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(54) Title: PIXEL BASED DEAD TIME CORRECTION

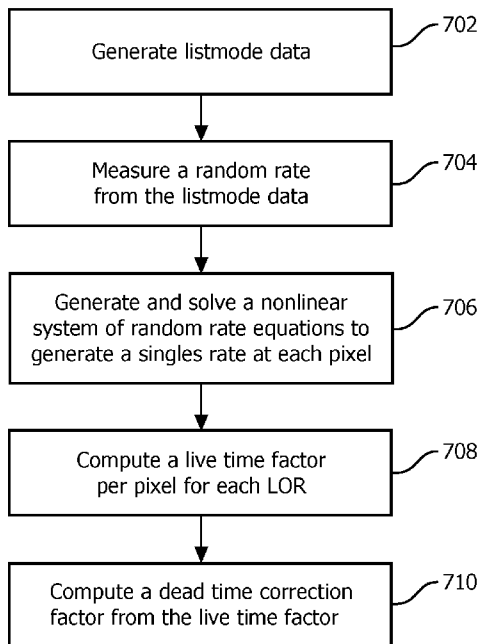


FIG. 7

(57) Abstract: A positron emission tomography (PET) apparatus and method employs a plurality of radiation detectors (20) disposed around an imaging region (16) and configured to detect 511 keV radiation events emanating from the imaging region. A calibration phantom is disposed in the imaging region. One or more processors are configured to: acquire and store listmode data of the phantom; measure a random rate for each line of response (LOR) from the listmode data using a coincident 511 keV events detector (34) with a time offset (54); determine a singles rate for each detector pixel from the random event rate, for example via a histogram plotting singles rate for each detector pixel; compute a live time factor of each LOR; compute a dead time correction factor as the reciprocal of the live time factor; and correct images according to the dead time correction factor.

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PIXEL BASED DEAD TIME CORRECTION

FIELD

The following relates generally to medical imaging. It finds particular application in calibration of a positron emission tomography (PET) detectors for quantitative analysis, imaging, or other tasks, and will be described with particular reference thereto.

5 However, it is to be understood that it also finds application in other usage scenarios and is not necessarily limited to the aforementioned application.

BACKGROUND

PET quantitative analysis techniques seek to quantitatively assess the tissue
10 radioactivity concentration, typically scaled by the injected activity per unit mass or another normalization factor. The quantitative analysis is based upon a linear relationship of patient image intensity with uptake of the imaging agent. For a fluoride-18 (F18) radioisotope, the most common quantitative image analysis metric is Standardized Uptake Value (SUV), which is calculated either pixel-wise yielding a parametric image, or over a Region of
15 Interest (ROI). However, the linear relationship used to transform image intensity to tissue radioactivity concentration is derived from a SUV calibration which is typically computed as a single curve for the entire system, i.e. the same SUV calibration curve is used for each detector pixel. The SUV calibration curve also incorporates pixel dead time. During clinical imaging the PET system typically operates near or in the so-called “paralyzed detector”
20 regime, in which detector dead time is a significant factor. This dead time results because there is minimum time between gamma particle detection events – that is, if two gamma events impinge on the detector in (too) short succession, then the second event will not be detected because the detector has not yet reset after detecting the first event. Because a single system-level SUV calibration curve is used, the dead time is assumed to be the same for all
25 pixels. In the SUV calibration curve, the dead time is seen as a sub-linearity to the singles rate-versus-radioactivity curve due to reduced observed counts at high radioactivity level caused by “missed” counts during the dead time.

SUV calibration typically employs a cylinder source which contains F18 at a high activity level. The calibration source is located at the gantry ISO center, and parallel to

patient bed (i.e. cylinder axis oriented along the axial direction). PET data acquisition is performed periodically, until the source is decayed to a level below detection. The reason for placing the cylinder source at the ISO centre is to factor out the variations caused by positioning and source unevenness. As the radioactivity concentration of the calibration source is known as a function of time throughout the decay process, the result is the desired curve relating image intensity to radioactivity level. This process is known as SUV calibration.

With reference to FIGURE 1, the difference between SUV calibration and patient scan is illustrated. The SUV calibration uses a uniform cylinder phantom, with detectors at locations A, B, and C getting the same amount of exposure and having the same singles count rate. However, during a patient scan, detectors at A and B receive more exposure than the detectors at C, thus their singles rates are different.

However, such detector pixel-level effects are not accounted for by the single system-level SUV calibration curve.

SUMMARY

In accordance with one aspect, a diagnostic imaging system comprises a plurality of radiation detectors and at least one processor. The plurality of radiation detectors are configured to detect coincident radiation events defining lines of response (LORs) emanating from an imaging region and detected by detector pixels of the radiation detectors. The at least one processor is configured to: cause the radiation detectors to acquire listmode data comprising singles events detected by the detector pixels; and compute a dead time correction factor for each LOR defined by a pair of detector pixels.

In accordance with another aspect, a method is disclosed for computing dead time correction factor per pixel in a positron emission tomography (PET) scanner. The method comprises: using PET radiation detectors, detecting a plurality of 511 keV radiation events emanating from an imaging region; and using an electronic data processing device, computing a dead time correction factor for each line of response (LOR) defined by a pair of detector pixels of the PET radiation detectors.

In according with another aspect, a positron emission tomography (PET) imaging system comprises PET radiation detectors disposed around an imaging region configured to detect radiation events emanating from the imaging region, a calibration

phantom configured to be disposed in the imaging region, the phantom comprising a positron-emitting radioisotope, and one or more processors configured to: acquire listmode data of the phantom using the PET radiation detectors as radioactivity of the phantom decays over time; determine a radioactivity level versus singles rate curve based on the acquired listmode data and a known radioactivity decay rate of the phantom over the acquisition of the listmode data; determine from the listmode data a random event rate for each line of response (LOR) connecting two detector pixels of the PET radiation detectors; determine a singles rate for each detector pixel based on the random event rates for the LORs; compute a live time factor of each LOR between detector pixel i and detector pixel j based on the singles rates for the detector pixels i and j ; and compute a dead time correction factor for each LOR as the reciprocal of the live time factor computed for the LOR.

One advantage resides in a dead time correction factor for each pixel in the system.

Another advantage resides in linking pixel singles rates to dead time correction factors.

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

BRIEF DESCRIPTION OF THE DRAWINGS

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 depicts differences between a cylindrical phantom and a patient.

FIGURE 2 illustrates a nuclear imaging system to be calibrated.

FIGURE 3 depicts a plot of average singles rate vs. radioactivity.

FIGURE 4 depicts dead time correction factor vs. singles rate per pixel plot and a live time factor vs. singles rate per pixel plot.

FIGURE 5 depicts an average singles rate per pixel vs. average random rate per pixel plot.

FIGURE 6 depicts two-dimensional histograms of singles rates for different frames of the calibration source

FIGURE 7 depicts a method for calibrating a diagnostic imaging system..

DETAILED DESCRIPTION OF EMBODIMENTS

Calibration techniques disclosed herein overcomes the problems described
5 above by providing a complete map of dead time corrections for each detector pixel derived
from signal measurement. Advantageously, the original SUV calibration technique remains
the same, but is extended by obtaining the mapping of detector elements' live time (or dead
time, which contains the same information as live time). For patient scans, the disclosed
techniques determine random events, which are estimated using delayed events, and the link
10 between detector element singles rate, radioactivity, live time, and dead-time correction is
established.

With reference to FIGURE 2, a positron emission tomography (PET) imaging
system **10** is to be calibrated for quantitative analysis, such as SUV. The calibration
technique uses a conventional calibration source **14** placed within an imaging region **16** (or
15 bore) of a PET scanner **10**. The illustrative PET scanner **10** further includes a patient bed or
support **18** via which a patient is loaded into the examination region **16** (not used during the
calibration procedure), and one or more PET detector rings **20**. The calibration source **14** is
as described previously with reference to the left diagram of FIGURE 1, i.e. a cylinder source
containing F18 at a high activity level located at the gantry ISO center (that is, equidistant
20 from all detectors of a PET detector ring), and parallel to the patient bed **18** (i.e. cylinder axis
oriented along the axial direction). Radiation events are detected by the PET detector rings **20**
via scintillator and silicon photomultipliers (SiPMs) or other detectors such as
photomultiplier tubes (PMT's), or avalanche photodiodes (APDs) or the like making up
detector arrays of the PET rings **20**. A calibration processor **24** performs the SUV calibration
25 including per-pixel dead time correction to generate an SUV calibration including dead time
26.

The calibration including dead time correction disclosed herein
advantageously leverages coincidence-based data processing machinery that is used during
patient (or, more generally, subject) imaging. Accordingly, subject imaging is first described.

30 During imaging, each detected gamma photon event is time stamped by a
clock **30**. In a digital PET system each event is typically time stamped on circuitry that
supports the SiPM. A coincident pair detector **34** compares the timestamps of the detected

events to determine pairs of events which define the end points and/or, e.g. occur within a preselected coincidences time window.

The ring of radiation detectors **20** (including crystals, (e.g., thousands) light detectors (e.g., hundreds, thousands), and support circuitry modules (e.g., tens)) are arranged
5 around the imaging region **16** to detect radiation events (e.g., gamma rays) emitted from within the imaging region **16**. As depicted, the plurality of detectors **20** can be arranged in a plurality of modules **22**, each of which sends digital signals indicative of at least energy and the time of each event. The scanner **10** further includes the support mechanism **18** for
10 positioning a patient or an imaging subject in the imaging region **16**. In some instances, the support mechanism **18** is linearly movable in an axial direction generally transverse to the PET ring or rings **20** to position the region of interest of the patient in the field of view, and in some imaging techniques to facilitate acquiring three dimensional imaging data.

In preparation for imaging with the scanner **10**, a suitable radiopharmaceutical is administered to the subject that will be scanned, and the subject is positioned within the
15 imaging region **16**. The radiopharmaceutical includes radioisotopes that undergo radioactive decay, which results in an emission of positrons. Each positron interacts with a nearby electron and annihilates, which produces two oppositely directed (180 degree) gamma rays having energies of about 511 keV each. The two oppositely directed gamma rays may strike opposing detectors at substantially the same time, i.e., coincidently.

20 The pair detector **34** identifies pairs of substantially simultaneous or coincident gamma ray detections belonging to corresponding electron-positron annihilation events. This processing can include, for example, energy windowing (e.g., discarding radiation detection events outside of a selected energy window disposed about 511 keV) and coincidence-detecting circuitry (e.g., discarding radiation detection event pairs temporally
25 separated from each other by greater than a selected time-window).

Upon identifying an event pair, a line of response (LOR) processor **36** processes the pair of events to identify a spatial LOR connecting the two gamma ray detections. Since the two gamma rays emitted by a positron-electron annihilation event are oppositely spatially directed, the electron-positron annihilation event is known to
30 have occurred somewhere on the LOR. In TOF-PET, the detectors and the time stamping of the clock **30** have sufficiently high temporal resolution to detect a time-of-flight (TOF) difference between the two substantially simultaneous gamma ray detections. In such TOF PET imaging systems, a TOF processor **38** analyzes the time difference between the times of

each event of the coincident pair to localize the positron-electron annihilation event along the LOR.

A reconstruction engine **40** reconstructs an imaging data set comprising LOR (optionally with TOF localization) into images that are stored in storage or memory **42**, and can be displayed, printed, archived, filmed, processed, transferred to another device, displayed on a monitor **44**, etc. A radiologist or other suitable clinician can use the raw data and/or reconstructed image to control the TOF-PET scanner **10**, diagnose the subject, etc.

To perform quantitative analysis, such as illustrative Standardized Uptake Value (SUV) analysis, an SUV analysis module **50** applies the SUV calibration **26** generated by the calibration processor **24** to convert image intensity values to normalized tissue radioactivity concentration values so as to generate SUV data. If SUV is computed on a per-pixel basis, then an SUV image results, which can be displayed on the monitor **44**. Alternatively, SUV can be computed for a region of interest (ROI) and presented as a numerical value for the ROI, again suitably displayed on the monitor **44**. As disclosed herein, the SUV calibration **26** included dead time correction on a per-pixel basis. As used herein, the term “detector pixel” denotes a detector image element of the PET ring **20** that is capable of detecting a single event.

It is to be appreciated that the processing described above as well as other processing can be performed by one or more processing components. Thus, the processing described herein can be processed by a single processing component, individual processing components, different combinations of processing components, and/or a combination thereof.

Having described subject imaging, the processing performed by the calibration processor **24** to generate the SUV calibration **26** is described. This calibration processing leverages the coincidence-based data processing machinery **34**, **36** used during imaging. In particular, the singles rate is estimated for each pixel based on a randoms rate measured using the pair detector **34** with an applied time offset **54** as described herein. The singles rate for each pixel is then used to estimate the dead time for that pixel.

To perform the calibration, the cylindrical phantom **14** is placed in the scanner **10** at the isocenter with its cylinder axis oriented horizontally, i.e. along the axial direction and transverse to the plane of the PET ring **20**. The cylinder source contains a radiopharmaceutical, e.g. F18, at a high radioactivity level that is assessed as it decays for true coincidences, random events, and singles rate. A single is any 511 keV event that is detected by a detector **20**, including true coincident events and random events and scatter

events. A true coincidence event consists of two 511 keV particles detected within the coincidence time window, from which it may be inferred that both 511 keV particles were produced by a single electron-proton annihilation event. A random event consists of two 511 keV particles (or particles falling within the energy window for 511 keV) that are detected within the coincidence time window, but which do not in fact originate from a single electron-proton annihilation event.

A random occurring within the coincidence time window cannot be distinguished from a true coincidence event. However, it is recognized herein that the random rate can be measured using the following rationale. Since the two events making up the random are statistically independent (e.g. not sourced from a common electron-proton annihilation event), it follows that the rate of occurrence of such event pairs should be independent of the time interval separating them. To quantify, denote the coincidence window as Δt , and two singles s_1, s_2 occurring at times t_1, t_2 respectively. Further define an offset time T . Then a randoms rate is defined as the rate of single pairs s_1, s_2 for which $t_2 - T$ lies within the coincidence window Δt of the time t_1 . In this estimate, the offset T is selected to be large enough to exclude true coincidence events – in other words, there should be no overlap between the coincidence window Δt and the offset window $T + \Delta t$. Because randoms are statistically independent, the offset rate (that is, the rate of events s_1, s_2 occurring at respective times t_1, t_2 where $t_2 - T$ lies within the coincidence window Δt of the time t_1) should equal the randoms rate.

In view of the foregoing, the randoms rate can then be measured by imposing a time offset **54** (previously denoted as offset T) on the pair detector **34**, so that the coincidence detection machinery **34** is leveraged to measure the randoms rate.

To perform the calibration, a listmode acquisition of the phantom **14** is performed by the PET scanner **10** to acquire listmode data for calibrating the PET scanner **10**, in particular the detectors **20**. The calibration source **14** is located at the gantry ISO centre, parallel to patient bed to factor out detector variations. The listmode acquisition is performed periodically, until the calibration source is decayed to a level such that the apparent dead time is zero.

The detectors **20** are typically paralyzable detectors where a single event occurring at the detector during dead time restarts the dead time period. The apparent dead time is directly correlated to the singles rate of the detector **20**, i.e. the pixel or crystal. However, the main output of a PET system is true coincidence events. Typically, the singles

rates for each detector **20**, i.e. pixel or crystal, are not available and not easily obtained in the hardware data chain. For example, the singles rate may be measured at the module level as a type of “dark current” metric for measuring performance of the detector module **22**. In practice, however, both singles and random events have a local spatial variance across the pixel pairs. The rate of random events is proportional to the square of the singles rate, i.e., the singles rate of each detection element, and in turn correlated to the detector dead time. As disclosed herein, using random events, which are readily available for each LOR, the singles rate can be estimated with a proper signal decomposition method. The random events rates are estimated as already described, using the delay technique which adds the time delay offset **54** to one of the coincidence paths, e.g., $T = 100$ ns, such that “coincidence” events with this offset **54** are classified as random events and not true coincidence events, and the randoms rate is measured on a per-detector pixel pair basis using the same machinery that measures the coincidence rate.

With continuing reference to FIGURE 2 and with further reference to FIGURE 3, the calibration processor **24** determines the relationship of a singles rate to radioactivity of the radiopharmaceutical through direct measurement of the singles rate during the SUV calibration. With reference to FIGURE 3, the calibration processor **24** averages the acquired single rate during SUV calibration for the entire system and assigns the average value to each detector **20** which is plotted against the detector exposure, i.e. the radioactivity of the phantom. The pixels of the detector **20** are arranged in the gantry in a tangential direction x , about $N_x = 576$ detector elements, and an axial direction y , about $N_y = 40$ detector elements, resulting in 23,040, i.e. $576 * 40$ or $N_x * N_y$, pixels in the system. With continuing reference to FIGURE 3, the plot is nearly linear, however, the slope decreases as the average singles rate increases, indicating a paralyzed state for the detector **20**. Again, this sub-linear slope is due to some singles events failing to be detected because they occur during the detector pixel dead time while it is resetting from detecting a previous singles event. The sub-linear relationship captured in the SUV calibration of FIGURE 3 conventionally provides the dead time correction – but it is a system-level correction, and cannot account for different dead times for different detector pixels.

The relationship of singles rate to a measured dead time is a determined dead time correction factor measured during SUV calibration, e.g. by extracting the dead time as a metric of the sub-linearity of the data of FIGURE 3. With reference to FIGURE 4, the dead time correction factor is plotted against the average singles rate per pixel (left side of the

figure). The dead time correction factor is suitably implemented as a multiplier for the coincidence window to compensate for dead time due to random events paralyzing the detector **20**. Additionally or alternatively, the calibration processor **24** calculates a live time factor from the dead time factor, or directly from the data of FIGURE 3. The live time factor is a reciprocal to the dead time correction factor – whereas the dead time measures the fraction of time the detector pixel is inactive due to paralysis, the live time measures the fraction of time the detector is active, i.e. in a non-paralyzed state. Said another way, the live time is an alternative (i.e. reciprocal) representation of the dead time, and when used in its broadest sense herein the term “dead time” encompasses its representation as a reciprocal, or live time, value. As seen in FIGURE 4, live time has a practical advantage over dead time in that the live time is a true probability-type value that ranges between zero and one. Live time can be viewed as the detector’s **20** probability of data loss in processing additional data. The live time factor is calculated as a function of detector’s **20** singles rate per pixel (right side of the figure). The left hand side of FIGURE 4 is the dead time correction factor vs. singles rate, and the right hand side of FIGURE 4 is the live time factor vs. singles rate. Both plots describe the same correction but in a reciprocal manner. At a lower singles rate, the live time factor is 1, indicating the detector is able to capture all photons, i.e. non-paralyzed. As the singles rate increases, the live time factor decreases. This means more single events, or counts, are not detected.

The processing of FIGURES 3-4 is typically performed on a module level or system level, as the PET coincidence detector machinery **34, 36** is not utilized. This means that conventionally the SUV calibration cannot provide a per-detector pixel dead time.

With reference to FIGURE 5, the random rate, i.e. delay rate, which is measured as the rate of “coincidence” events with the time offset **54** for one pixel, is typically a square function of the singles rate, i.e. for a detector pixel pair i, j where detector pixel i has a (ground truth) singles rate S_i and detector pixel j has a (ground truth) singles rate S_j , the randoms rate R_{ij} for the pixel pair i, j is $R_{ij} \propto S_i \times S_j$ (where the symbol “ \propto ” is used in its conventional sense to denote a proportional relationship). In one embodiment, the singles rate for each detection element is used, computed using the relation $R_{ij} = 2\tau S_i S_j$ where τ is the coincidence window width and R_{ij} is acquired for each pixel pair i, j using the coincidence machinery **34, 36** with the offset **54** applied. In another embodiment, for SUV calibration, the singles rate for all detection elements is consistent after accounting for normalization differences (due to the radial symmetry of the cylinder calibration source **14**, and neglecting

any pixel-to-pixel variations), and so the system singles rate averaged over the number of pixels can be taken as the per-detector pixel singles rate.

In the following, the singles rate per-detector pixel computed from the random rates R_{ij} is described in further detail. The measured random rate R_{ij} , also referred to herein as the delay rate, between a detector pair i and j is related to the corresponding singles rate of each detector i and detector j according to:

$$R_{ij} = 2\tau S_i * S_j \quad (1)$$

where R_{ij} is the measured random rate of the line of response from i to j ; τ is the coincidence window width; and S_i and S_j are the singles rate at the respective detector pixels i and j . This equation can be solved for each pixel pair i, j in the gantry for which a line of response can be defined (in a suitable approach, a LOR is defined for each pixel pair i, j for which the line connecting pixels i and j passes through the imaging region **16**). Considering all such pixel pairs i, j , Equation 1 forms a system of nonlinear equations with one equation for each detector pair i, j , where R_{ij} are known random rate measurements from the SUV calibration and S_i and S_j are unknowns. The system of equations is heavily overdetermined since each pixel i can pair with a large number of other pixels j , and vice versa. In one embodiment, the calibration processor **24** resolves the nonlinear system of equations using a global optimization method such as least squares minimization method or the like.

In another embodiment, with reference to FIGURE 6, the calibration processor solves the nonlinear system of equations by generating a 2D histogram **600, 602, 604** of the random events. The histogram **600, 602, 604** is a map of the singles rate with a scaling factor. The scaling factor is obtained as

$$\alpha = \frac{S}{\sum s_{xy}} \quad (2)$$

Where S is the system singles rate (e.g. as provided in the calibration data of FIGURE 3); s_{xy} is the singles rate derived from random events for a detector pixel in 2D space, where $x=0, 1, \dots, Nx$, and $y=0, 1, \dots, Ny$. The summation of all individual singles rates should be the same as the system singles rate S . The histogram **600, 602, 604** divided into a top half **606** and bottom half **608** of the ring of detectors **20** in the gantry. In this particular embodiment there are 6 total frames representing a part of the bed position of the entire scan of the body, where, in continuing reference to FIGURE 6, histograms of frame 2 **600**, frame 4 **602**, and frame 6 **604**, are shown. The intensity of each pixel corresponds to the singles rate derived from random events. In one embodiment, the singles rate is represented as colors in

the histogram. In another embodiment, the singles rate is visually represented according to grey scale intensity. From the histograms **600**, **602**, **604**, pixels with high singles rates varies from pixels with low singles rates by as much as 30%. In another embodiment, the 2D histogram can be represented in a lookup table.

5 To obtain dead time per pixel, the calibration processor **24** calculates the live time (LT) of two pixels i and j at the ends of each LOR. The calibration processor **24** calculates the live time as a combination of the singles rates of each detector using

$$LT_{ij} = f(S_i) * f(S_j) \quad (3)$$

10 where f is the live time factor for the singles rate per pixel and LT_{ij} is the live time factor for the LOR between i and j . For example, $f(S_i)$ is the live time factor corresponding to the singles rate S_i read from the plot of FIGURE 4. The dead time correction factor is calculated as the inverse of the live time factor for the LOR depicted as

$$DT_{ij} = \frac{1}{LT_{ij}} \quad (4)$$

15

where DT_{ij} is the dead time correction factor for each LOR from i to j . In one illustrative approach for implementing the correction, the determined dead time correction factor DT_{ij} is used as a multiplier to the coincident window Δt to correct the true coincidences rate for the dead time. The calibration processor **24** stores the dead time correction factor DT_{ij} in the correction memory **26** as part of the SUV calibration for use by the system when performing SUV or other quantitative analysis of a patient image.

20

With reference to FIGURE 7, to summarize, a method for computing deadtime time correction factor per pixel is depicted. At a step **702**, listmode data are acquired of the calibration phantom **14**. At a step **704**, a random rate is determined from the listmode data for each LOR by applying the pair detector **34** to the listmode data with the offset **54**. At a step **706**, a nonlinear system of random rate equations is generated in accord with Equation 1 and solved to generate a singles rate at each detector pixel. The nonlinear system is suitably solved using a 2D histogram or the like as described with reference to FIGURE 6, or by a least squares optimization method, or so forth. At a step **708**, a live time factor is computed for each LOR of a coincident pair using Equation 3. At a step **710**, a dead time correction factor is computed as the reciprocal the live time for each LOR as per Equation 4.

25

30

The SUV calibration of FIGURE 3 can be adjusted to remove the sub-linearity introduced by the dead time, since the dead time is now corrected separately, e.g. by scaling the coincidence window as $DT_{ij}\Delta t$. One way to do this is to fit the lower portion of the singles rate-vs.-radioactivity curve to a straight line, since dead time is negligible in this region of the SUV calibration. This linearized SUV calibration curve is suitably stored as part of the SUV calibration **26** (along with the data of FIGURE 4 or a parametric equation derived therefrom, e.g. function f , and optionally FIGURE 5, or the scaling factor τ extracted from this curve).

The SUV analysis module **50** can apply the SUV calibration **26** as follows.

Given a listmode imaging dataset for a subject, the randoms R_{ij} for each LOR i, j is obtained by applying the pair detector **34** to the list mode data with the offset **54**. Equation 1 is applied to generate a system of equations that are solved to determine the singles rates S_i and S_j for respective detector pixels i, j . Equation 3 is then applied (leveraging the calibration data of FIGURE 4 stored as part of the SUV calibration **26** as the function f) to generate the live time LT_{ij} for the LOR i, j . The dead time DT_{ij} is then the reciprocal of this as per Equation 4. Thereafter, the list mode imaging data set is processed in the usual way, e.g. applying the coincidence machinery **34**, **36** without the offset **54**, but with the coincidence window adjusted for each pixel pair i, j according to $DT_{ij}\Delta t$, in order to generate LOR data that is reconstructed by the reconstruction engine **40** to generate an image with dead time correction. This image may be useful by itself, insofar as the image is made more accurate by eliminating the distorting effect of dead time. If quantitative analysis is desired, the image is processed by the linearized version of the SUV calibration curve (i.e. linearized version of FIGURE 3, again stored as part of the SUV calibration **26**) to convert intensity values to (normalized) activity or uptake levels.

As used herein, a memory includes any device or system storing data, such as a random access memory (RAM) or a read-only memory (ROM). An electronic data processing device including a processor with suitable firmware or software implements the various processing components **24**, **34**, **36**, **38**, **40**, **50**. Such an electronic data processing device may comprise any device or system processing input data to produce output data, such as a microprocessor, a microcontroller, a graphic processing unit (GPU), an application-specific integrated circuit (ASIC), a FPGA, and the like; a controller includes any device or system controlling another device or system, and typically includes at least one processor; a user input device includes any device, such as a mouse or keyboard, allowing a technician of

the user input device to provide input to another device or system; and a display device includes any device for displaying data, such as a liquid crystal display (LCD) or a light emitting diode (LED) display.

5 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 or the equivalents thereof.

CLAIMS:

1. A positron emission tomography (PET) system comprising:
 - a plurality of radiation detectors (20) configured to detect coincident radiation event pairs defining lines of response (LORs) emanating from an imaging region and detected by detector pixels of the radiation detectors; and
 - at least one processor configured to:
 - cause the radiation detectors to acquire listmode data comprising singles events detected by the detector pixels; and
 - compute a dead time correction factor for each LOR defined by a pair of detector pixels.
2. The system according to any one of claims 1-2, wherein the computing the dead time correction factor for each LOR includes:
 - determining a random rate for each LOR from the listmode data; and
 - determining a singles rate for each detector pixel from the determined random rates.
3. The system according to claim 2, wherein the operation of determining a singles rate for each detector pixel comprises solving a system of equations $R_{ij} \propto S_i * S_j$, where R_{ij} is the determined random rate of the LOR defined by detector pixels i and j ; the symbol " \propto " denotes a proportional relationship; and S_i and S_j are unknown singles rates for detector pixels i and j respectively.
4. The system according to claim 3, wherein solving the system of equations $R_{ij} \propto S_i * S_j$ includes the at least one processor further configured to:
 - generate a histogram map of the singles rate per pixel, wherein the histogram includes a scaling factor.

5. The system according to any one of claims 2-4, wherein the computing the dead time correction factor further includes the at least one processor further configured to:

compute a live time LT_{ij} factor for the LOR defined by detector pixels i and j based on the singles rates S_i and S_j for the detector pixels i and j respectively.

6. The system according to claim 5, wherein the computing the dead time correction factor includes the at least one processor further configured to:

compute the dead time correction factor from the live time factor using $DT_{ij} = \frac{1}{LT_{ij}}$ where DT_{ij} is the dead time correction factor for each LOR from i to j .

7. A method for computing dead time correction factor per detector pixel in a positron emission tomography (PET) scanner, the method comprising:

using PET radiation detectors, detecting a plurality of 511 keV radiation events emanating from an imaging region; and

using an electronic data processing device, computing a dead time correction factor for each line of response (LOR) defined by a pair of detector pixels of the PET radiation detectors.

8. The method according to any one of claims 7, wherein computing the dead time correction factor includes:

determining a random rate for each LOR; and

determining a singles rate for each detector pixel of the PET radiation detectors from the determined random rates.

9. The method according to claim 8, wherein the operation of determining a singles rate for each detector pixel comprises solving a system of equations $R_{ij} = 2\tau S_i * S_j$, where R_{ij} is the determined random rate of the LOR defined by detector pixels i and j ; τ is a coincidence window width; and S_i and S_j are unknown singles rates for detector pixels i and j respectively.

10. The method according to claim 9, wherein solving the system of equations $R_{ij} = 2\tau S_i * S_j$ includes the at least one processor further configured to:

generating a histogram map of the singles rate per pixel, wherein the histogram includes a scaling factor.

11. The method according to any one of claims 8-10, wherein computing the dead time correction factor includes:

compute a live time factor LT_{ij} for the LOR defined by detector pixels i and j based on the singles rates S_i and S_j for the detector pixels i and j respectively.

12. The method according to 11, wherein computing the dead time correction factor includes:

compute the dead time correction factor from the live time factor LT_{ij} using $DT_{ij} = \frac{1}{LT_{ij}}$ where DT_{ij} is the dead time correction factor for each LOR between i and j .

13. The method according to any one of claims 7-12 wherein the detecting comprises acquiring PET imaging data for an imaging subject, and the method further comprises:

using the electronic data processing device, reconstructing the PET imaging data to generate a PET image of the imaging subject and transforming the PET image to generate Standardized Uptake Value (SUV) data for the imaging subject comprising a parametric SUV image or an SUV value for a region of interest;

wherein the reconstructing and transforming includes correcting the PET imaging data for detector dead time using the dead time correction factors for the LORs.

14. A non-transitory computer readable medium carrying software for controlling one or more processors to perform the method of any of claims 7-13.

15. A positron emission tomography (PET) imaging system comprising:
 PET radiation detectors (20) disposed around an imaging region configured to detect radiation events emanating from the imaging region; and
 a calibration phantom (14) configured to be disposed in the imaging region, the phantom comprising a positron-emitting radioisotope; and
 one or more processors configured to:

acquire listmode data of the phantom using the PET radiation detectors as radioactivity of the phantom decays over time;

determine a radioactivity level versus singles rate curve based on the acquired listmode data and a known radioactivity decay rate of the phantom over the acquisition of the listmode data;

determine from the listmode data a random event rate for each line of response (LOR) connecting two detector pixels of the PET radiation detectors;

determine a singles rate for each detector pixel based on the random event rates for the LORs;

compute a live time factor of each LOR between detector pixel i and detector pixel j based on the singles rates for the detector pixels i and j ; and

compute a dead time correction factor for each LOR as the reciprocal of the live time factor computed for the LOR.

16. The system according to claim 15, wherein the operation of determining a singles rate for each detector pixel comprises solving a system of equations $R_{ij} = 2\tau S_i * S_j$, where R_{ij} is the determined random rate of the LOR defined by detector pixels i and j ; τ is the coincidence window width of the coincident 511 keV events detector of the PET imaging system; and S_i and S_j are unknown singles rates for detector pixels i and j respectively.

17. The system according to claim 16, wherein solving the system of equations $R_{ij} = 2\tau S_i * S_j$ includes the at least one processor further configured to:

perform a least squares optimization of the singles rate per detector pixel.

18. The system according to any one of claims 15-17, wherein the one or more processors are further configured to:

adjust a coincidence window width of a coincident 511 keV event pair detector (34) of the PET imaging system for each LOR using the dead time correction factor computed for the LOR.

19. The system according to claim 18, wherein the coincidence window width is adjusted for each LOR defined by pixel pair i, j according to $DT_{ij}\Delta t$, where Δt is the coincidence window width and DT_{ij} is the dead time correction factor for the LOR.

20. The system according to any one of claims 15-19, wherein the operation of determining from the listmode data a random event rate for each LOR uses a coincident 511 keV events detector (34) of the PET imaging system with a predetermined time offset (54) large enough to avoid detecting true coincident 511 keV event pairs produced by electron-positron annihilation events.

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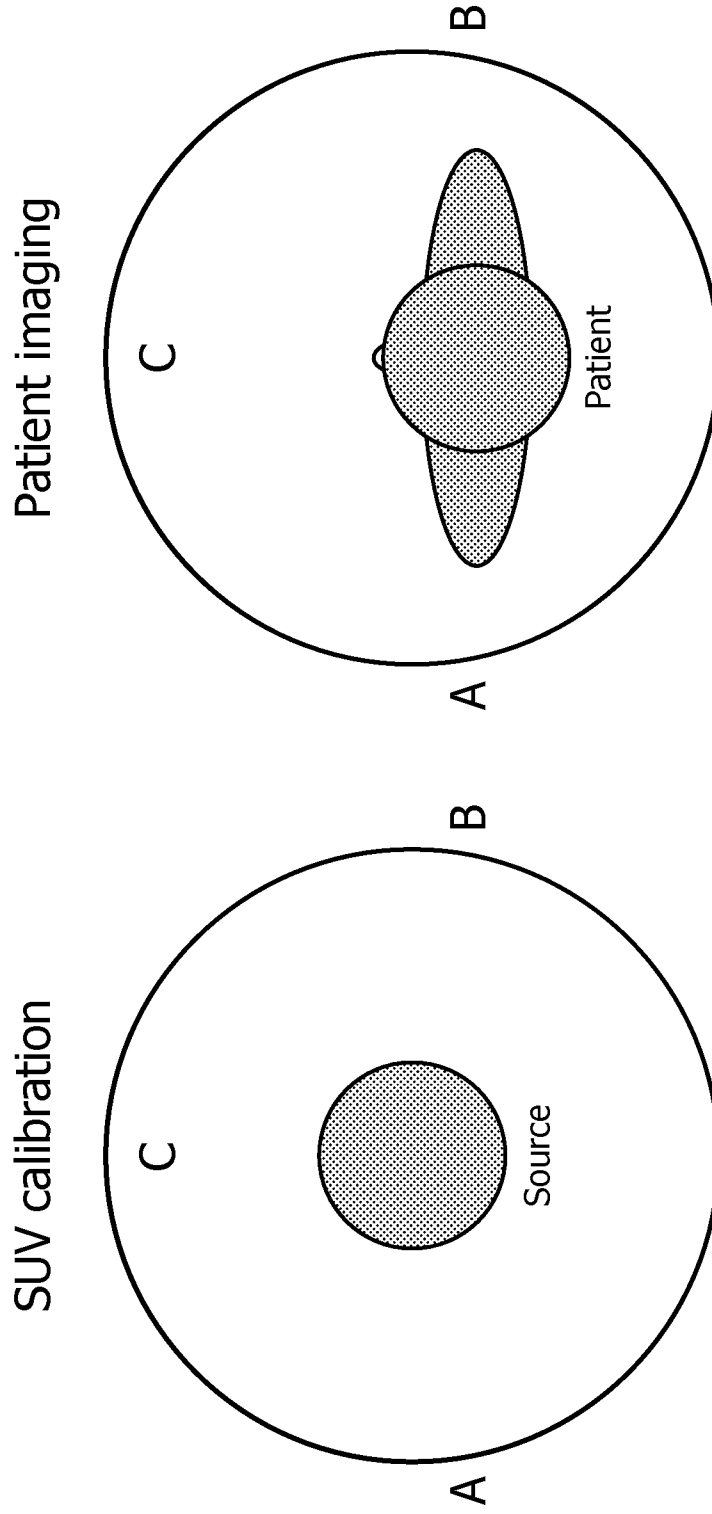


FIG. 1
Prior art

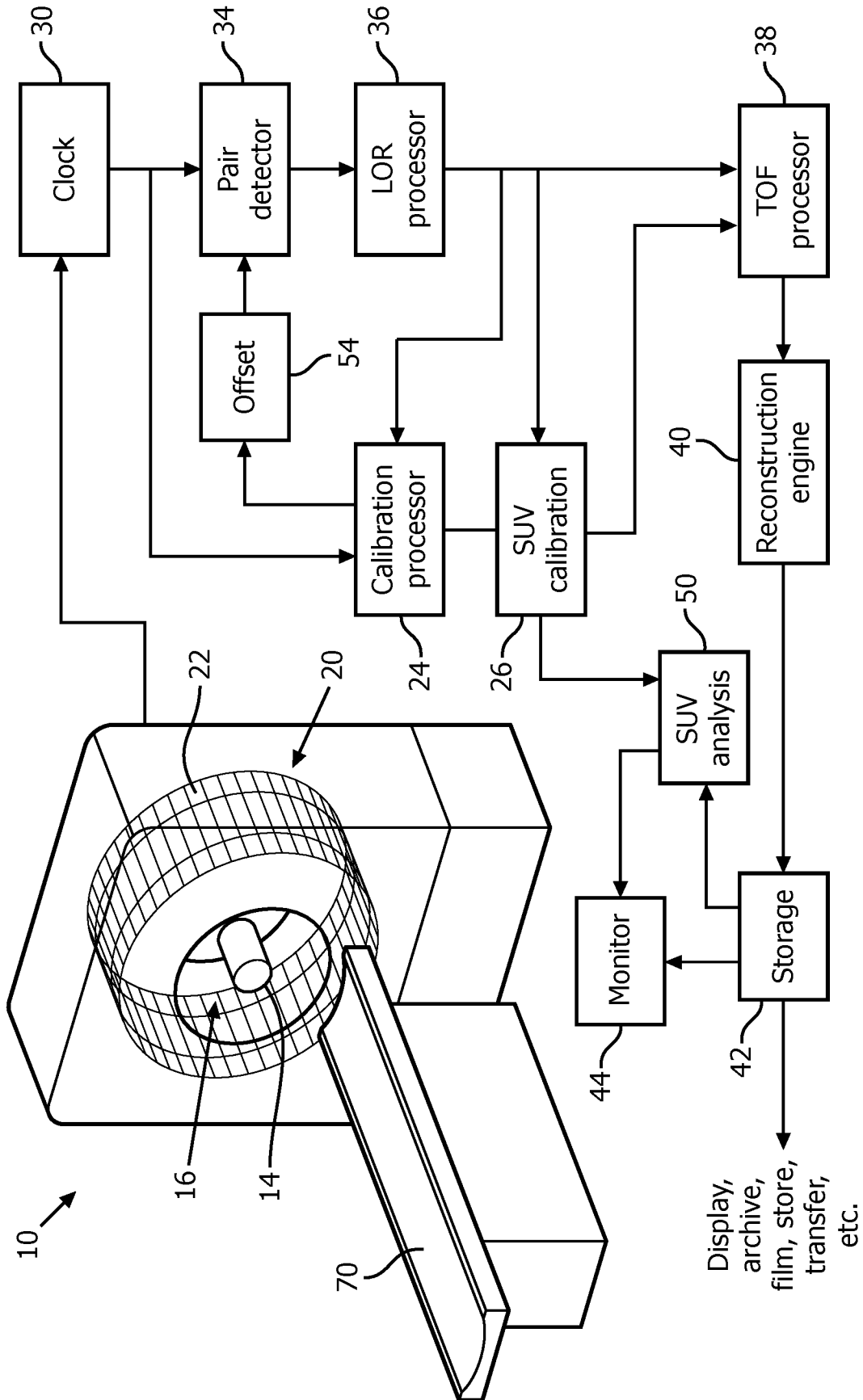


FIG. 2

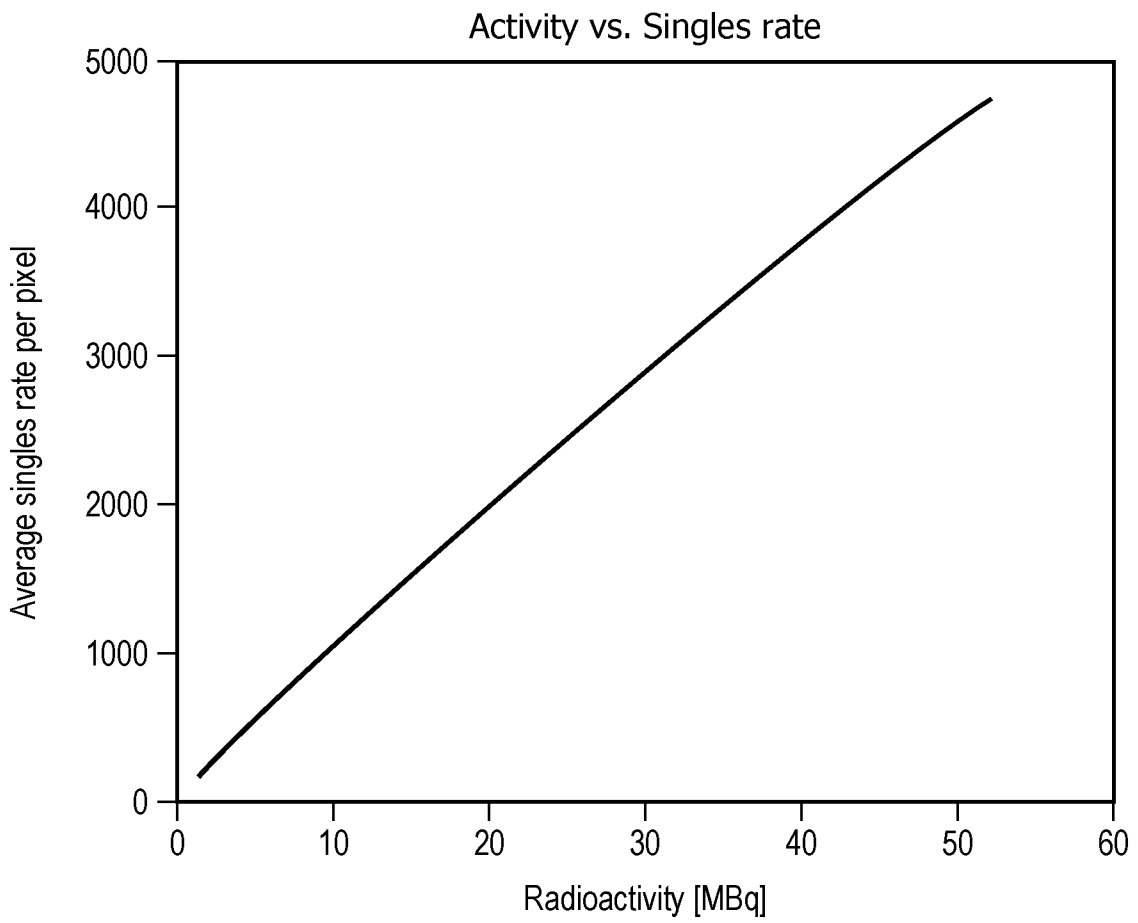


FIG. 3

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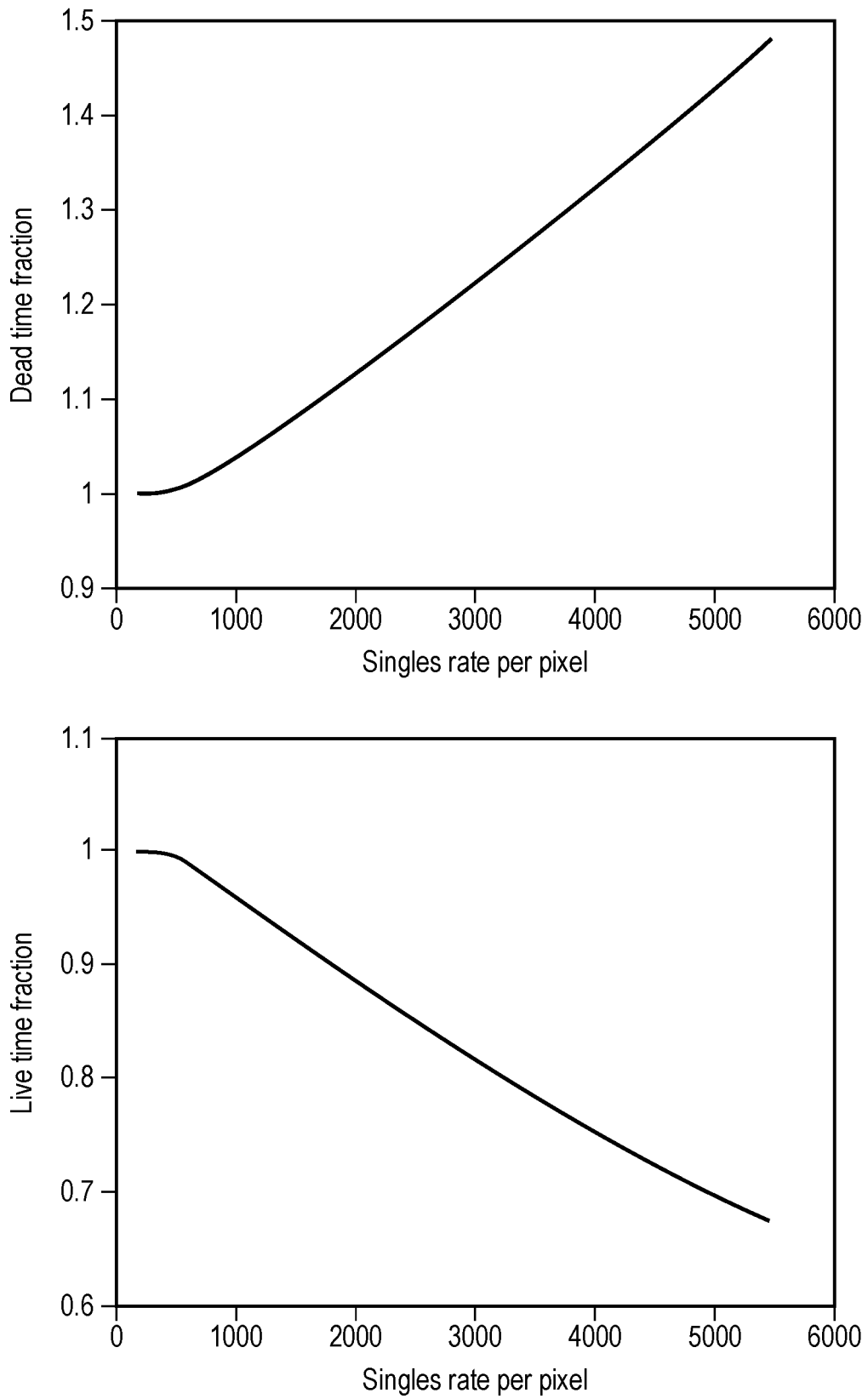


FIG. 4

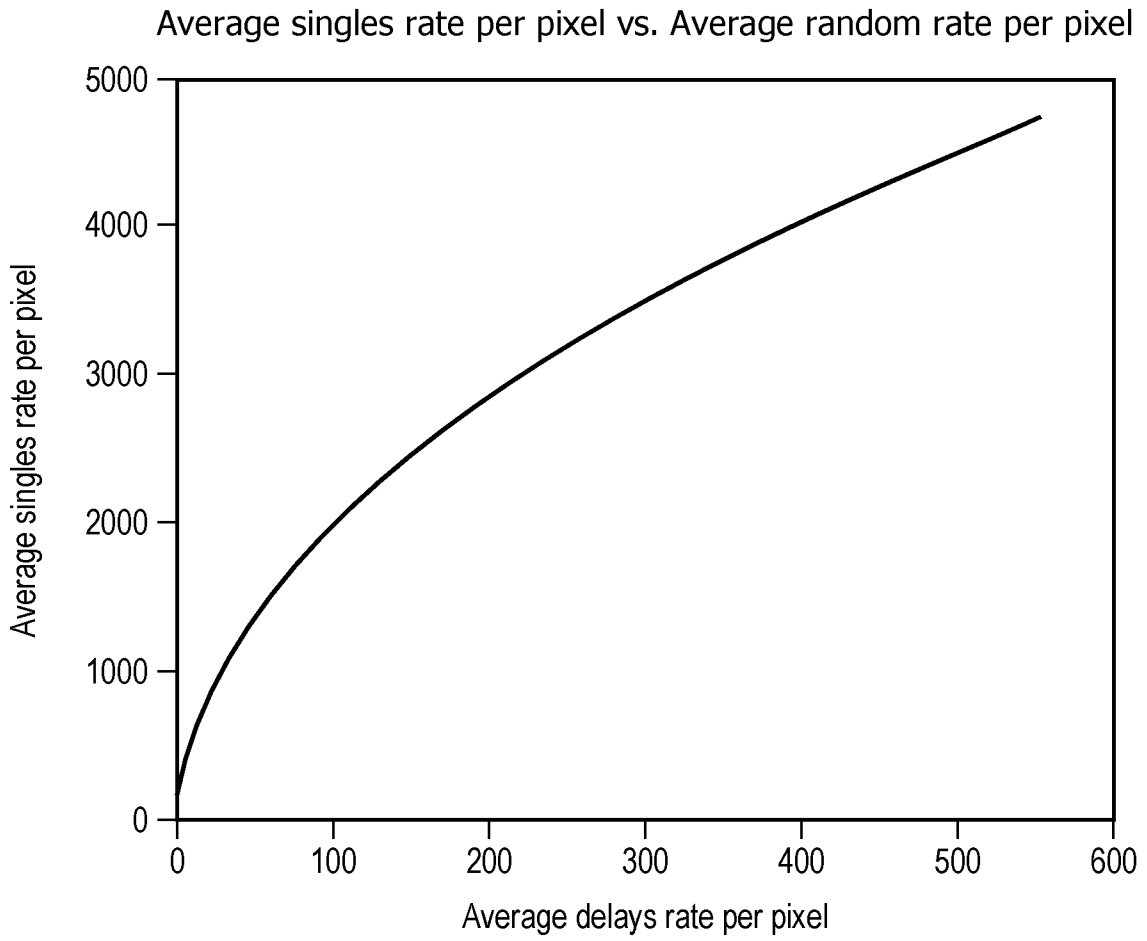


FIG. 5

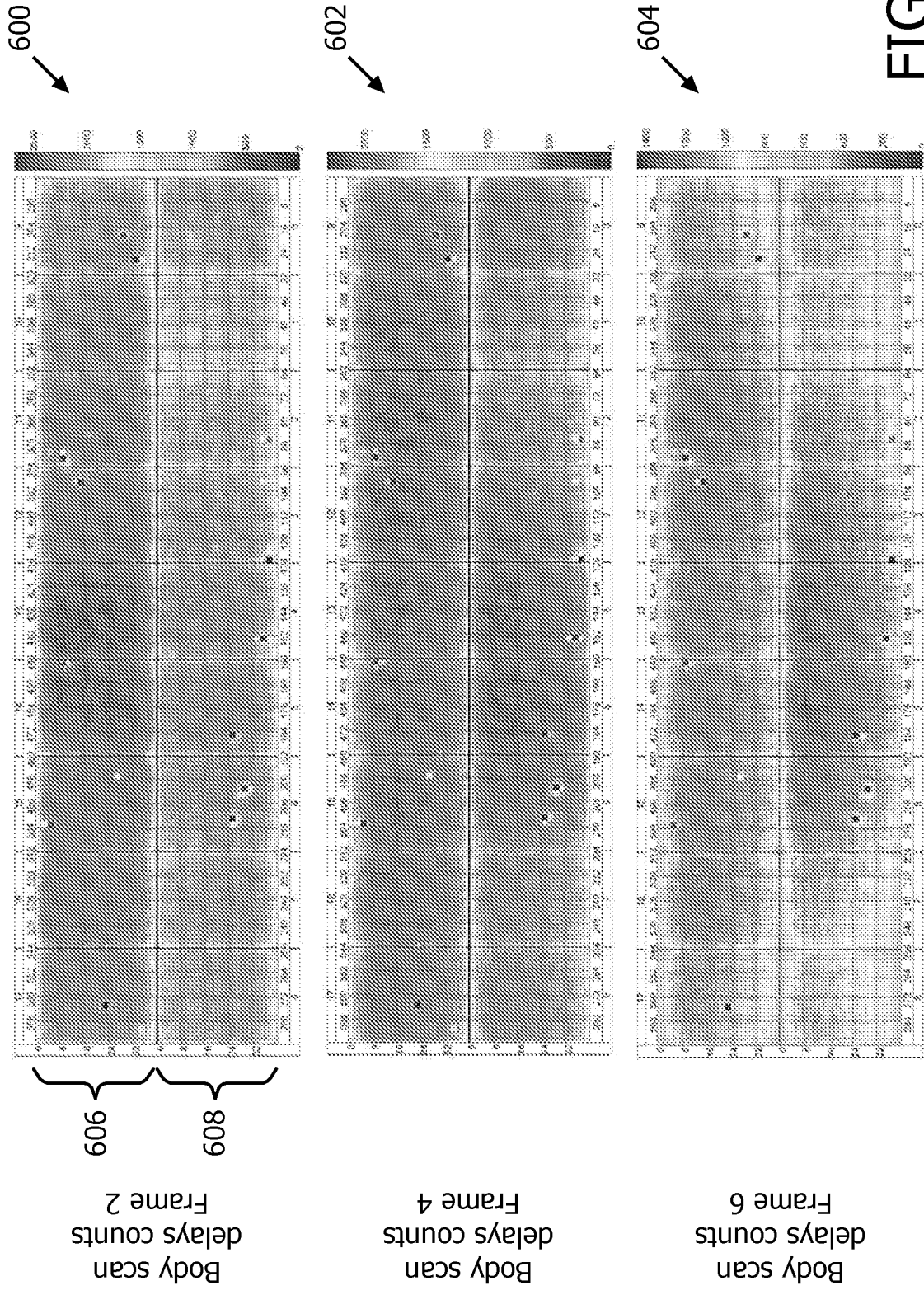


FIG. 6

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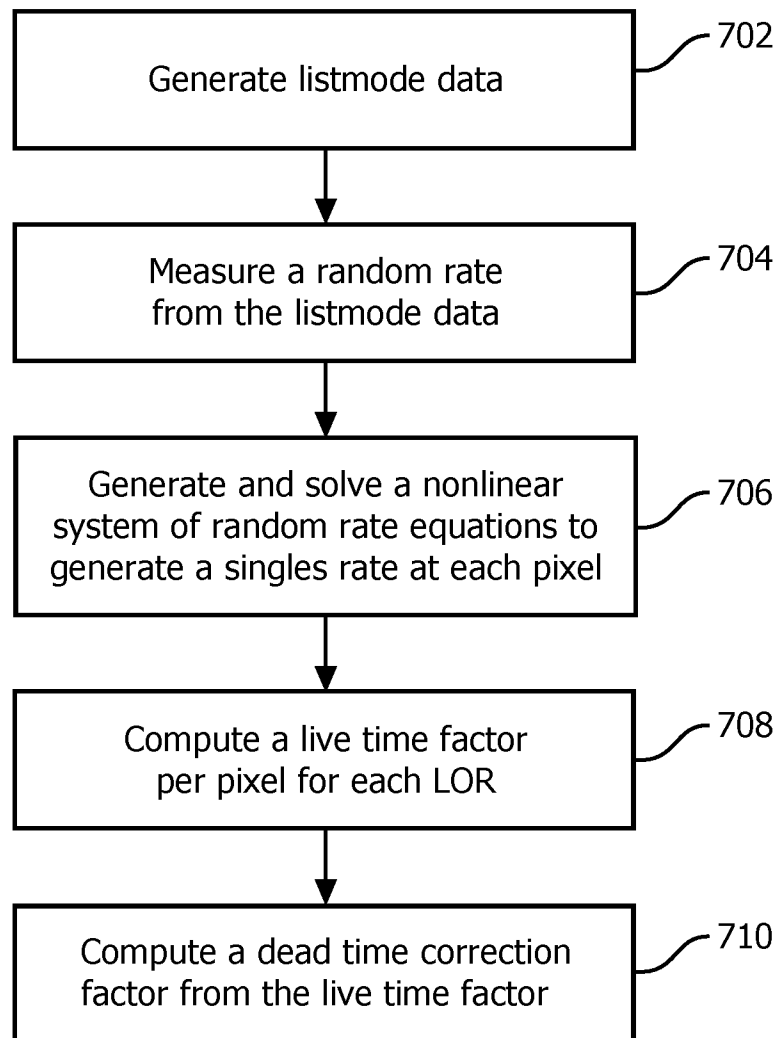


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2015/059594

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01T1/17 G01T1/24
ADD.
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
G01T
Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Further documents are listed in the continuation of Box C.

See patent family annex.

* Special categories of cited documents :

<p>"A" document defining the general state of the art which is not considered to be of particular relevance</p> <p>"E" earlier application or patent but published on or after the international filing date</p> <p>"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</p> <p>"O" document referring to an oral disclosure, use, exhibition or other means</p> <p>"P" document published prior to the international filing date but later than the priority date claimed</p>	<p>"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</p> <p>"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone</p> <p>"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art</p> <p>"&" document member of the same patent family</p>
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Date of the actual completion of the international search 24 February 2016	Date of mailing of the international search report 03/03/2016
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Van Ouytsel, Krist'1

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Y	US 5 241 181 A (MERTENS JOHN D [US] ET AL) 31 August 1993 (1993-08-31) column 9, lines 37-60; figure 6	20
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International application No
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PCT/IB2015/059594

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