as the annihilation quantum signal and every registered signal resulting from depositing energy > $E_{min}$ is identified as deexcitation quantum signal.

**[0040]** Other events: when three detection modules registered energy greater than $E_{min}$ or no module registered energy of a value greater than $E_{min}$, they are not used for image reconstruction for events $\mu$ = 3 and $\mu$ = 4.

**[0041]** In the next step, for events with multiplicity $\mu$ = 3 with annihilation into two gamma quanta, position ($\vec{r_a}$) and time ($t_a$) of annihilation is determined in step 115. For the purpose of computing, the momentum conservation principle implying movement of annihilation quanta opposite to each other in a straight line is used. The coordinates of the point of annihilation into two gamma quanta can be determined analytically based on the measurement of position of reaction of gamma quanta in detection modules and difference in times of arrival of these quanta to the reaction positions according to the known formula:

$$\vec{r_a} = \frac{\vec{r_1} + \vec{r_2}}{2} + \frac{\vec{r_1} - \vec{r_2}}{|\vec{r_1} - \vec{r_2}|} \cdot (t2 - t1) \cdot \frac{c}{2} \qquad \text{(Formula II)}$$

where:

$\vec{r_a}$ - vector indicating the point of annihilation
$\vec{r_1}$ - vector of position of reaction of gamma quantum in detection module 1
$\vec{t_1}$ -gamma quantum reaction time registered in module 1
$\vec{r_2}$ - vector of position of reaction of gamma quantum in detection module 2
$t_2$ -gamma quantum reaction time registered in module 2

c - speed of light in vacuum

**[0042]** Time of annihilation into two gamma quanta can be calculated from the formula:

$$t_a = \frac{t_1 + t_2}{2}$$

(Formula III)

$t_a$ - The time of annihilation at a point, whose coordinates are defined by the vector $\vec{r_a}$
$t_1$ -gamma quantum reaction time registered in module 1
$t_2$ -gamma quantum reaction time registered in module 2

**[0043]** The position and time of annihilation using the presented method may also by determined for events with a multiplicity of $\mu = 4$, in which annihilation occurred with emission of three gamma quanta. In this case, the momentum conservation principle implying movement of three annihilation quanta in one plane is used. An exemplary way of determining the vector indicating the point of annihilation into three gamma quanta ($\vec{r_a}$) and determining the time of annihilation into three gamma quanta ($t_a$), performed in step 115, is minimising the variable $\chi^2$ defined as:

$$\chi^2(v, t_a) = \sum_{i=1}^{3}(\,(t_i - t_a)c\, - d_{iv})^2$$

(Formula IV)

where:

i - index of detection module which registered one of three annihilation gamma quanta
v- index of searched voxel
$d_{iv}$ - distance between the position of reaction of gamma quantum in the i-th module and the centre of the v-th voxel
$t_a$ - searched time in which annihilation took place
$t_i$ - gamma quantum reaction time registered in i-th module
c - speed of light in vacuum

**[0044]** For annihilation into three gamma quanta by using the momentum conservation principle, the number of searched voxels in the examined object is limited to voxels lying in the plane defined by three points which are the positions of reaction of gamma quanta in three detection modules. As the voxel in which annihilation ($v_a$) took place, and as annihilation time ($t_a$), the values for which $\chi^2(v_a, t_a)$ reaches a minimum value ($\chi^2_{min}$) are selected, while the value $\chi^2_{min}$ can also be used to assess the coplanarity of registered gamma quanta, and thus can constitute a criterion for rejecting events for which at least one of the gamma quanta is scattered.

**[0045]** Then, the distribution of time difference $\Delta t$ is calculated for each voxel separately: 114, 115, as follows:

$$\Delta t = t_a - t_e$$

(Formula V)

where:

$\Delta t$ - time difference
$t_e$ - deexcitation quantum emission time
$t_a$ - time of annihilation

**[0046]** Deexcitation quantum emission time ($t_e$) is calculated as time in which the deexcitation quantum interacted in the detection module less the time of flight of the quantum from the position of emission to the position of reaction in the scintillator material:

$$t_e = t_\mu - d_e/c \qquad \text{(Formula VI)}$$

where:

$t_\mu$ - interaction time of deexcitation gamma quantum in the detection module;
$d_e$ - distance between the position of emission of deexcitation quantum and the position of reaction of gamma quantum in detection module;

it is assumed that the position of emission of deexcitation quantum is equivalent to the position of annihilation for the same event (Formula VI). This assumption may introduce a slight blur of 20 ps, negligible compared to ortho-positronium lifetime.

**[0047]** Distribution of time difference $\Delta t$ is approximately the sum of three distributions:

$$N(\Delta t) = N_b(\Delta t) + N_{p\text{-}Ps}(\Delta t) + N_{o\text{-}Ps}(\Delta t) \qquad \text{(Formula VII)}$$

where:

$N_b(\Delta t)$ - convolution of function describing the resolution of measurement of time difference $\Delta t$ with exponential function describing distribution of lifetimes of positron with direct positron annihilation
$N_{p\text{-}Ps}(\Delta t)$ - convolution of function describing the resolution of measurement of time difference $\Delta t$ with exponential function describing distribution of lifetimes of para-positronium
$N_{o\text{-}Ps}(\Delta t)$ - convolution of function describing the resolution of measurement of time difference $\Delta t$ with exponential function describing distribution of lifetimes of ortho-positronium

**[0048]** Thus $N(\Delta t)$ can also be expressed in a more explicit form by means of the equation:

$$N(\Delta t) = R(\Delta t) * N_b^0\, e^{-\Delta t/\tau b} + R(\Delta t) * N_p^0\, e^{-\Delta t/\tau p\text{-}Ps} + R(\Delta t) * N_o^0\, e^{-\Delta t/\tau o\text{-}Ps} \qquad \text{(Formula VIII)}$$

where:

$R(\Delta t)$ - resolution function
$N_b^0$ - number of direct annihilations
$N_p^0$ - number of annihilations via para-positronium
$N_o^0$ - number of annihilations via ortho-positronium
$\tau_b$ - lifetime of the positron undergoing direct annihilation
$\tau_{p\text{-}Ps}$ - lifetime of para-positronium
$\tau_{o\text{-}Ps}$ - lifetime of ortho-positronium
e - Euler's number

In the above equation (Formula VIII), the symbol "*" indicates convolution of functions, whereas the values of $N_b^0$, $N_p^0$, $N_o^0$ refer to the number of reconstructed annihilation with multiplicity of $\mu = 3$ recorded during the entire imaging 117, wherein the sum of $N_b^0$, $N_p^0$, $N_o^0$ is equal to $N_0$ and it is the number of all events reconstructed from the whole imaging 117, which can be written as:

$$\mathrm{N}_0 = \sum_{\Delta t=0}^{\infty} N(\Delta t)$$

(Formula IX)

When fitting the function (Formula VIII) to the data, it is assumed that $\tau_{p\text{-}Ps}$ = 0.125 ns, and it is taken into account that positronium in the triplet state is formed three times more often than in the singlet state ($3N_p^0 = N_o^0$) while the probability of creation of positronium is expressed as:

$$P_{poz} = (N_p^0 + N_o^0)/N_0$$

(Formula X)

**[0049]** Finally, the measured distribution of the time difference Δt is matched with the formula:

$$N(\Delta t) = R(\Delta t) * (1 - P_{poz})\, N_0\, e^{-\Delta t/\tau b} + R(\Delta t) * \tfrac{1}{4}\, N_0\, P_{poz}\, e^{-\Delta t/\tau p\text{-}Ps} + R(\Delta t) * \tfrac{3}{4}\, N_0\, P_{poz}\, e^{-\Delta t/\tau o\text{-}Ps}$$

(Formula XI)

**[0050]** In the formula (Formula XI) $\tau_{o\text{-}Ps}$, $P_{poz}$ and $\tau_b$ are treated as free parameters. The lifetime of para-positronium $\tau_{p\text{-}Ps}$ is 125 ps, the lifetime of positron undergoing free annihilation $\tau_b$ is about 300 ps, which causes that the two first parts of a matching function (Formula XI) and resolution of Δt determination, amounting to about 100 ps for a tomograph with polymer scintillation strips are relevant only in parts of the spectrum below 1 ns, while for the Δt > 1ns dominates the third part of the matching function: $\tfrac{3}{4}\, N_0\, P_{poz}\, e^{-\Delta t/\tau o\text{-}Ps}$.

**[0051]** Indicators $\tau_{o\text{-}Ps}$ and $P_{poz}$ are determined based on the distribution of N(Δt) by using the formula (Formula XI) separately for every voxel. Moreover, in the formula (Formula XI) an approximation was used that ortho-positronium annihilates only into two gamma quanta through the effect of "pick off". In fact, annihilations into three gamma quanta take place with a much larger decay constant. This approximation is satisfied with an accuracy of about 1%.

**[0052]** With sufficiently large statistics of events it is possible to independently determine the parameters $\tau_{o\text{-}Ps}$ from a fit to distribution of N(Δt)

$$N(\Delta t) = N_4\, e^{-\Delta t/\tau o\text{-}Ps},$$

(Formula XII)

determined for annihilation events into three gamma quanta ($\mu$ = 4), where $N_4$ is the number of annihilations of multiplicity of $\mu$ = 4 registered during the entire imaging 117.

**[0053]** Such procedures described above for the multiplicity $\mu$ = 4 and $\mu$ = 3 allow one to define morphometric indicators $t_{o\text{-}Ps}$ and $P_{poz}$ regardless of the gamma quanta attenuation in the body, so it is not necessary to perform correction taking into account the density distribution of the examined object's body (anatomical image), which is currently used for reconstruction of metabolic image and SUV index. This is due to the fact that energetic and angular distributions of gamma quanta for events with multiplicity of $\mu$ = 3 (for annihilation into two gamma quanta) are identical for all three parts of the equation described by Formula XI, and due to the fact that the absorption in the body of an examined object leads only to change in the value of $N_0$ and $N_4$. Indicators $\tau_{o\text{-}Ps}$ and $P_{poz}$ for annihilation into three gamma quanta can be determined in addition for larger areas of the body in case of suspicion of metabolic disorders in these areas. For example, in the course of evaluation of image $T_{o\text{-}Ps}(x,y,z)$ and $P_{poz}(x,y,z)$, one can select any area of Ω in the image using computer software to visualize 140 and start the procedure 117 to calculate the coefficients $\tau_{o\text{-}Ps}$ and $P_{poz}$ within the selected areas.

**[0054]** Variance of Δt described with exponential distribution $\tau_{o\text{-}Ps} e^{-\Delta t/\tau o\text{-}Ps}$ equals $(\tau_{o\text{-}Ps})^2 \sim= 4\ \mathrm{ns}^2$. It is therefore more than two orders of magnitude greater than the variance resulting from experimental resolution of about 0.01 $\mathrm{ns}^2$. Therefore, the accuracy of $\tau_{o\text{-}Ps}$ determination in given area depends mainly on statistics of events recorded for this area. Thus, in order to achieve in a given voxel the accuracy of determination of $\tau_{o\text{-}Ps}$ of about 100 ps, the statistics of about 1000 events per voxel is required.

**[0055]** Preferably, in the first step, the mean morphometric parameters $\tau_{o\text{-}Ps}$ and $P_{poz}$ for the entire scanned area are determined; they are then used as initial parameters in fitting performed separately for each voxel.

**[0056]** Fig. 2 is a block diagram of the process of image reconstruction $\tau_{o\text{-}Ps}(x, y, z)$ and $P_{poz}(x, y, z)$ in the second embodiment using a TOF-PET/CT hybrid tomograph. The hybrid tomograph may comprise two types of detectors: TOF-PET detectors performing the measurement in step 210 and CT detectors performing detection in step 230, wherein the detection layer of TOF-PET comprises scintillators enabling achievement of time resolution of the detection system 210 of less than 100 ps.

**[0057]** The design of the TOF-PET/CT hybrid tomograph may vary. For example, the hybrid tomograph may comprise two scintillation chambers, one of which includes CT detectors, and the other includes TOF-PET detectors; then, the examined object is moved from one chamber to another during imaging. In addition, a tomograph may comprise a system of TOF-PET and CT detection layers stacked one on another, surrounding the tomograph detection chamber, in which the PET 210 detectors and the CT 230 register at the same time signals of gamma radiation and x-ray radiation.

**[0058]** As in the TOF-PET tomograph according to the first embodiment (Fig. 1), a TOF-PET/CT hybrid tomograph registers annihilation and deexcitation gamma quanta resulting from the decay of a radiotracer contained in the pharmaceutical, administered to the examined object before PET scanning commences. The recorded data is converted in step 211 and stored on a computer disk in step 212.

**[0059]** In the next step 213, the stored signals are identified and selected taking into account the multiplicity of events. Annihilation data 217 and 221 obtained from events $\mu = 2$ and $\mu = 3$ can be used to reconstruct a metabolic image M (x, y, z) 223, based on procedures 220, 221, and 222, known to specialist. A metabolic image 232 may be improved based on the examined object's density distribution obtained in step 234 on the basis of CT measurement data obtained in step 230, taken in steps 231 and 232 and reconstructed in step 233, in accordance with methods known to specialists.

**[0060]** However, data 217 obtained from events with multiplicity $\mu = 3$ and $\mu = 4$, recorded by the TOF-PET 210 detection system is used to reconstruct 214, 215, 218 of images: $T_{o\text{-}Ps}(x,y,z)$ and $P_{poz}$ (x, y, z) 219.

**[0061]** The images obtained: $T_{o\text{-}Ps}(x,y,z)$ or $P_{poz}(x, y, z)$ 219 can be, similarly to metabolic image M(x, y, z) 223, superimposed over the anatomical image 234 in order to improve the diagnostic capabilities.

**[0062]** Fig. 3 is a block diagram of the process of image reconstruction $T_{o\text{-}Ps}(x,y,z)$ and $P_{poz}(x, y, z)$ according to the third embodiment using a TOF-PET/MRI hybrid tomograph. TOF-PET/MRI hybrid tomograph, similarly to TOF-PET/CT tomograph (Fig. 2) can contain two types of detectors: TOF-PET detectors 310 and MRI 330 detection layer for generating a magnetic field and recording nuclear magnetic resonance signals. The design of the hybrid tomograph may vary; for example the layer of TOF-PET 310 and MRI 330 detectors can be arranged parallel, one on another, surrounding the detector chamber of hybrid tomograph and allowing simultaneous recording of signals of gamma quanta and nuclear magnetic resonance. TOF-PET 310 and MRI 330 layers may also be physically separated, allowing the sequential scanning, wherein registration of gamma radiation and nuclear magnetic resonance signals takes place in a predetermined time interval. Reconstruction of images $T_{o\text{-}Ps}(x,y,z)$ or $P_{poz}(x,y,z)$ and M(x, y, z) may be carried out analogously to the first or second embodiment (Fig. 1-2); wherein the MRI 330 detectors of the hybrid tomograph allow obtaining morphological images which can be used for correction of metabolic image M(x, y, z), and images $T_{o\text{-}Ps}(x,y,z)$ or $P_{poz}$ P (x, y, z) 319 can be superimposed over morphological image in order to improve the diagnostic capabilities. A metabolic Image may be improved in step 332 based on morphological images in step 334 on the basis of MRI measurement data obtained in step 330, taken in steps 331 and 332 and reconstructed in step 333, in accordance with methods known to specialists.

**[0063]** Indicators $\tau_{o\text{-}Ps}$ and $P_{poz}$ determined by the presented method using a hybrid tomograph as per the first, second or third embodiment may be related to each other:

$$(\tau_{o\text{-}Ps} \cdot P_{poz})^{-1} \qquad \text{(Formula XIII)}$$

**[0064]** The expression (Formula XIII) determines well the degree of advancement of cell metabolism abnormality, wherein the larger the value $(\tau_{o\text{-}Ps} \cdot P_{poz})^{-1}$ the greater the severity of metabolic abnormalities. The advantage of the indicator described by Formula XIII is the fact that the values of $\tau_{o\text{-}Ps}$ and $P_{poz}$ do not depend on the time, so they do not have to be corrected due to the time elapsed from the injection of a radiopharmaceutical to an examined object to the time of imaging and due the weight and volume of the examined object. In addition, for the determination of the $\tau_{o\text{-}Ps}$ and $P_{poz}$, it is not necessary to know the physical and biological decay time of the radiopharmaceutical or the initial activity and time of injection of the radiopharmaceutical. Hence, the possibility of making systematic errors in determining the $\tau_{o\text{-}Ps}$ and $P_{poz}$ is lower.

**[0065]** Currently, for the evaluation of the PET tomographic images in view of quantitative determination of cellular metabolism, the SUV index is used. The higher the SUV the greater the risk of occurrence of tissue with cells with disturbed metabolism in a given region of the body. The SUV index does not depend on the lifetime of ortho-positronium $\tau_{o\text{-}Ps}$ and the probability of positronium production $P_{poz}$. Therefore, the presented method allows for association of SUV index with $\tau_{o\text{-}Ps}$ and $P_{poz}$ parameters, obtaining thereby a new index defined as:

$$W = SUV / (\tau_{o\text{-}Ps} \cdot P_{poz}) \qquad \text{(Formula XIV)}$$

**[0066]** In addition, the W index being a combination of indicators: SUV, $\tau_{o\text{-}Ps}$, and $P_{poz}$ is more "sensitive" to the occurrence of metabolic abnormalities in cells.

**[0067]** Fig. 4, 5, and 6 are diagrams depicting design of tomographs used in procedures outlined respectively in Figures 1, 2, and 3.

**[0068]** TOF-PET tomograph shown in Figure 4 includes TOF-PET 101 detection modules, which contain scintillators with time resolution of less than 100ps. Data from these modules is transferred to the TOF-PET 102 data acquisition system, from which data is transferred to the data reconstruction system 103, which is responsible for carrying out the steps 113-123 of the procedure in Fig. 1. The resulting data is transmitted to the visualization module 104 performing step 140 of the procedure in Fig. 1.

**[0069]** TOF-PET/CT hybrid tomograph shown in Figure 5, in addition to modules 201-204 analogous to modules 101-104 in Fig. 4, contains also the detection module CT 205, data acquisition system CT 206 and the data reconstruction system CT 207 (implementing steps 233, 234) from which data may be combined with the TOF-PET image in step 240.

**[0070]** TOF-PET/MRI hybrid tomograph shown in Figure 6, in addition to modules 301-304 analogous to modules 101-104 in Fig. 4, contains also the detection module MRI 305, data acquisition system MRI 306 and the data reconstruction system MRI 307 (implementing steps 333, 334) from which data may be combined with the TOF-PET image in step 340.

**[0071]** The use of isotope tracers according to the presented method, wherein the daughter nucleus deexcites with emission of gamma quanta of energy different from the energy of annihilation quantum, a method of measuring the positron lifetime in living organisms was developed to be performed by methods known to TOF-PET tomographs specialists. The use of a tomograph with a detection system achieving time resolution of 100 ps made it possible to measure the difference ($\Delta t$) between the time of annihilation $t_a$ and time of emission of deexcitation quantum $t_e$; the appropriate choice of isotope tracers for which the average lifetime of the excited nucleus is less than 100ps made it possible to adopt the approximation that the position of deexcitation is identical with the position of annihilation, which allowed determination of time of emission of deexcitation quantum $t_e$ for each voxel of the examined object separately. The measured distribution of time difference $N(\Delta t)$ made it possible, by means of the matching function, to determine lifetime of ortho-positronium $\tau_{o\text{-}Ps}$ and the probability of production of positronium $P_{poz}$ for each voxel of the examined object body. The values obtained were used to reconstruct two images: $\tau_{o\text{-}Ps}(x, y, z)$ and $P_{poz}(x, y, z)$ as a function of position in the examined object, which were not obtained by the PET technique. Images $\tau_{o\text{-}Ps}(x, y, z)$ and $P_{poz}(x, y, z)$ represent distribution of density of tissue and allow to determine the size of free volumes between cells in tissues in the nanometre scale, which allows detection of metabolic disorders even at a very early stage and allows for a quantitative assessment of severity of these disorders. In addition, information from images $\tau_{o\text{-}Ps}(x, y, z)$ and $P_{poz}(x, y, z)$ can be used to understand the process of destruction of the diseased cells and for development of new medicines.

**[0072]** It should be noted that the method of obtaining images of lifetime of ortho-positronium is completely non-invasive - it does not require collection of tissues of living organisms, and the area of the body possible to be examined depends exclusively on the imaging field of view used in the TOF-PET tomograph; for example, tomographs with polymer scintillation strips allow images of lifetimes of ortho-positronium even for the whole body of the examined object simultaneously.

**[0073]** In addition, the use of "fast" polymer scintillators to register events with two ($\mu = 2$) and three ($\mu = 3$) gamma quanta, allowed determination of time of recording gamma quanta with a better accuracy than 50ps and the position of annihilation with a better accuracy than 1 cm. This provided the possibility to reconstruct the annihilation position (x, y, z) for each event separately with a centimetre-fraction accuracy and time accuracy better than 50ps. Measurement of time and position of reaction of deexcitation quantum using polymer scintillators allows to determine the difference in time between the moment of emission of the positron and its annihilation with accuracy better than 100 ps.

**[0074]** The detection system of TOF-PET tomograph was designed to record also annihilations into three gamma quanta. In this case, it is possible to determine additional lifetime indicators of ortho-positronium and the probability of production of positronium for larger areas of the body, despite the fact that these events are statistically less frequent.

**[0075]** An important advantage of the presented method is the possibility of obtaining, while a single imaging, not only images of $\tau_{o\text{-}Ps}(x, y, z)$ and $P_{poz}(x, y, z)$ but also the metabolic image M(x, y, z), which can be superimposed over each other. This is due to the fact that in the TOF-PET tomograph the detection modules can register deexcitation and annihilation radiation. These modules are identified by the presented method, by introducing the energy criterion $E_{min}$, which is a border value of the energy that the deexcitation and annihilation quanta may deposit in the scintillators. On the basis of $E_{min}$ it is identified which of the modules registered an annihilation quantum, and which registered a deexcitation quantum.

**[0076]** Furthermore, in order to obtain three images: M(x, y, z), $\tau_{o\text{-}Ps}$(x, y, z) and $P_{poz}$(x, y, z) the radiopharmaceutical is administered to the examined object only once, and the technique of placing the examined object into the scintillation chamber and imaging time is not different from the PET technique.

**[0077]** The presented method of reconstruction of images: $\tau_{o\text{-}Ps}$(x, y, z) and $P_{poz}$(x, y, z) may also be used in TOF-PET/CT and TOF-PET/MRI hybrid tomographs, in which the detection systems for registration of gamma quanta allow achieving time resolution of 100 ps. The obtained CT or MRI images can then be superimposed over $\tau_{o\text{-}Ps}$(x, y, z) and $P_{poz}$(x, y, z) images, thereby increasing the diagnostic capabilities.

**[0078]** In addition, the obtained indicators of $\tau_{o\text{-}Ps}$ and $P_{poz}$ can be linked to the SUV index to give a new W index, which is more "sensitive" to the presence of metabolic abnormalities in the tissues.

**[0079]** While the technical solutions presented herein have been depicted, described, and defined with reference to particular preferred embodiment(s), such references and examples of implementation in the foregoing specification do not imply any limitation on the invention. Various modifications and changes may be made thereto without departing from the scope of the technical solutions presented. The presented embodiments are given as example only, and are not exhaustive of the scope of the technical solutions presented herein. Accordingly, the scope of protection is not limited to the preferred embodiments described in the specification, but is only limited by the claims that follow.

## Claims

**1.** A tomograph for imaging an interior of an examined object, the tomograph comprising:

- TOF-PET detection modules (101, 201, 301), comprising scintillators having a time resolution of less than 100 ps, configured to register annihilation quanta and deexcitation quanta; and
- a data reconstruction system (103, 203, 303) configured to register and identify signals of an event registered in at least two detection modules within a predetermined time interval, the event resulting from a decay of a radioisotope, the decay involving emission of a positron from the radioisotope and subsequent emission of a deexcitation quantum from the daughter nucleus of the radioisotope, the daughter nucleus in excited state having a lifetime not exceeding 100ps, wherein the event involves emission of annihilation gamma quanta resulting from the annihilation of the emitted positron and emission of the deexcitation quantum, wherein the reconstruction system (103, 203, 303) is configured to register and identify the signals of the events comprising:
    - three gamma quanta ($\mu$ = 3), wherein two of the three gamma quanta meet criteria for identification of quanta from annihilation of electron with positron into two gamma quanta, and a third gamma quantum meets a criterion for identification of gamma quanta from deexcitation of daughter nucleus of the radioisotope; and
    - four gamma quanta ($\mu$ = 4), wherein two of four gamma quanta meet the criteria for identification of quanta from annihilation of electron with positron into two gamma quanta or three of four gamma quanta meet the criteria of annihilation of electron with positron into three gamma quanta and at least one gamma quantum meets a criterion for identification of gamma quanta from deexcitation of a daughter nucleus,
- and wherein the data reconstruction system (103, 203, 303) is further configured:
    - to calculate, on the basis of a time difference ($\Delta$t) between a time of annihilation ($t_a$) and a time of emission of a deexcitation quantum ($t_e$) for the identified events, the following indicators: the ortho-positronium lifetime ($\tau_{o\text{-}Ps}$) and the probability of production of positronium ($P_{poz}$); and
    - to reconstruct an ortho-positronium $T_{o\text{-}Ps}$(x,y,z) lifetime image and a probability of production of positronium $P_{poz}$(x,y,z) as a function of position in the imaged object on the basis of the calculated indicators.

**2.** The tomograph according to claim 1 wherein the TOF-PET detection modules (101, 201, 301) comprise polymer scintillation strips for absorbing gamma quanta.

**3.** The tomograph according to claim 1 wherein the TOF-PET detection modules (101, 201, 301) comprise polymer scintillation panels for absorbing gamma quanta.

**4.** The tomograph according to claim 1 wherein the tomograph is a hybrid TOF-PET/CT tomograph further comprising a CT detection module (205) and a visualization module configured to receive hybrid images containing information about the lifetime of ortho-positronium, the probability of production of positronium, the density distribution of the radiopharmaceutical, and the electron density distribution as a function of position.

**5.** The tomograph according to claim 1 wherein the tomograph is a hybrid TOF-PET/MRI tomograph further comprising an MRI detection module (305), a visualization module (340) to receive hybrid images containing information about the lifetime of ortho-positronium, the probability of production of positronium, the density distribution of the radiopharmaceutical, and the hydrogen atoms density distribution as a function of position.

**6.** A method of imaging using a TOF-PET tomograph, the method comprising the steps of:

- introducing into a scintillation chamber of the tomograph an object comprising a radioisotope to undergo a decay process involving emission of a positron from a radioisotope and subsequent emission of a deexcitation quantum from the daughter nucleus of the radioisotope, the daughter nucleus in excited state having a lifetime not exceeding 100ps
- recording the deexcitation quanta emitted by the daughter nucleus and annihilation quanta resulting from annihilation of the positron emitted by the radioisotope in a TOF-PET detection module (101, 201, 301) comprising scintillators having a time resolution less than 100 ps;
- determining detection modules that registered the signals of an event recorded in at least two detection modules within a predetermined time interval, the event being a result of the decay of the radioisotope and involving emission of annihilation quanta and emission of the deexcitation quantum, wherein the event comprises:
  - three gamma quanta ($\mu = 3$), wherein two of the three gamma quanta meet criteria for identification of quanta from annihilation of electron with positron into two gamma quanta and a third gamma quantum meets a criterion for identification of gamma quanta from deexcitation of daughter nucleus of the radioisotope and
  - four gamma quanta ($\mu = 4$), wherein two of four gamma quanta meet the criteria for identification of quanta from annihilation of electron with positron into two gamma quanta or three of four gamma quanta meet the criteria of annihilation of electron with positron into three gamma quanta and at least one gamma quantum meets a criterion for identification of gamma quanta from deexcitation of a daughter nucleus of the radioisotope;
- performing reconstruction of the position of annihilation of the positron into two gamma quanta and into three gamma quanta ($r_a$) and the time of annihilation of positron into two gamma quanta and into three gamma quanta ($t_a$) for the events;
- performing reconstruction of a time difference ($\Delta t$) between a time of the positron annihilation $t_a$ and an emission time of the deexcitation quantum $t_e$ where the position of emission of the deexcitation quantum is considered as the position of annihilation of the positron;
- calculating, for every voxel of the object, on the basis of the time difference ($\Delta t$) between a time of the positron annihilation ($t_a$) and an emission time of the deexcitation quantum ($t_e$), the following indicators: the ortho-positronium lifetime ($\tau_{o\text{-}Ps}$) and the probability of production of positronium ($P_{poz}$) and
- reconstructing, on the basis of the calculated indicators ($\tau_{o\text{-}Ps}$, $P_{poz}$), an image of the average lifetime of ortho-positronium $\tau_{o\text{-}Ps}(x,y,z)$ and an image of a probability of production of positronium $P_{poz}(x,y,z)$ as a function of position in the imaged object.

**7.** The method according to claim 6 wherein the detection modules that registered the annihilation quanta and detection modules that registered the deexcitation quanta are distinguished by the difference in the values of energy deposited in those modules by the gamma quanta, whereas the range of the energy used to identify the annihilation and deexcitation gamma quanta is optimized for the energy resolution of the tomograph and for the energy of deexcitation quantum by maximizing the probability of correct identification and selection efficiency as a function of an $E_{min}$ value.

**8.** The method according to claim 6 wherein in the first step, the morphometric-average parameters $\tau_{o\text{-}Ps}$ and $P_{poz}$ for the entire scanned area are determined; next, the average parameters $\tau_{o\text{-}Ps}$ and $P_{poz}$ are used as initial parameters in matching, performed separately for each voxel.

**9.** The method according to claim 6 wherein the obtained image comprises information about the lifetime of ortho-positronium, the probability of production of positronium and the density distribution of the radiopharmaceutical as a function of position in the examined object.

**10.** The method according to claim 6 further comprising acquisition of data by using the CT detector module (205), and generating a hybrid image that contains information on the lifetime of positronium $\tau_{o\text{-}Ps}(x, y, x)$, the probability of production of positronium $P_{poz}(x, y, z)$, the density of radiopharmaceutical distribution M(x, y, z) and the electron density distribution A(x, y, z) as functions of position in the object.

**11.** The method according to claim 6 further comprising data acquisition by using the MRI detector module (305), and generating a hybrid image that contains information on the lifetime of positronium $\tau_{o\text{-}Ps}(x, y, x)$, the probability of production of positronium $P_{poz}(x, y, z)$, the density of radiopharmaceutical distribution M(x, y, z) and the hydrogen atoms density distribution B(x, y, z) as a function of position in the object.

**Patentansprüche**

**1.** Tomograph zur Abbildung eines Inneren eines untersuchten Objekts, wobei der Tomograph umfasst:

- TOF-PET-Erfassungsmodule (101, 201, 301), umfassend Szintillatoren mit einer Zeitauflösung von weniger als 100 ps, die konfiguriert sind, um Annihilationsquanten und Entregungsquanten zu registrieren; und
- ein Datenrekonstruktionssystem (103, 203, 303), das konfiguriert ist, um Signale eines Ereignisses zu registrieren und zu identifizieren, das in mindestens zwei Erfassungsmodulen innerhalb eines vorbestimmten Zeitintervalls registriert ist, wobei das Ereignis aus einem Zerfall eines Radioisotops resultiert, wobei der Zerfall die Emission eines Positrons aus dem Radioisotop und nachfolgende Emission eines Entregungsquantums aus dem Tochterkern des Radioisotops beinhaltet, wobei der Tochterkern im angeregten Zustand eine Lebensdauer von nicht mehr als 100 ps aufweist, wobei das Ereignis die Emission von Annihilationsgammaquanten beinhaltet, die aus der Annihilation des emittierten Positrons und der Emission des Entregungsquantums resultiert, wobei das Rekonstruktionssystem (103, 203, 303) konfiguriert ist, um die Signale der Ereignisse zu registrieren und zu identifizieren, umfassend:
  - drei Gammaquanten ($\mu = 3$), wobei zwei der drei Gammaquanten Kriterien zur Identifizierung von Quanten aus der Annihilation von Elektron mit Positron in zwei Gammaquanten erfüllen und ein drittes Gammaquantum ein Kriterium zur Identifizierung von Gammaquanten aus der Entregung des Tochterkerns des Radioisotops erfüllt; und
  - vier Gammaquanten ($\mu = 4$), wobei zwei von vier Gammaquanten die Kriterien zur Identifizierung von Quanten aus der Annihilation von Elektron mit Positron in zwei Gammaquanten erfüllen oder drei von vier Gammaquanten die Kriterien der Annihilation von Elektron mit Positron in drei Gammaquanten erfüllen und mindestens ein Gammaquantum ein Kriterium zur Identifizierung von Gammaquanten aus der Entregung eines Tochterkerns erfüllt,
  - und wobei das Datenrekonstruktionssystem (103, 203, 303) ferner konfiguriert ist für:
    - eine Berechnung der folgenden Indikatoren auf der Grundlage einer Zeitdifferenz ($\Delta t$) zwischen einer Annihilationszeit ($t_a$) und einer Emissionszeit eines Entregungsquantums ($t_e$) für die identifizierten Ereignisse: der Orthopositronium-Lebensdauer ($\tau_{o\text{-}PS}$) und der Wahrscheinlichkeit der Produktion von Positronium ($P_{poz}$); und
    - eine Rekonstruktion eines Bildes der Lebensdauer eines Orthopositroniums $\tau_{o\text{-}Ps}(x,y,z)$ und einer Wahrscheinlichkeit der Produktion von Positronium $P_{poz}(x,y,z)$ in Abhängigkeit der Position in dem abgebildeten Objekt auf der Grundlage der berechneten Indikatoren.

**2.** Tomograph nach Anspruch 1, wobei die TOF-PET-Erfassungsmodule (101, 201, 301) Polymerszintillationsstreifen zum Absorbieren von Gammaquanten umfassen.

**3.** Tomograph nach Anspruch 1, wobei die TOF-PET-Erfassungsmodule (101, 201, 301) Polymerszintillationsplatten zum Absorbieren von Gammaquanten umfassen.

**4.** Tomograph nach Anspruch 1, wobei der Tomograph ein hybrider TOF-PET-/CT-Tomograph ist, der ferner ein CT-Erfassungsmodul (205) und ein Visualisierungsmodul umfasst, konfiguriert, um Hybridbilder zu empfangen, die Informationen über die Lebensdauer von Orthopositronium, die Wahrscheinlichkeit der Produktion von Positronium, die Dichteverteilung des Radiopharmazeutikums und die Elektronendichteverteilung in Abhängigkeit der Position enthalten.

5. Tomograph nach Anspruch 1, wobei der Tomograph ein hybrider TOF-PET-/MRI-Tomograph ist, der ferner ein MRT-Erfassungsmodul (305) und ein Visualisierungsmodul (340) umfasst, um Hybridbilder zu empfangen, die Informationen über die Lebensdauer von Orthopositronium, die Wahrscheinlichkeit der Produktion von Positronium, die Dichteverteilung des Radiopharmazeutikums und die Wasserstoffatomdichteverteilung in Abhängigkeit der Position enthalten.

6. Verfahren zur Abbildung unter Verwendung eines TOF-PET-Tomographen, wobei das Verfahren die Schritte umfasst:

   - Einführen eines ein Radioisotop umfassenden Objekts in eine Szintillationskammer des Tomographen, um einen Zerfallsprozess zu durchlaufen, der die Emission eines Positrons aus einem Radioisotop und die anschließende Emission eines Entregungsquantums aus dem Tochterkern des Radioisotops beinhaltet, wobei der Tochterkern im angeregten Zustand eine Lebensdauer von nicht mehr als 100 ps aufweist;
   - Aufzeichnen der von dem Tochterkern emittierten Entregungsquanten und der Annihilationsquanten, die sich aus der Annihilation des durch das Radioisotop emittierten Positrons ergeben, in einem TOF-PET-Erfassungsmodul (101, 201, 301), das Szintillatoren mit einer Zeitauflösung von weniger als 100 ps umfasst;
   - Bestimmen von Erfassungsmodulen, die die in mindestens zwei Erfassungsmodulen innerhalb eines vorgegebenen Zeitintervalls aufgezeichneten Signale eines Ereignisses registrieren, wobei das Ereignis ein Ergebnis des Zerfalls des Radioisotops ist und die Emission von Annihilationsquanten und die Emission des Entregungsquantums beinhaltet, wobei das Ereignis umfasst:
   - drei Gamma-Quanten ($\mu = 3$), wobei zwei der drei Gamma-Quanten Kriterien zur Identifizierung von Quanten aus der Annihilation von Elektron mit Positron in zwei Gammaquanten erfüllen und ein drittes Gammaquantum ein Kriterium zur Identifizierung von Gammaquanten aus der Entregung des Tochterkerns des Radioisotops erfüllt, und
   - vier Gammaquanten ($\mu = 4$), wobei zwei von vier Gammaquanten die Kriterien zur Identifizierung von Quanten aus der Annihilation von Elektron mit Positron in zwei Gammaquanten erfüllen oder drei von vier Gammaquanten die Kriterien der Annihilation von Elektron mit Positron in drei Gammaquanten erfüllen und mindestens ein Gammaquantum ein Kriterium zur Identifizierung von Gammaquanten aus der Entregung eines Tochterkerns des Radioisotops erfüllt;
   - Durchführen von Rekonstruktion der Position der Annihilation des Positrons in zwei Gammaquanten und in drei Gammaquanten ($r_a$) und der Zeit der Annihilation des Positrons in zwei Gammaquanten und in drei Gammaquanten ($t_a$) für die Ereignisse;
   - Durchführen von Rekonstruktion einer Zeitdifferenz ($\Delta t$) zwischen einer Zeit der Positronenannihilation $t_a$ und einer Emissionszeit des Entregungsquantums $t_e$, wobei die Position der Emission des Entregungsquantums als die Position der Annihilation des Positrons betrachtet wird;
   - Berechnen der folgenden Indikatoren für jedes Voxel des Objekts auf der Grundlage der Zeitdifferenz ($\Delta t$) zwischen einer Zeit der Positronenannihilation ($t_a$) und einer Emissionszeit des Entregungsquantums ($t_e$): der Orthropositronium-Lebensdauer ($\tau_{o\text{-}Ps}$) und der Wahrscheinlichkeit der Produktion von Positronium ($P_{poz}$), und
   - Rekonstruieren auf der Grundlage der berechneten Indikatoren ($\tau_{o\text{-}Ps}$, $P_{poz}$) eines Bildes der durchschnittlichen Lebensdauer von Orthopositronium $\tau_{o\text{-}Ps}(x,y,z)$ und eines Bildes einer Wahrscheinlichkeit der Produktion von Positronium $P_{poz}(x,y,z)$ in Abhängigkeit der Position in dem abgebildeten Objekt.

7. Verfahren nach Anspruch 6, wobei sich die Erfassungsmodule, die die Annihilationsquanten registriert haben, und die Erfassungsmodule, die die Entregungsquanten registriert haben, durch die Differenz der in diesen Modulen durch die Gammaquanten abgelagerten Energiewerte unterscheiden, wohingegen die Energiespanne, die verwendet wird, um die Annihilations- und Entregungsgammaquanten zu identifizieren, für die Energieauflösung des Tomographen und für die Energie des Entregungsquantums optimiert wird, indem die Wahrscheinlichkeit einer korrekten Identifizierung und Selektionseffizienz in Abhängigkeit eines $E_{min}$-Wertes maximiert wird.

8. Verfahren nach Anspruch 6, wobei im ersten Schritt die morphometrischen Durchschnittsparameter $\tau_{o\text{-}Ps}$ und $P_{poz}$ für den gesamten abgetasteten Bereich bestimmt werden; als nächstes die Durchschnittsparameter $\tau_{o\text{-}Ps}$ und $P_{poz}$ als Ausgangsparameter beim Zuordnen verwendet werden, separat für jedes Voxel durchgeführt.

9. Verfahren nach Anspruch 6, wobei das erhaltene Bild Informationen über die Lebensdauer von Orthopositronium, die Wahrscheinlichkeit der Produktion von Positronium und die Dichteverteilung des Radiopharmazeutikums in

Abhängigkeit der Position in dem untersuchten Objekt umfasst.

**10.** Verfahren nach Anspruch 6, ferner umfassend den Erwerb von Daten durch Verwendung des CT-Erfassungsmoduls (205), und Erzeugen eines Hybridbildes, das Informationen über die Lebensdauer von Positronium $\tau_{o\text{-}Ps}(x, y, x)$, die Wahrscheinlichkeit der Produktion von Positronium $P_{poz}(x, y, z)$, der Dichte der radiopharmazeutischen Verteilung M(x, y, z) und der Elektronendichteverteilung A(x, y, z) in Abhängigkeit der Position in dem Objekt enthält.

**11.** Verfahren nach Anspruch 6, ferner umfassend den Datenerwerb durch Verwendung des MRT-Erfassungsmoduls (305), und Erzeugen eines Hybridbildes, das Informationen über die Lebensdauer von Positronium $\tau_{o\text{-}Ps}(x, y, x)$, die Wahrscheinlichkeit der Produktion von Positronium $P_{poz}(x, y, z)$, die Dichte der radiopharmazeutischen Verteilung M(x, y, z) und die Wasserstoffatomdichteverteilung B(x, y, z) in Abhängigkeit der Position in dem Objekt enthält.

## Revendications

**1.** Tomographe pour imager l'intérieur d'un objet examiné, le tomographe comprenant :

- des modules de détection TOF-PET (101, 201, 301), comprenant des scintillateurs ayant une résolution temporelle inférieure à 100 ps, configurés pour enregistrer des quanta d'annihilation et des quanta de désexcitation ; et
- un système de reconstruction de données (103, 203, 303) configuré pour enregistrer et identifier des signaux d'un événement enregistré dans au moins deux modules de détection dans un intervalle de temps prédéterminé, l'événement résultant d'une désintégration d'un radio-isotope, la désintégration impliquant l'émission d'un positron à partir du radio-isotope et l'émission subséquente d'un quantum de désexcitation à partir du noyau fils du radio-isotope, le noyau fils à l'état excité ayant une durée de vie ne dépassant pas 100 ps, dans lequel l'événement implique l'émission de quanta gamma d'annihilation résultant de l'annihilation du positron émis et de l'émission du quantum de désexcitation, dans lequel le système de reconstruction (103, 203, 303) est configuré pour enregistrer et identifier les signaux des événements comprenant :
    - trois quanta gamma ($\mu = 3$), dans lequel deux des trois quanta gamma répondent à des critères d'identification de quanta provenant de l'annihilation de l'électron avec le positron en deux quanta gamma, et un troisième quantum gamma répond à un critère d'identification de quanta gamma provenant de la désexcitation du noyau fils du radio-isotope ; et
    - quatre quanta gamma ($\mu = 4$), dans lequel deux des quatre quanta gamma répondent aux critères d'identification des quanta provenant de l'annihilation de l'électron avec le positron en deux quanta gamma ou trois des quatre quanta gamma répondent aux critères d'annihilation de l'électron avec le positron en trois quanta gamma et au moins un quantum gamma répond à un critère d'identification des quanta gamma provenant de la désexcitation d'un noyau fils,
    - et dans lequel le système de reconstruction de données (103, 203, 303) est en outre configuré :
        - pour calculer, sur la base d'une différence de temps ($\Delta t$) entre un temps d'annihilation ($t_a$) et un temps d'émission d'un quantum de désexcitation ($t_e$) pour les événements identifiés, les indicateurs suivants : la durée de vie de l'ortho-positronium ($\tau_{o\text{-}Ps}$) et la probabilité de production de positronium ($P_{poz}$) ; et
        - pour reconstruire une image de durée de vie de l'ortho-positronium $\tau_{o\text{-}Ps}(x, y, z)$ et une probabilité de production de positronium $P_{poz}(x, y, z)$ comme une fonction de la position dans l'objet imagé sur la base des indicateurs calculés.

**2.** Tomographe selon la revendication 1, dans lequel les modules de détection TOF-PET (101, 201, 301) comprennent des bandes de scintillation en polymère pour absorber les quantas gamma.

**3.** Tomographe selon la revendication 1, dans lequel les modules de détection TOF-PET (101, 201, 301) comprennent des panneaux de scintillation en polymère pour absorber les quanta gamma.

**4.** Tomographe selon la revendication 1, dans lequel le tomographe est un tomographe TOF-PET/CT hybride comprenant en outre un module de détection CT (205) et un module de visualisation configuré pour recevoir des images hybrides contenant des informations sur la durée de vie de l'ortho-positronium, la probabilité de production de positronium, la distribution de densité du produit radiopharmaceutique et la distribution de densité électronique comme une fonction de la position.

**5.** Tomographe selon la revendication 1, dans lequel le tomographe est un tomographe TOF-PET/IRM hybride comprenant en outre un module de détection IRM (305), un module de visualisation (340) pour recevoir des images hybrides contenant des informations sur la durée de vie de l'ortho-positronium, la probabilité de la production de positronium, la distribution de densité du produit radiopharmaceutique et la distribution de densité des atomes d'hydrogène comme une fonction de la position.

**6.** Procédé d'imagerie utilisant un tomographe TOF-PET, le procédé comprenant les étapes de :

- introduction dans une chambre de scintillation du tomographe d'un objet comprenant un radio-isotope pour subir un processus de désintégration impliquant l'émission d'un positron à partir d'un radio-isotope et l'émission subséquente d'un quantum de désexcitation du noyau fils du radio-isotope, le noyau fils à l'état excité ayant une durée de vie ne dépassant pas 100 ps ;
- enregistrement des quanta de désexcitation émis par le noyau fils et des quanta d'annihilation résultant de l'annihilation du positron émis par le radio-isotope dans un module de détection TOF-PET (101, 201, 301) comprenant des scintillateurs ayant une résolution temporelle inférieure à 100 ps ;
- détermination des modules de détection qui ont enregistré les signaux d'un événement enregistré dans au moins deux modules de détection dans un intervalle de temps prédéterminé, l'événement étant un résultat de la désintégration du radio-isotope et impliquant l'émission de quanta d'annihilation et l'émission du quantum de désexcitation, où l'événement comprend :
    - trois quanta gamma ($\mu = 3$), dans lequel deux des trois quanta gamma répondent à des critères d'identification de quanta provenant de l'annihilation de l'électron avec le positron en deux quanta gamma et un troisième quantum gamma répond à un critère d'identification de quanta gamma provenant de la désexcitation du noyau fils du radio-isotope et
    - quatre quanta gamma ($\mu = 4$), dans lequel deux des quatre quanta gamma répondent aux critères d'identification des quanta provenant de l'annihilation de l'électron avec le positron en deux quanta gamma ou trois des quatre quanta gamma répondent aux critères d'annihilation de l'électron avec le positron en trois quanta gamma et au moins un quantum gamma répond à un critère d'identification des quanta gamma provenant de la désexcitation d'un noyau fils du radio-isotope ;
    - réalisation de la reconstruction de la position d'annihilation du positron en deux quanta gamma et en trois quanta gamma ($r_a$) et du temps d'annihilation du positron en deux quanta gamma et en trois quanta gamma ($t_a$) pour les événements ;
    - réalisation de la reconstruction d'une différence de temps ($\Delta t$) entre un moment de l'annihilation du positron $t_a$ et un temps d'émission du quantum de désexcitation $t_e$ où la position d'émission du quantum de désexcitation est considérée comme la position d'annihilation du positron ;
    - calcul, pour chaque voxel de l'objet, sur la base de la différence de temps ($\Delta t$) entre un temps de l'annihilation du positron ($t_a$) et un temps d'émission du quantum de désexcitation ($t_e$), des indicateurs suivants :la durée de vie de l'ortho-positronium ($\tau_{o\text{-}Ps}$) et la probabilité de production de positronium ($P_{poz}$) et
    - reconstruction, à partir des indicateurs calculés ($\tau_{o\text{-}Ps}$, $\tau$), d'une image de la durée de vie moyenne de l'ortho-positronium $\tau_{o\text{-}Ps}(x, y, z)$ et d'une image d'une probabilité de production de positronium $P_{poz}(x, y, z)$ en fonction de la position dans l'objet imagé.

**7.** Procédé selon la revendication 6, dans lequel les modules de détection qui ont enregistré les quanta d'annihilation et les modules de détection qui ont enregistré les quanta de désexcitation se distinguent par la différence des valeurs de l'énergie déposée dans ces modules par les quanta gamma, tandis que la gamme de l'énergie utilisée pour identifier les quanta gamma d'annihilation et de désexcitation est optimisée pour la résolution énergétique du tomographe et pour l'énergie du quantum de désexcitation en maximisant la probabilité d'une identification correcte et d'une efficacité de sélection comme une fonction d'une valeur $E_{min}$.

**8.** Procédé selon la revendication 6, dans lequel dans la première étape, les paramètres de moyenne morphométrique $\tau_{o\text{-}Ps}$ et $P_{poz}$ pour la zone balayée entière sont déterminés ; ensuite, les paramètres moyens $\tau_{o\text{-}Ps}$ et $P_{poz}$ sont utilisés comme paramètres initiaux dans l'appariement, effectué séparément pour chaque voxel.

**9.** Procédé selon la revendication 6, dans lequel l'image obtenue comprend des informations sur la durée de vie de l'ortho-positronium, la probabilité de production de positronium et la distribution de densité du produit radiopharmaceutique comme une fonction de la position dans l'objet examiné.

**10.** Procédé selon la revendication 6, comprenant en outre l'acquisition de données en utilisant le module détecteur

CT (205) et la génération d'une image hybride qui contient des informations sur la durée de vie du positronium $\tau_{o\text{-}Ps}(x, y, x)$, la probabilité de production de positronium $P_{poz}(x, y, z)$, la densité de distribution de produit radiopharmaceutique $M(x, y, z)$ et la distribution de densité électronique $A(x, y, z)$ comme des fonctions de position dans l'objet.

**11.** Procédé selon la revendication 6, comprenant en outre l'acquisition de données en utilisant le module détecteur IRM (305), et la génération d'une image hybride qui contient des informations sur la durée de vie du positronium $\tau_{o\text{-}Ps}(x, y, x)$, la probabilité de production de positronium $P_{poz}(x, y, z)$, la densité de distribution de produit radiopharmaceutique $M(x, y, z)$ et la distribution de densité des atomes d'hydrogène $B(x, y, z)$ comme une fonction de la position dans l'objet.

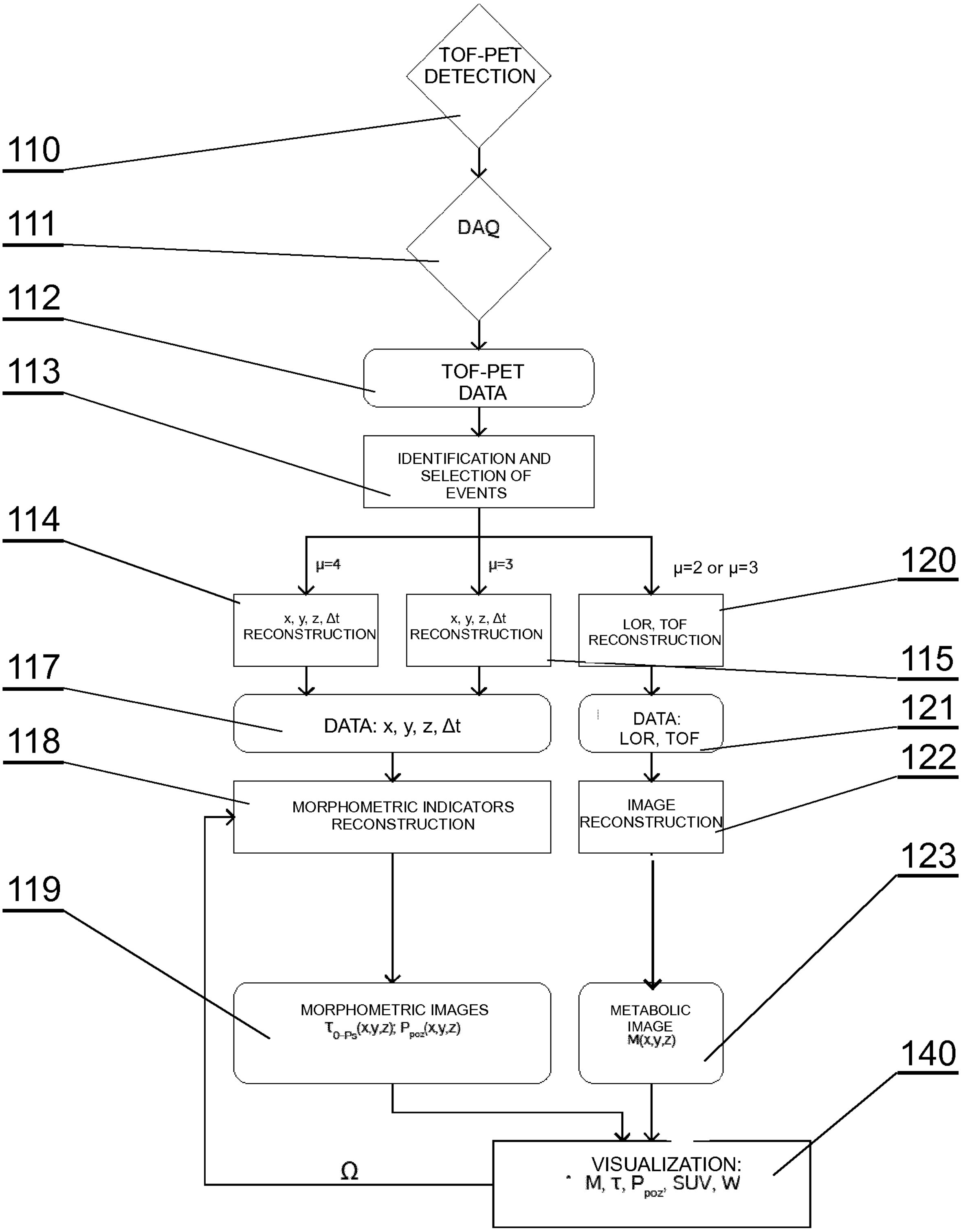
TOF-PET DETECTION
110
DAQ
111
112
TOF-PET DATA
113
IDENTIFICATION AND SELECTION OF EVENTS
114
μ=4
μ=3
μ=2 or μ=3
120
x, y, z, Δt RECONSTRUCTION
x, y, z, Δt RECONSTRUCTION
LOR, TOF RECONSTRUCTION
115
117
DATA: x, y, z, Δt
DATA: LOR, TOF
121
118
MORPHOMETRIC INDICATORS RECONSTRUCTION
IMAGE RECONSTRUCTION
122
119
123
MORPHOMETRIC IMAGES
$\tau_{0-Ps}(x,y,z)$; $P_{poz}(x,y,z)$
METABOLIC IMAGE
M(x,y,z)
140
Ω
VISUALIZATION:
M, τ, $P_{poz}$, SUV, W

Fig. 1

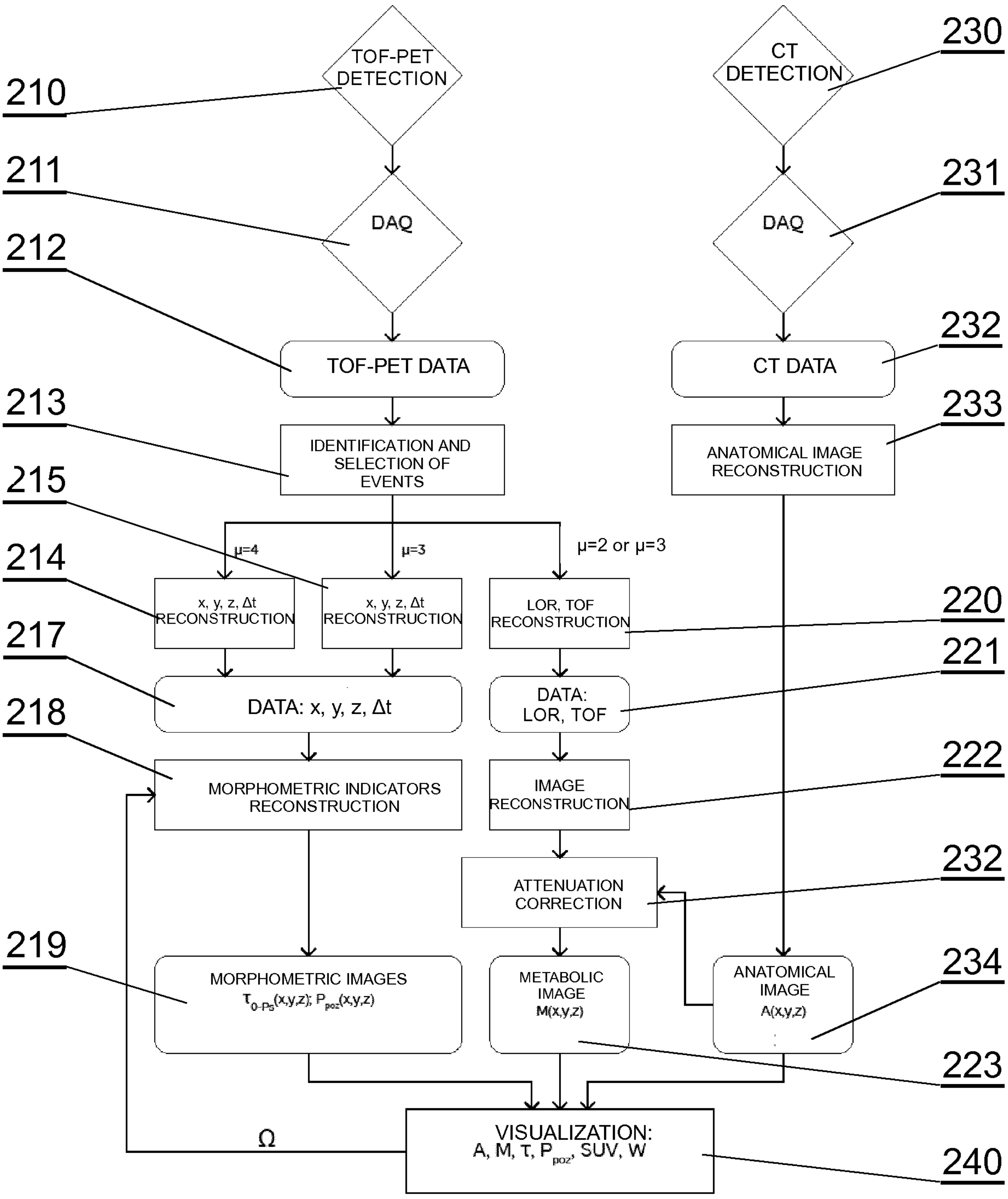
TOF-PET DETECTION
CT DETECTION
DAQ
DAQ
TOF-PET DATA
CT DATA
IDENTIFICATION AND SELECTION OF EVENTS
ANATOMICAL IMAGE RECONSTRUCTION
μ=4
μ=3
μ=2 or μ=3
x, y, z, Δt RECONSTRUCTION
x, y, z, Δt RECONSTRUCTION
LOR, TOF RECONSTRUCTION
DATA: x, y, z, Δt
DATA: LOR, TOF
MORPHOMETRIC INDICATORS RECONSTRUCTION
IMAGE RECONSTRUCTION
ATTENUATION CORRECTION
MORPHOMETRIC IMAGES τ0-Ps(x,y,z); Ppoz(x,y,z)
METABOLIC IMAGE M(x,y,z)
ANATOMICAL IMAGE A(x,y,z)
VISUALIZATION: A, M, τ, Ppoz, SUV, W
Ω
210
211
212
213
215
214
217
218
219
230
231
232
233
220
221
222
232
234
223
240

Fig. 2

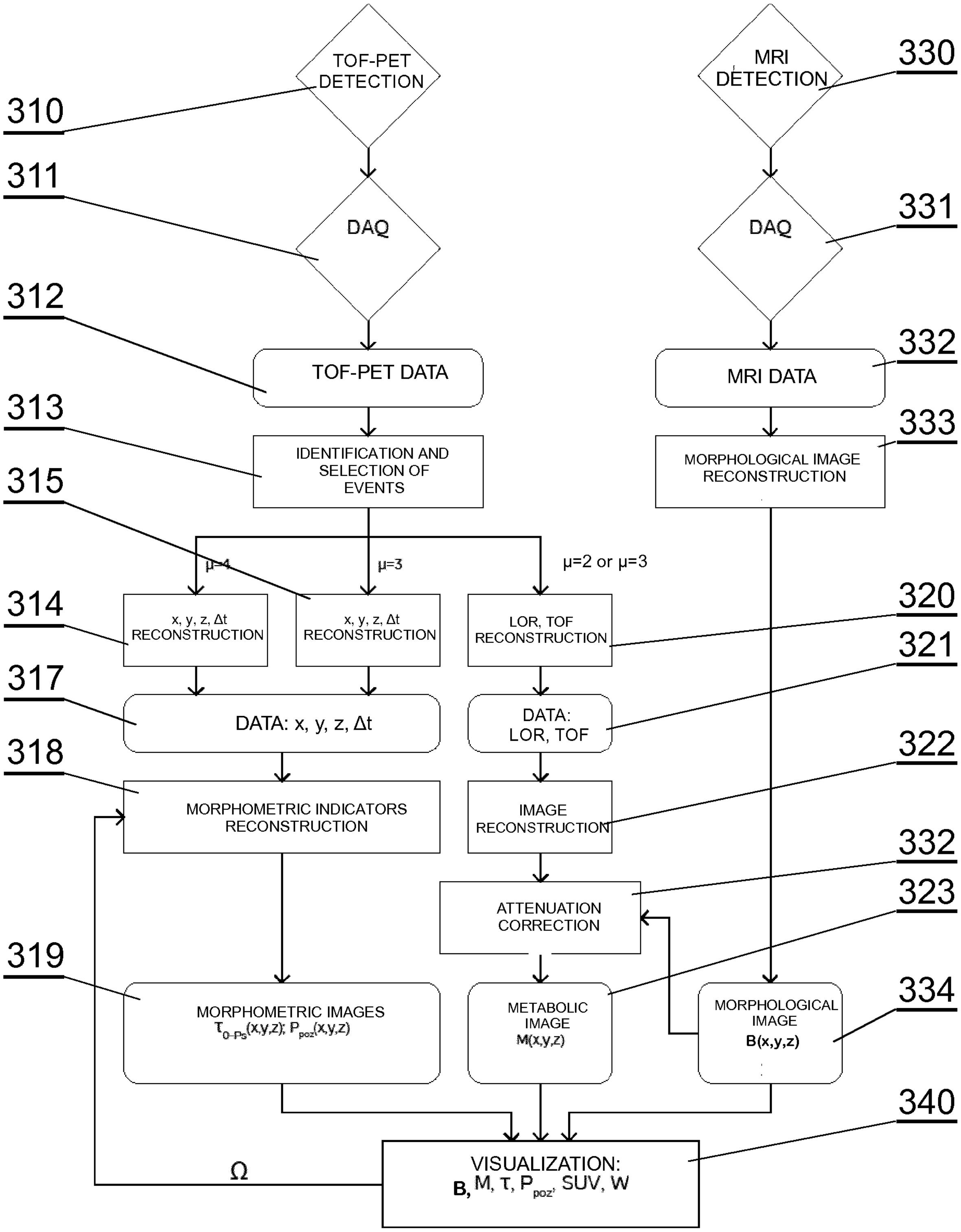
310
TOF-PET DETECTION
311
DAQ
312
TOF-PET DATA
313
IDENTIFICATION AND SELECTION OF EVENTS
315
330
MRI DETECTION
331
DAQ
332
MRI DATA
333
MORPHOLOGICAL IMAGE RECONSTRUCTION
μ=4
μ=3
μ=2 or μ=3
314
x, y, z, Δt RECONSTRUCTION
x, y, z, Δt RECONSTRUCTION
LOR, TOF RECONSTRUCTION
320
317
DATA: x, y, z, Δt
DATA: LOR, TOF
321
318
MORPHOMETRIC INDICATORS RECONSTRUCTION
IMAGE RECONSTRUCTION
322
332
ATTENUATION CORRECTION
323
319
MORPHOMETRIC IMAGES $\tau_{0-Ps}(x,y,z)$; $P_{poz}(x,y,z)$
METABOLIC IMAGE M(x,y,z)
MORPHOLOGICAL IMAGE B(x,y,z)
334
340
Ω
VISUALIZATION: B, M, τ, $P_{poz}$, SUV, W

Fig. 3

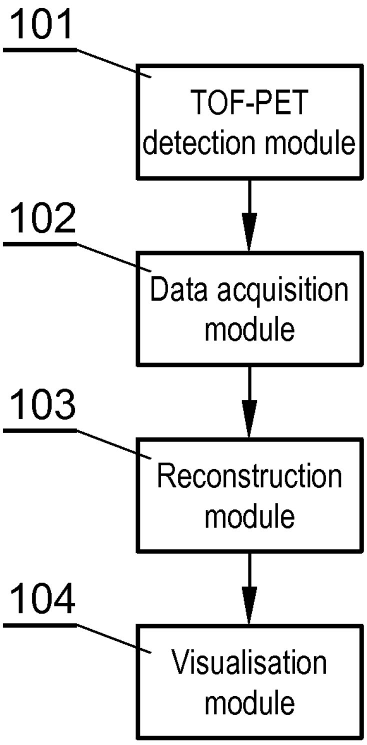

Fig. 4

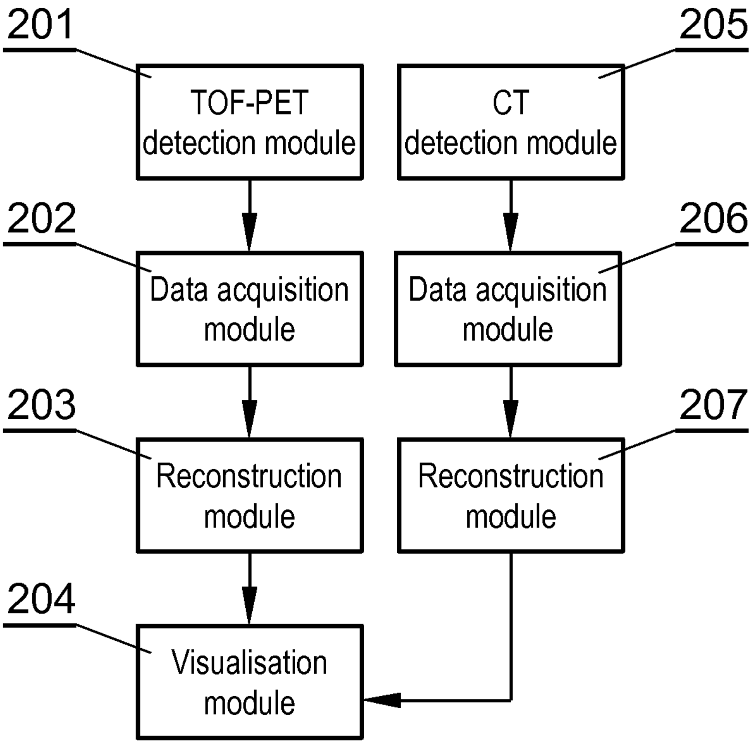

Fig. 5

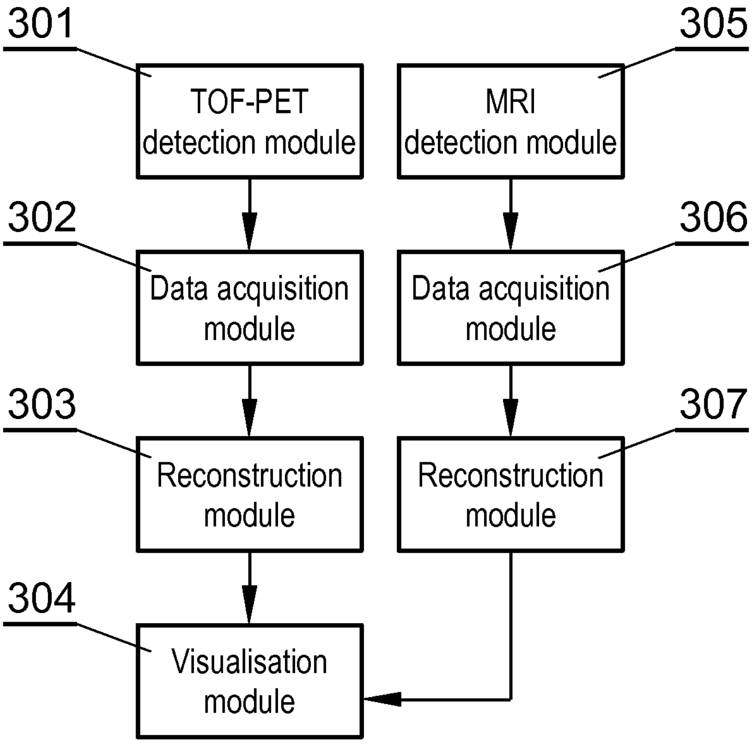

Fig. 6

## REFERENCES CITED IN THE DESCRIPTION

### Patent documents cited in the description

- WO 2011008119 A **[0012] [0024]**
- WO 2011008118 A **[0012] [0024]**
- WO 2012135725 A **[0013]**

### Non-patent literature cited in the description

- **R. PIETRZAK et al.** Influence of neoplastic therapy on the investigated blood using positron annihilation lifetime spectroscopy. *NUKLEONIKA,* 2013, vol. 58 (1), 199-202 **[0019]**