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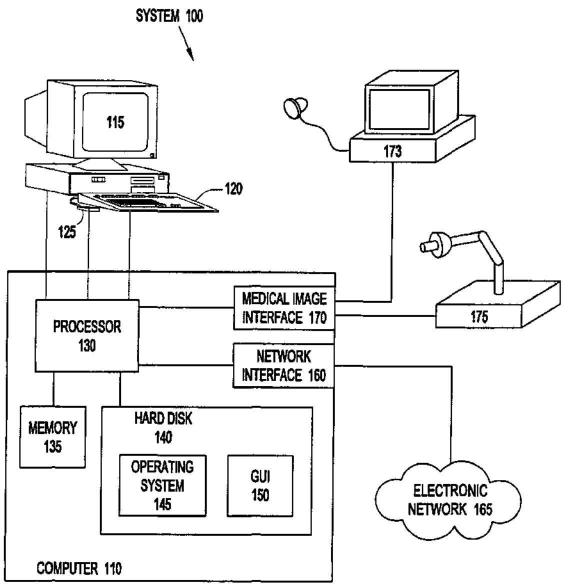
(54) **Title:** SEED LOCALIZATION SYSTEM AND METHOD IN ULTRASOUND BY FLUOROSCOPY AND ULTRASOUND FUSION



(57) **Abstract:** A seed localization system and method in which a 5 computer-based system is used to determine the three- dimensional (3D) position of radiotherapy seeds with respect to an area of affected tissue, such as the prostate, using ultrasound (US) and fluoroscopy (FL) imaging, so that a radiotherapy dose may be calculated. One embodiment the present invention may be used to determine the 3D position of implanted brachytherapy seeds. An alternative embodiment of the invention may be used to determine the 3D position of implanted objects other than brachytherapy seeds. The seed localization system and method includes a graphical user interface useful for assisting a user of the seed localization system in its operation.

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SEED LOCALIZATION SYSTEM AND METHOD IN ULTRASOUND BY FLUOROSCOPY AND ULTRASOUND FUSION

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to systems and methods for the treatment of cancer using radiation, and, more specifically, to systems and methods for the treatment of cancer using implanted brachytherapy seeds.

2. Background

Brachytherapy, a useful technique for treating cancer, is a radiation treatment using a solid or enclosed radioisotopic source on the surface of the body or a short distance from the area to be treated. With respect to prostate cancer, for example, brachytherapy involves the implantation of radiotherapy seeds into the prostate. The effectiveness of the brachytherapy treatment depends, however, on the particularized placement of the implanted brachytherapy seeds to achieve a preferred radiotherapy dose.

The radiotherapy dose administered to the patient may be calculated by observing the three dimensional (3D) positions of the brachytherapy seeds with respect to the affected tissue. Computed tomography (CT) is one technique used to determine the three dimensional locations of the seeds. A common problem with using CT, however, is that many operating rooms do not contain CT equipment. This makes it impossible to evaluate and subsequently adjust the dose of radiotherapy while the patient is in the treatment position. For example, if "cold spots" are found after imaging with CT, then the patient must be re-treated.

Therefore, it would be advantageous to provide a system and method that provide the capability of determining the three-dimensional location of brachytherapy seeds without requiring use of CT.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a three dimensional illustration of a preferred implant geometry used to orient the coordinate space for the system and method of the present invention;

Figure 2 is a side view of an implant geometry used with an embodiment of the present invention;

Figure 2a is an anterior-posterior (AP) view of an implant geometry showing the positions of the implanted markers used with an embodiment of the present invention;

Figure 2b is a side view illustrating the geometry of FL image capture used in an embodiment of the present invention;

Figure 2c is a schematic illustration of three FL images showing markers distinguishable from seeds;

Figure 3 is a block diagram of an embodiment of the system of the present invention;

Figure 4 is a flow chart diagram of an embodiment of a method according to the present invention;

Figure 5 is a block diagram of the structure of a graphical user interface of an embodiment of the present invention; and

Figure 6 is a screen shot display of the graphical user interface according to an embodiment of the present invention.

SUMMARY OF THE INVENTION

The present invention provides a system and method for determining the three-dimensional (3D) position of implanted radiotherapy seeds with respect to an area of affected tissue, such as the prostate, so that a radiotherapy dose may be calculated. While in one aspect the invention determines the 3D position of implanted brachytherapy seeds, in another aspect the invention determines the 3D position of implanted objects other than brachytherapy seeds (e.g., fiducial markers). The present invention uses ultrasound (US) and fluoroscopy (FL) imaging and does not require computed tomography (CT) imaging.

In one aspect, the invention provides a method and system for determining the position of implanted seeds with increased accuracy by determining the 3D seed positions in the most recently acquired US treatment volume/image, or group of US treatment data.

The present invention also provides a system and method for determining the 3D position of implanted radiotherapy seeds with respect to an area of affected tissue such that the dosimetry to the affected tissue may be determined intraoperatively, permitting dynamic adjustment of the treatment plan.

The present invention further provides a system and method of user visualization of the 3D position of implanted brachytherapy seeds by providing an interactive, computer-generated, graphical user interface.

Those of skill in the art, upon inspection of this specification and the drawings hereto, will appreciate that many features and variations are provided by the system and method according to the present invention.

DETAILED DESCRIPTION OF VARIOUS EMBODIMENTS

The present invention comprises a system and method for determining the three-dimensional (3D) position of radiotherapy seeds with respect to an area of affected tissue, such as the prostate, using ultrasound (US) and fluoroscopy (FL) imaging, so that a radiotherapy dose may be calculated. One embodiment of the present invention may be used to determine the 3D position of implanted brachytherapy seeds. An alternative embodiment of the invention may be used to determine the 3D position of implanted objects other than brachytherapy seeds.

Figure 1 illustrates a 3D view of the implant geometry of one embodiment of the invention. Referring now to Figure 1, an ultrasound probe 10 is inserted into the rectum (beneath prostate 20) and images are formed in vertical slices through prostate 20. These vertical image slices are planes parallel to the plane of template 30 and orthogonal to the axis of probe 10. The "base" and "apex" planes of the prostate (not shown) are the vertical planes farthest from the template 30 and closest to template 30, respectively. Typically in standard practice, a therapist plans where within a region of prostate 20 to implant brachytherapy seeds 40. Brachytherapy seeds 40 are typically cylinders 0.8 mm in diameter and 4.5 mm in length. The planned 3D position of a seed 40 is specified by a triple of (x,y,z) coordinates specifying the center of the seed 40 cylinder. The (x,y) coordinates of the triple correspond to one of the holes in template 30. The x coordinate corresponds to the horizontal axis of template 30 and the y coordinate corresponds to the vertical axis of template 30. The z coordinate is the depth within prostate 20 (i.e., some vertical plane parallel to template 30, between the apex and the base, and orthogonal to the axes of probe 10 and needles 50). Markers 45 are preferably spherical in shape to distinguish them from seeds 40, although other shapes are possible. Markers 45 are inserted prior to inserting seeds 40 and may be placed around the periphery of the prostate 20. Markers 45 are not coplanar. (By definition, A set of N points $\{(x_i, y_i, z_i) | i = 1,\ldots,N\}$ are coplanar if and only if there exists 4 constants A,B,C,D such that $A^2 + B^2 + C^2 + D^2 \neq 0$ and $Ax_i + By_i + Cz_i + D = 0$ for all $i = 1,\ldots,N$.)

Further details concerning radioactive seed implant planning, delivery, and verification may be found in Wallner, Kent et al., "Prostate Brachytherapy Made Complicated," SmartMedicine Press, Seattle, Washington, 1997, the entire disclosure of which is hereby incorporated into this specification as if set forth herein. Further details concerning standards for practice with respect to prostate seed implant brachytherapy may be found in articles by Yu, Yan et al., "Permanent Prostate Seed Implant Brachytherapy: Report of the American Association of Physicists in Medicine Task Group No. 64," Medical Physics, Volume 26, No. 10, October 1999, pp. 2054-2076, and Nag, Subir et al., "American Brachytherapy Society (ABS) Recommendations for Transperineal Permanent Brachytherapy of Prostate Cancer," International Journal of Radiation Oncology Biology Physics," Volume 44, No. 4, 1999, pp. 789-799, the entire disclosures of which are hereby incorporated into this specification as if set forth herein.

As shown in Figure 1, template 30 is registered with respect to ultrasound probe 10. Brachytherapy seeds 40 may be preloaded into hollow needles 50 (though other methods are possible) and placed through specific pre-planned holes in template 30. Needles 50 are inserted into prostate 20 using template 30 as a guide until they are seen on the ultrasound image appearing on an ultrasound image monitor (not shown). The therapist may then appropriately position seeds 40 within prostate 20. Seeds 40 are held in place by a central stylet while needles 50 are withdrawn, leaving seeds 40 embedded at discrete locations within a region of prostate 20.

In an alternative embodiment, seeds 40 in Figure 1 may represent implanted objects other than brachytherapy seeds. Further, in another alternative embodiment of the invention the tissue to be treated may be tissue other than prostate 20.

Figure 2 is a side view of one embodiment of the implant geometry. Referring now to Figure 2, cylindrical seeds 40 are located in prostate 20 at points usually between the base plane 60 and apex plane 70. Markers 45, often spherical, may be placed around the periphery of prostate 20. Prostate 20, typically 40-60 mm in length, is well visualized in the US, but cannot be as clearly seen in the FL 90. Seeds 40 are well visualized in the FL 90, but cannot always be seen in the US. Referring back to Figure 1, implant needles 50 and markers 45 can be seen in both the US and the FL 90. Only five brachytherapy seeds 40 are shown in Figure 2, although typically 70-120 seeds are implanted.

In an alternative embodiment of the invention, seeds 40 in Figure 2 may represent implanted objects other than brachytherapy seeds. Further, in another alternative embodiment of the invention the tissue to be treated may be tissue other than prostate 20.

Figure 2a illustrates an anterior-posterior (AP) view of the implanted markers 45. In a preferred embodiment, at least four markers 45 are implanted around the periphery of prostate 20. In one embodiment of the present invention, as shown in Figure 2a, near apex plane 70 the left marker 103 is below prostate 20 and the right marker 104 is above prostate 20. Markers 45 are preferably not located in the same plane as seeds 40. To prevent the markers 45 from being coplanar, the opposite convention is used near base plane 60, i.e., the left marker 101 is above prostate 20 and the right marker 102 is below prostate 20. The markers 45 are preferably chosen for imaging characteristics that allow them to be distinguishable from seeds 40. Since seeds 40 are typically cylindrical, in one embodiment of the invention the markers 45 are spherical.

Figure 2b illustrates a side view of the FL imaging geometry. At least two FL images of the prostate seeds 40 and markers 45 are necessary. By way of example, three FL images 201, 202, and 203 are shown in Figure 2b. The therapist can orient the FL imaging equipment "on-line" to maximize the visibility of seeds 40 and markers 45. For example, in some imaging positions, many of the seeds may overlap and not be distinguishable. These positions are to be avoided. As those skilled in the art will appreciate, imaging positions with greater "disparity" (i.e., greater separation between the images) lead to more accurate 3D reconstruction of the seed and marker positions.

Figure 2c is a schematic illustration of three FL images 201-203. At least two FL images of the seeds 40 and markers 45 are necessary. Markers 45 may be chosen to be easily distinguishable from seeds 40. The seeds 40 and markers 45 in each image are located. The markers 45 are matched between the images as described herein. There are typically 70-120 implanted seeds in the prostate. Once the markers are matched, the system 100 automatically matches the seeds as described herein.

Figure 3 illustrates seed localization system 100 according to an embodiment of the present invention. In one embodiment, seed localization system 100 is implemented using programmed instructions executing on a standard personal computer platform. In this embodiment seed localization system 100 includes a personal computer 110 having a standard set of peripherals, including a color monitor 115 or other suitable monitor, keyboard 120, mouse 125, microprocessor 130, memory 135, non-volatile storage such as a hard disk drive 140, and a standard operating system software 145 such as Microsoft® Windows™. In one embodiment, system 100 is also connected to an electronic network 165 through a network interface 160. In one embodiment, application software instructions are implemented in seed localization system 100 using the C++ programming language. Seed localization system 100 is capable of storing image data and processing stored image data in the manner described herein. In one embodiment, a user interacts with seed localization system 100 using graphical user interface 150.

Figure 4 illustrates an embodiment of a method 200 according to the present invention. Each step corresponds to a cell in Figure 4. By way of example only, each step is numbered. The ordering or combination of the following steps may differ from the numerical ordering in Figure 4 as would occur to one of ordinary skill in the art. Further, the column labeled "User or System 100" denotes that the steps therein may be performed either by the user (using system 100) or automatically by system 100, in different embodiments as described below.

Referring now to Figure 4, the method of the present invention comprises the following steps:

(1) In Step 1, the user selects for input one 3D US image of the prostate 20. Any one of several methods or combinations thereof may be used to acquire a 3D US image. In one embodiment, the 3D image is "captured" directly from an ultrasound imaging device 173 using a medical image interface 170 (shown in Fig. 3. In another embodiment, the 3D image is loaded from non-volatile storage 140 or received via electronic network 165 (shown in Fig. 3) according to standard protocols for medical images, such as "Digital Imaging and Communications in Medicine" (DICOM) protocols.

Any one of several methods or combinations thereof may be used to directly "capture" a 3D US image of prostate 20. In one embodiment, a method is used wherein US probe 10 is moved ("stepped") from base plane 60 to apex plane 70 in small increments, and system 100 acquires a discrete 2D image after each step using the medical image interface 170. The spacing between adjacent images (the step size or Z resolution) is a known value usually less than or equal to 2 mm. The X and Y resolutions of the images are also fixed through a "template registration" process that is known to those skilled in the art. The collection of 2D images are then assembled into a 3D image using standard techniques known to those skilled in the art.

Further details concerning template registration may be found in Mutic, Sasa et al., "A Simple Technique for Alignment of Perineal Needle Template to Ultrasound Image Grid for Permanent Prostate Implants," Medical Physics, Volume 27, No. 1, January 2000, pp. 141-143, the entire disclosure of which is hereby incorporated into this specification as if set forth herein.

(2) In Step 2, the user inputs the number $M \geq 4$ of markers 45 implanted into the prostate. Typically $4 \leq M \leq 8$. If the user does not enter at least $M \geq 4$ an error message is displayed to the user. In an alternative embodiment of the invention, seed localization system 100 retrieves the number of implanted markers 45 from memory 135 or hard disk 140 or another input or memory device. In one embodiment of the invention system 100 receives the number of implanted markers via an electronic network 165 such as via FTP over the Internet (by way of example only).

(3) In Step 3, the user locates the M highly visible markers 45 in the 3D US image using seed localization system 100. M is known from step 2. In an alternative embodiment of the invention, seed localization system 100 may automatically locate M visible markers 45 using a variety of discrimination techniques known to those skilled in the art of medical imaging. The coordinates of these highly visible markers 45 are stored in memory as a series of 3D vectors $Q_1, Q_2, .., Q_M$. By way of example only, the memory in which coordinate vectors are stored may be memory typically associated with the personal computer of system 100 such as memory areas 135 (Figure 3).

An arbitrary 3D point, X, in the 3D US image has a scalar intensity $I(X)$. Typically, $I(X) = 0$ if the point is completely dark, and $I(X) = 255$ if the point is completely bright. Because seeds 40 and markers 45 reflect more sonic energy than tissue, the seeds and markers appear in the 3D US image with greater scalar intensity, i.e., the seeds and markers show up as bright spots in the 3D US volume (i.e., 3D US image).

(4) In Step 4, the user selects for input K 2D FL images $J_k, k = 1, \ldots, K$ of the prostate 20. In one embodiment of

the invention, these images are "captured" directly from a fluoroscopy imaging device 175 using a medical image interface 170. In another embodiment, the 2D images are loaded from non-volatile storage 140 or received via electronic network 165 according to standard protocols for medical images, such as "Digital Imaging and Communications in Medicine" (DICOM) protocols.

Any one of several methods or combinations thereof may be used to directly "capture" a 2D FL image of prostate 20. In one embodiment, a C-arm device consisting of a x-ray source 80 and fluoroscopy image 90 (shown in Fig. 2) is used. The C-arm is positioned at K discrete positions that cut across prostate 20 and such that seeds 40 and markers 45 are visible in the fluoroscopy image 90. At each position, a FL image J_k is acquired using medical image interface 170. The C-arm positions at which the images are acquired do not need to be known and are chosen to maximize the visibility of seeds 40 and markers 45 and to provide "maximum disparity" for reconstruction according to standard techniques known to those skilled in the art. In one embodiment of the invention, US probe 10 is not within the body for enhanced image clarity.

(5) In Step 5, the user locates the M highly visible markers 45 in each 2D FL image $J_k, k=1,\ldots,K$ using seed localization system 100. M is known from step 2. In an alternative embodiment of the invention, seed localization system 100 may automatically locate M visible markers 45 using a variety of discrimination techniques known to those skilled in the art of medical imaging. Because there are K FL images and M markers, the number of 2D positions determined by system 100 is $K \times M$. In one embodiment of the

invention each 2D position is stored in memory 135 for later recall and processing.

An arbitrary 2D point, X, in a 2D FL image J_k has a scalar intensity $J_k(X)$. Typically, $J_k(X)=0$ if the point is completely dark, and $J_k(X)=255$ if the point is completely bright. Because markers 45 absorb more x-ray energy than tissue, the markers appear in the 2D FL image with lesser scalar intensity, i.e., the markers show up as dark spots in the 2D FL image. Recall that the markers 45 may be chosen so that they are distinguishable from the cylindrical seeds 40 in each FL image. In one embodiment of the invention the markers 45 are spherical balls.

(6) In Step 6, in a preferred embodiment the user matches the marker points between the K images, i.e., orders the marker points so that marker point m $(1 \le m \le M)$ in FL image 1 corresponds to marker point m in FL image 2, and so on through FL image K. In an alternative embodiment, seed localization system 100 may automatically perform these functions according to standard techniques known to those skilled in the art.

(7) In Step 7, the user inputs the number N of brachytherapy seeds 40 implanted using seed localization system 100. Typically $70 \le N \le 120$. In one embodiment, system 100 requires that the user enter at least $N \ge 1$ seeds 40. If the user does not enter at least $N \ge 1$ an error message is displayed to the user.

In an alternative embodiment of the invention, seed localization system 100 retrieves the number of implanted seeds 40 from memory 135 or hard disk 140 or another input or memory device. In one embodiment of the invention system 100 receives the number of implanted seeds via an electronic network 165 such as via FTP over the Internet (by way of example only).

(8) In Step 8, the user locates the N seeds 40 in each 2D FL image $J_k, k=1,\ldots,K$ using seed localization system 100. N is known from step 7. In an alternative embodiment of the invention, seed localization system 100 may automatically locate the N seeds 40 using a variety of discrimination techniques known to those skilled in the art of medical imaging. Because there are K FL images and N seeds, the number of 2D positions determined by system 100 is $K \times N$. In one embodiment of the invention each 2D position is stored in memory 135 for later recall and processing.

Because seeds 40 absorb more x-ray energy than tissue, the seeds appear in the 2D FL image with lesser scalar intensity, i.e., the seeds show up as dark spots in the 2D FL image.

(9) In Step 9, system 100 automatically matches or correlates the seed points between the K images, i.e., orders the seed points so that seed point n ($1 \le n \le N$) in FL image 1 corresponds to seed point n in FL image 2, and so on through FL image K.

(10) In Step 10, system 100 reconstructs, in the FL coordinate system, the 3D seed positions $R_1, R_2, \ldots, R_N$ and the 3D marker positions $P_1, P_2, \ldots, P_M$ according to standard techniques known to those skilled in the art.

(11) In Step 11 seed localization system 100 finds a solution $3x3$ matrix T and a $3x1$ vector t that maps each 3D FL seed point R_i to its corresponding 3D US location S_i. In one embodiment of the invention an initial estimate for the pair (T,t) is found by seed localization system 100 by finding the unique solution to the optimization problem

$\min_{T,t} \sum_{i=1}^{M} \| Q_i - TP_i - t \|^2$. Given the initial estimate, a final estimate is found by seed localization system 100 by solving the optimization problem $\max_{T,t} \sum_{i=1}^{N} I(TR_i + t)$. The maximization problem may or may not have a unique solution. If the maximization problem has no unique solution, a locally optimal solution may be determined. The maximization operation is useful to optimize the transformation pair (T,t) in order to more precisely correlate the 3D US seed positions to the 3D US image.

(12) In Step 12 seed localization system 100 determines or calculates the 3D seed positions $\{S_i = TR_i + t \mid i = 1,\ldots,N\}$ in the US image and displays them in the 3D US image. Seeds 40 may appear within the 3D US image on the monitor as transparent, colored cylinders.

(13) Using seed localization system 100, the user visualizes the positions of seeds 40 with respect to the 3D US image by viewing the image displayed on the monitor 115.

Thus, a system and method has been shown for determining the three-dimensional (3D) position of implanted brachytherapy seeds with respect to an area of affected tissue. The system and method allows the practitioner to calculate a radiotherapy dose by examining images generated using ultrasound (US) and fluoroscopy (FL) imaging but not requiring computed tomography (CT) imaging. The system may incorporate portable C-arm FL systems as well. There is no requirement to use a fixed (pre-determined) FL imaging geometry or to accurately calibrate the FL images (e.g., each FL image may have a different, unknown magnification). There is also no requirement for a fixed external, fiducial system.

Further, because the present invention reconstructs the seed positions from fluoroscopic images rather than from other images, the invention may be practiced in a wider variety of settings than was possible in the prior art. For example, the invention may be practiced in an operating room. There is no need for a radiotherapy simulator couch or other specialized equipment.

Because the invention may be practiced intraoperatively, the invention does not require the patient to be carefully repositioned in another room having specialized medical imaging equipment. Further, the inventive system and method differs from the prior art in that seed positions are not determined based on planned, pre-implant seed coordinates but rather on the actual 3D seed positions at the time of implant in the most recently acquired US treatment volume/image. Thus, the 3D seed locations are identified much more accurately than in prior art systems and the user may validate the result. The dosimetry to the tissue under treatment may be determined intraoperatively, permitting dynamic adjustment of the treatment plan.

As shown in Figure 3, one embodiment of the present invention comprises a computer-readable media 135 or 140 (by way of example only) on which is embodied a set of programmed instructions that cause one or more processors 130 to perform a sequence of Steps 1-13 (reference Figure 4). In one embodiment said processors and computer-readable media are comprised within computer 110. In one embodiment of the invention, computer-readable medium 140 is a hard disk. Operating system 145 and graphical user interface (GUI) 150 are stored on hard disk 140 in one embodiment of the invention.

Referring again to Figure 3, one embodiment of the invention includes a medical image interface 170. In this embodiment computer 110 acquires ultrasound and fluoroscopic images from ultrasound imaging device 173 and fluoroscopic imaging device 175 respectively. In an alternative embodiment of the invention, a network interface 160 is provided in addition to or instead of medical image interface 170. In this alternative embodiment computer 110 acquires ultrasound and fluoroscopic images through either medical image interface 170 or network interface 160. In one embodiment of the invention medical images are obtained through network interface 160 via a connection to an electronic network 165 as shown.

One embodiment of the present invention comprises a computer-generated, graphical user interface (GUI) 150 to guide the user in accomplishing Steps 1-13 described above (reference Figure 4). GUI 150 is preferably implemented on computer system 110 using monitor 115, keyboard 120, and mouse 125 in the manner known to those of skill in the art. GUI 150 forms an improved 3D image of the region of implanted seeds by analyzing US and FL data. GUI 150 then allows the user to identify the location of each implanted seed in the region by displaying the improved 3D image.

Figure 5 illustrates one embodiment of graphical user interface 150 in greater detail. Through processor 130 (Figure 3), GUI 150 interacts with data input sources such as keyboard 120, mouse 125, memory 135, and hard disk 140. GUI 150 also interacts with medical image interface 170 as well as network interface 160 via processor 130.

From any of these data sources, GUI 150 is provided with 3D US data 151 representing an image of a 3D region of implanted seeds according to Step 1 of the present invention (reference Figure 4). References to "Steps" discussed herein are made with respect to Figure 4. GUI 150 is also provided with FL data 153 representing a plurality of K FL images of the same region according to Step 4 of the present invention.

Data analyzer 152 analyzes 3D US data 151. In one embodiment of the invention, data analyzer 152 also uses data 155 input from sources 120, 125, 135, 140, 160, or 170 (shown in Fig. 3) to analyze 3D US data 151. Data analyzer 152 receives a number M corresponding to the number of implanted markers according to Step 2 of the present invention. This number M is comprised within data 155.

Data analyzer 152 locates the M highly visible markers according to Step 3 of the present invention. As previously noted, in one embodiment of the invention the user provides input 155 to locate M highly visible markers. In an alternative embodiment, data analyzer 152 automatically locates M highly visible markers using a variety of discrimination techniques known to those skilled in the art of medical imaging.

Data analyzer 152 stores the 3D coordinates of these highly visible markers in memory as a series of vectors $Q_1, Q_2, .., Q_M$. By way of example only, the memory in which coordinate vectors are stored may be memory typically associated with the personal computer of system 100 such as memory areas 135 or 140 (reference Figure 3).

Data analyzer 152 also analyzes FL data 153. Data analyzer 152 locates each implanted marker appearing in each FL image $J_1, J_2, \ldots, J_K$ comprised within FL data 153 according to Step 5 of the present invention. As previously noted, in one embodiment of the invention the user provides input 155 to locate each implanted marker appearing in each FL image $J_1, J_2, \ldots, J_K$. In an alternative embodiment, data analyzer 152 automatically locates each marker using a variety of discrimination techniques known to those skilled in the art of medical imaging.

In one embodiment of the invention, data analyzer 152 stores the FL coordinates 157 of each marker in memory. By way of example only, the memory in which FL coordinates 157 are stored may be memory typically associated with the personal computer of system 100 such as memory areas 135 or 140 (Figure 3).

Similarly to that described above, data analyzer 152 locates each implanted seed appearing in each FL image $J_1, J_{2,} \ldots, J_K$ comprised within FL data 153 according to Step 8 of the present invention. As previously noted, in one embodiment of the invention the user provides input 155 to locate each implanted seed appearing in each FL image $J_1, J_{2,} \ldots, J_K$. In an alternative embodiment, data analyzer 152 automatically locates each seed using a variety of discrimination techniques known to those skilled in the art of medical imaging.

In one embodiment of the invention, data analyzer 152 stores the FL coordinates 157 of each seed in memory. By way of example only, the memory in which FL coordinates 157 are stored may be memory typically associated with the personal computer of system 100 such as memory areas 135 or 140 (Figure 3).

According to Steps 6 and 9 of the present invention, coordinate reconstructor 154 receives from data analyzer 152 the discrete 2D positions 157 of each seed (and marker) appearing on images $J_1, J_{2,} \ldots, J_K$, to determine which 2D positions correspond to the same seed (and marker). Coordinate reconstructor 154 then reconstructs the 3D FL coordinates $R_1, R_{2,} \ldots, R_N$ of the seeds and the 3D FL coordinates

$P_1, P_2, \ldots, P_M$ according to Step 10 of the invention. In one embodiment of the invention, coordinate generator 154 stores each set of coordinates R_i and P_i for later recall and processing. By way of example only, the memory in which the 3D FL coordinates are stored may be memory typically associated with the personal computer of system 100 such as memory areas 135 or 140 (shown in Fig. 3).

Coordinate correlator 156 maps each 3D FL marker point P_i provided by coordinate generator 154 to its corresponding 3D US location Q_i provided by data analyzer 152 according to Step 11 of the present invention. It then maps each 3D FL seed point R_i to its corresponding 3D US location S_i. Improved image generator 158 then generates a 3D image that displays each seed's position within the 3D US image according to Step 13 of the invention. Then, according to step 13 of the present invention, a user may visualize the improved image on monitor 115.

Figure 6 illustrates a screen shot 600 of a PC display according to one embodiment of GUI 150. Figure 6 is given by way of example only. As can be seen in Figure 6, GUI 150 has several unique features. The "Back" button 610 allows the user to backup to fix errors (e.g., move backward from Step 4 to Step 3). The "ArchiveSave" button 620 allows the user to save his work at any given step and to later resume the method at that step. As noted above, one of ordinary skill in the art will recognize that Steps 1-13 may be ordered differently than shown in Figure 4 and yet be within the scope of this invention. GUI 150 allows the user of the inventive system to practice the steps of the inventive method in a manner flexible to the user.

As illustrated in Figure 6, GUI 150 allows the user to select a 3D US image 630 from among a plurality of 3D US images 640. Likewise, GUI 150 allows the user to select FL images 650 for analysis. GUI 150 also allows the user to visualize the determined 3D seed positions with respect to the 3D US image.

While the above description is set forth in specific detail, these details should not be construed as limitations on the scope of the invention but rather as an exemplification of embodiments thereof. Other variations may occur to a skilled artisan while remaining within the spirit and scope of the invention. By way of example only, the invention may be used to identify objects in tissue other than the prostate. The inventive system and method may also be used for other medical therapies or other 3D medical imaging purposes. Still other non-medical 3D imaging uses of the invention will be apparent to those of ordinary skill in the art.

CLAIMS

1. A system for determining a position of at least one implanted object in a body, comprising:
an ultrasound imager configured to forming an ultrasound image of a portion of the body containing the at least one implanted object;
a fluoroscopy imager configured to form a plurality of fluoroscopic images of the portion of the body; and
a computer system coupled to said ultrasound imager and to said fluoroscopy imager, said computer system processing the ultrasound image and the plurality of fluoroscopic images to calculate the position of the at least one implanted object in the body.

2. The system of claim 1, wherein the at least one implanted object includes a plurality of brachytherapy seeds used in a radiation treatment of affected tissue.

3. The system of claim 1, wherein said computer system includes:
a processor for processing the ultrasound image and the plurality of fluoroscopic images; and
a monitor coupled to said processor and configured to display a three-dimensional image of the portion of the body showing the position of the at least one implanted object in the body.

4. The system of claim 3, wherein said computer system further includes a graphical user interface coupled to said processor, said graphical user interface enabling a user to interact with said processor.

5. The system of claim 4, wherein said graphical user interface includes:

a first data input adapted to receive data regarding the ultrasound image;

a second data input adapted to receive data regarding the plurality of fluoroscopic images; and

a data analyzer coupled to said first data input and to said second data input and adapted to calculate from the ultrasound image a series of three-dimensional coordinates $Q_1, Q_2, \ldots, Q_M$ associated with M markers placed in the portion of the body and visible in the ultrasound image and the plurality of fluoroscopic images, wherein $M \geq 4$.

6. The system of claim 5, wherein said data analyzer is further adapted to calculate:

at least one set of two-dimensional coordinates for the at least one implanted object in each of the plurality of fluoroscopic images; and

M sets of two-dimensional coordinates for the M markers in each of the plurality of fluoroscopic images.

7. The system of claim 6, wherein said graphical user interface further includes a coordinate reconstructor coupled to said data analyzer and adapted to determine:

a series of three-dimensional coordinates $R_1, R_2, \ldots, R_N$ associated with N implanted objects; and

a series of three-dimensional coordinates $P_1, P_2, \ldots, P_M$ associated with the M markers.

8. The system of claim 7, wherein said graphical user interface further includes a coordinate correlator adapted to associate each of the series of three-dimensional coordinates P_i with each of the series of three-dimensional coordinates Q_i for each of the M makers, wherein $1 \le i \le M$.

9. The system of claim 8, wherein said coordinate correlator is further adapted to:

determine a $3x3$ matrix T and a $3x1$ vector t by solving an optimization problem; and

map each of the series of three-dimensional coordinates $R_1, R_{2,} \ldots, R_N$ to a series of three-dimensional coordinates $S_1, S_{2,} \ldots, S_N$ by a transformation $S_j = TR_j + t$, wherein $1 \le j \le N$.

10. The system of claim 9, wherein:

an initial estimate for (T,t) is found by solving a first optimization problem $\min_{T,t} \sum_{i=1}^{M} \left\| Q_i - TP_i - t \right\|^2$;

a subsequent estimate for (T,t) is found by solving a second optimization problem $\max_{T,t} \sum_{j=1}^{N} I(TR_j + t)$, wherein $I(X)$ is a scalar intensity of point X in the ultrasound image; and

if the second optimization problem has no unique solution, the subsequent estimate for (T,t) is found through a locally optimal solution.

11. A method for locating a plurality of implanted seeds, comprising the steps of:

obtaining a three-dimensional ultrasound image of a region containing the plurality of implanted seeds;

obtaining a plurality of two-dimensional fluoroscopic images of the region;

matching the plurality of implanted seeds in the three-dimensional ultrasound image with corresponding ones in the plurality of two-dimensional fluoroscopic images; and

calculating a plurality of three-dimensional coordinates of the plurality of implanted seeds by analyzing the three-dimensional ultrasound image and the plurality of two-dimensional fluoroscopic images.

12. The method of claim 11, further comprising the step of implanting a plurality of brachytherapy seeds used in a radiotherapy as the plurality of implanted seeds.

13. The method of claim 11, further comprising the step of placing M markers in the region, the M markers being visible in the three-dimensional ultrasound image and in the plurality of two-dimensional fluoroscopic images.

14. The method of claim 13, further comprising the steps of:

locating the M markers within the three-dimensional ultrasound image, wherein $M \geq 4$; and

calculating a series of three-dimensional coordinates $Q_1, Q_2, \ldots, Q_M$ of the M markers by analyzing the three-dimensional ultrasound image.

15. The method of claim 14, further comprising the steps of:

locating the plurality of implanted seeds and the M markers in each of the plurality of two-dimensional fluoroscopic images;

calculating a first plural sets of two-dimensional coordinates for the plurality of implanted seeds appearing in the plurality of two-dimensional fluoroscopic images;

calculating a second plural sets of two-dimensional coordinates for the M markers appearing in the plurality of two-dimensional fluoroscopic images;

determining a first series of three-dimensional coordinates $R_1, R_2, \ldots, R_N$ of the plurality of implanted seeds from the first plural sets of two-dimensional coordinates, wherein N is a number of the plurality of implanted seeds; and

determining a second series of three-dimensional coordinates $P_1, P_2, \ldots, P_M$ of the M markers from the second plural sets of two-dimensional coordinates.

16. The method of claim 15, further comprising the step of associating each P_i with a corresponding Q_i, wherein $1 \le i \le M$.

17. The method of claim 16, wherein the step of associating includes finding a $3x3$ matrix T and a $3x1$ vector t by determining a solution to an optimization problem.

18. The method of claim 17, further comprising the step of finding a series of three-dimensional coordinates $S_1, S_2, \ldots, S_N$ of the N implanted seeds by a transformation $S_j = TR_j + t$, wherein $1 \le j \le N$.

19. A computer-readable medium on which is embodied a set of programmed instructions that causes a processor to perform a sequence of steps, said sequence of steps comprising:

obtaining a three-dimensional ultrasound image of a region containing a plurality of implanted seeds;

obtaining a plurality of two-dimensional fluoroscopic images of the region;

forming an improved three-dimensional image of the region by analyzing the three-dimensional ultrasound image in combination with the plurality of two-dimensional fluoroscopic images; and

identifying a location for each of the plurality of implanted seeds in the region by analysis of the improved three-dimensional image.

20. The computer-readable medium of claim 19, said sequence of steps further comprising calculating a plurality of three-dimensional coordinates for the plurality of implanted seeds.

21. A computer-generated graphical user interface for determining positions of a plurality of brachytherapy seeds with respect to an implanted region, the graphical user interface prompting and coordinating execution of a sequence of steps performed cooperatively by a user and a computer processor, said sequence of steps comprising:
obtaining a three-dimensional ultrasound image of the implanted region;
obtaining a plurality of two-dimensional fluoroscopic images of the implanted region;
forming an improved three-dimensional image of the implanted region by analyzing the three-dimensional ultrasound image in combination with the plurality of two dimensional-fluoroscopic images; and
identifying a position for each of the plurality of brachytherapy seeds in the implanted region in the improved three-dimensional image.

22. The graphical user interface of claim 21, the plurality of brachytherapy seeds being used in radiotherapy treatment of an abnormal tissue in the implanted region.

23. The graphical user interface of claim 21, said sequence of steps further comprising inputting a number M corresponding to a number of markers and a number N corresponding to a number of the plurality of brachytherapy seeds in the implanted region.

24. The graphical user interface of claim 23, said sequence of steps further comprising:
locating the M markers within the three-dimensional ultrasound image, where $M \geq 4$; and
storing on a computer-readable medium a series $Q_1, Q_2, \ldots, Q_M$ of three-dimensional coordinates associated with the M markers.

25. The graphical user interface of claim 24, said sequence of steps further comprising:
locating the N brachytherapy seeds and the M markers appearing in each of said plurality of two-dimensional fluoroscopic images;
storing on the computer-readable medium a plural sets of two-dimensional coordinates for the N brachytherapy seeds and the M markers appearing in each of said plurality of two-dimensional fluoroscopic images; and
deriving a first series $R_1, R_2, \ldots, R_N$ of three-dimensional coordinates for the N brachytherapy seeds and a second series $P_1, P_2, \ldots, P_M$ of three-dimensional coordinates for the M markers from the plural sets of two-dimensional coordinates.

26. The graphical user interface of claim 25, said sequence of steps further comprising associating each P_i with a corresponding Q_i for $1 \leq i \leq M$.

27. The graphical user interface of claim 26, said step of associating further comprising determining a solution to an optimization problem.

28. The graphical user interface of claim 25, said sequence of steps further comprising finding a $3x3$ matrix T and a $3x1$ vector t through an optimization process, wherein an estimate for (T,t) is found by solving a minimization problem $\min_{T,t} \sum_{i=1}^{M} \|Q_i - TP_i - t\|^2$.

29. The graphical user interface of claim 28, said step of finding a $3x3$ matrix T and a $3x1$ vector t through an optimization process further comprising the steps of:

solving a maximization $\max_{T,t} \sum_{j=1}^{N} I(TR_j + t)$, wherein $I(X)$ is a scalar intensity of point X in the three-dimensional ultrasound image; and

solving a localized optimization problem for (T,t) in response to the maximization problem having no unique solution.

30. The graphical user interface of claim 28, wherein said sequence of steps further comprises calculating a series of derived three-dimensional coordinates $S_1, S_{2,} \ldots, S_N$ of the N brachytherapy seeds, wherein $S_j = TR_j + t$ for $1 \le j \le N$.

31. A process for locating a plurality of objects in a region, comprising the steps of:

placing a plurality of markers in the region, the plurality of markers being visible via a first imaging mode and a second imaging mode and being distinguishable from the plurality of objects;

forming a first image of the first imaging mode of the region;

identifying a first plurality of markings in the first image corresponding to the plurality of markers;

forming a second image and a third image of the second imaging mode of the region;

identifying a second plurality of markings in the second image corresponding to the plurality of markers;

identifying a third plurality of markings in the third image corresponding to the plurality of markers;

establishing a correlation between the first image, the second image, and the third image by matching the first plurality of markings with the second plurality of markings and the third plurality of markings;

deriving a set of object coordinates corresponding to the plurality of objects in the second image and in the third image; and

calculating a series of three-dimensional coordinates for the plurality of objects in response to the correlation between the first image, the second image, and the third image and to the set of object coordinates.

32. The process of claim 31, wherein:

said step of identifying a first plurality of markings includes deriving a first set of marker coordinates $Q_1, Q_2, \ldots, Q_M$ for the plurality of markers, wherein $M \geq 4$ is a number of the markers;

said steps of identifying a second plurality of markings identifying a third plurality of markings include deriving a second set of marker coordinates $P_1, P_2, \ldots, P_M$ for the M markers; and

said step of deriving a set of coordinates corresponding to the plurality of objects in the second image and in the third image includes deriving a set of object coordinates $R_1, R_2, \ldots, R_N$, wherein N is a number of the plurality of objects.

33. The process of claim 32, wherein said step establishing a correlation between the first image, the second image, and the third image includes a step of finding a $3x3$ matrix T and a $3x1$ vector t by solving a first optimization problem $\min_{T,t} \sum_{i=1}^{M} \|Q_i - TP_i - t\|^2$.

34. The process of claim 33, wherein said step of finding a $3x3$ matrix T and a $3x1$ vector t further includes solving a second optimization problem $\max_{T,t} \sum_{j=1}^{N} I(TR_j + t)$, wherein $I(X)$ is a scalar intensity at a point X in the first image.

35. The process of claim 34, wherein said step of finding a 3x3 matrix T and a 3x1 vector t further includes solving a localized optimization problem in response to the second optimization problem not having a unique solution.

36. The process of claim 33, wherein said step of calculating a series of three-dimensional coordinates for the plurality of objects includes deriving the series of three-dimensional coordinates $S_1, S_2, \ldots, S_N$ of the N implanted seeds by a transformation $S_j = TR_j + t$, wherein $1 \le j \le N$.

37. The process of claim 31, further comprising the step of implanting a plurality of brachytherapy seeds used in a radiation therapy into a portion of a patient's body as the plurality of objects in the region.

38. The process of claim 31, wherein said step of placing a plurality of markers in the region includes placing at least four markers uncoplanar with each other in the region;

39. The process of claim 31, wherein:

said step of forming a first image of the first imaging mode includes forming a three-dimensional ultrasound image of the region; and

said step of forming a second image and a third image of the second imaging mode includes forming a plurality of two-dimensional fluoroscopic images of the region.

40. The process of claim 31, generating a three-dimensional visual display of the region indicating the plurality of objects in accordance with the series of three-dimensional coordinates for the plurality of objects.

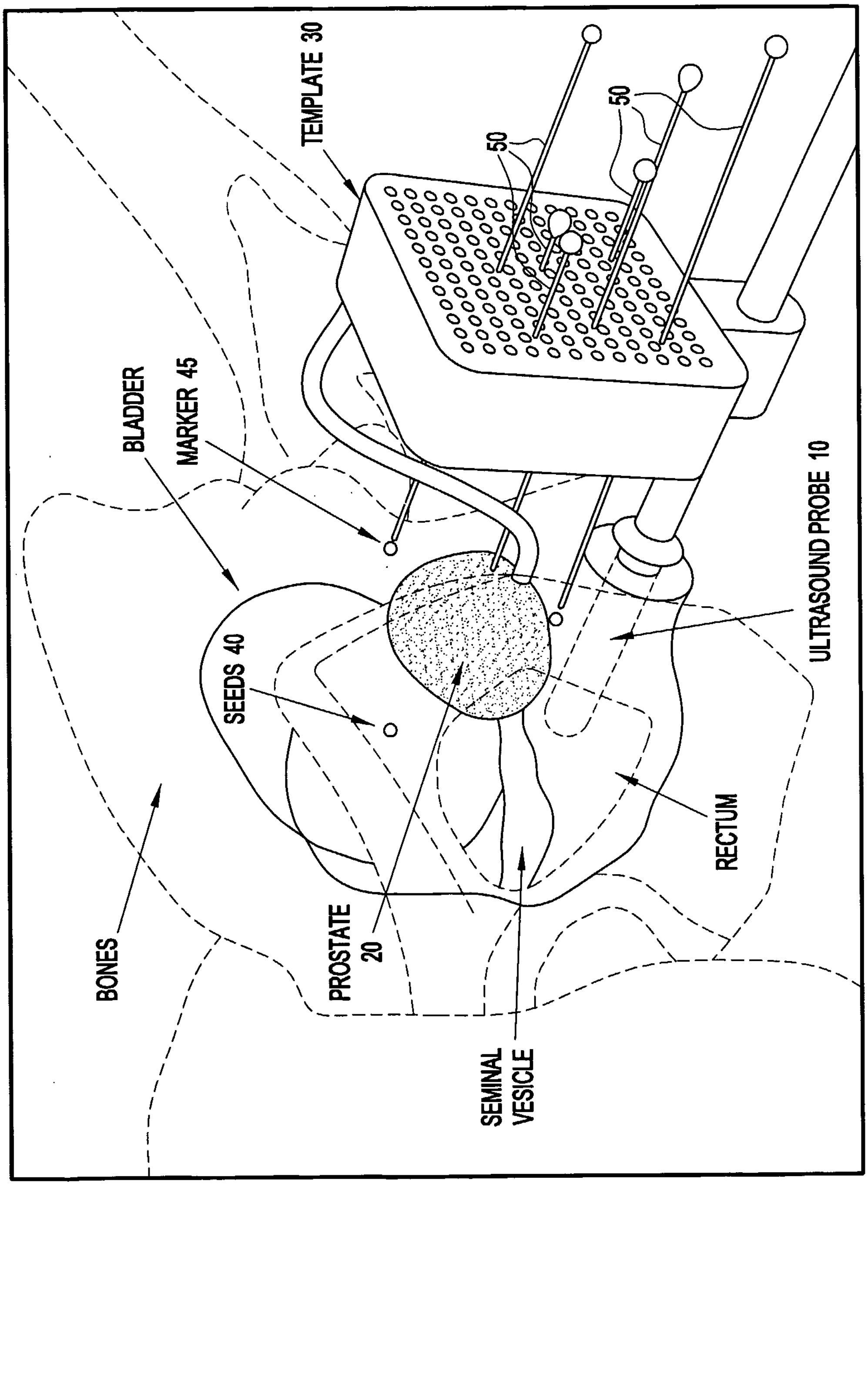
TEMPLATE 30
50
50
BLADDER
MARKER 45
SEEDS 40
ULTRASOUND PROBE 10
RECTUM
BONES
PROSTATE
20
SEMINAL
VESICLE

FIG. 1

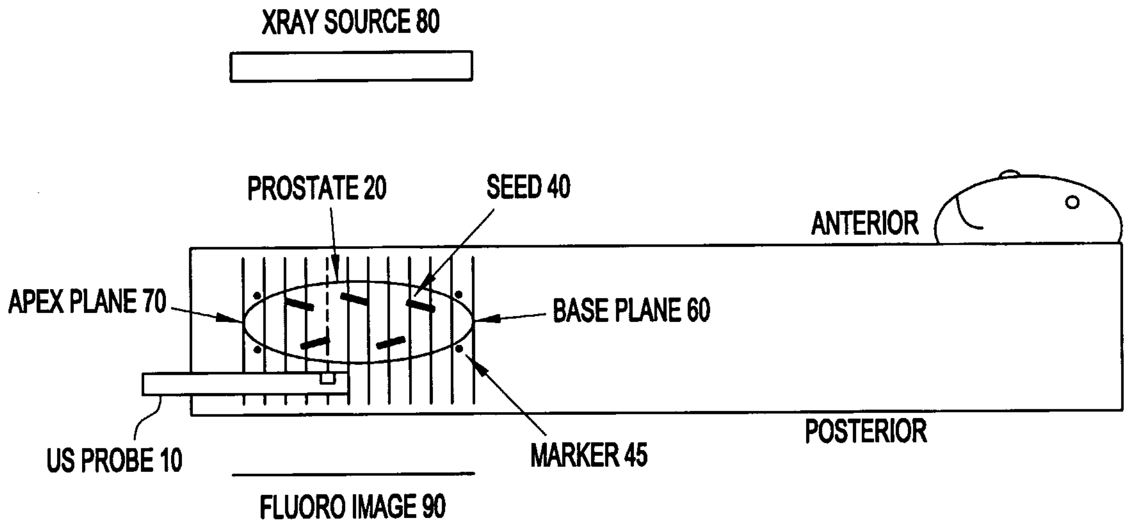
XRAY SOURCE 80
PROSTATE 20
SEED 40
ANTERIOR
APEX PLANE 70
BASE PLANE 60
US PROBE 10
MARKER 45
POSTERIOR
FLUORO IMAGE 90

Fig. 2

AP View of Prostate and Point Markers

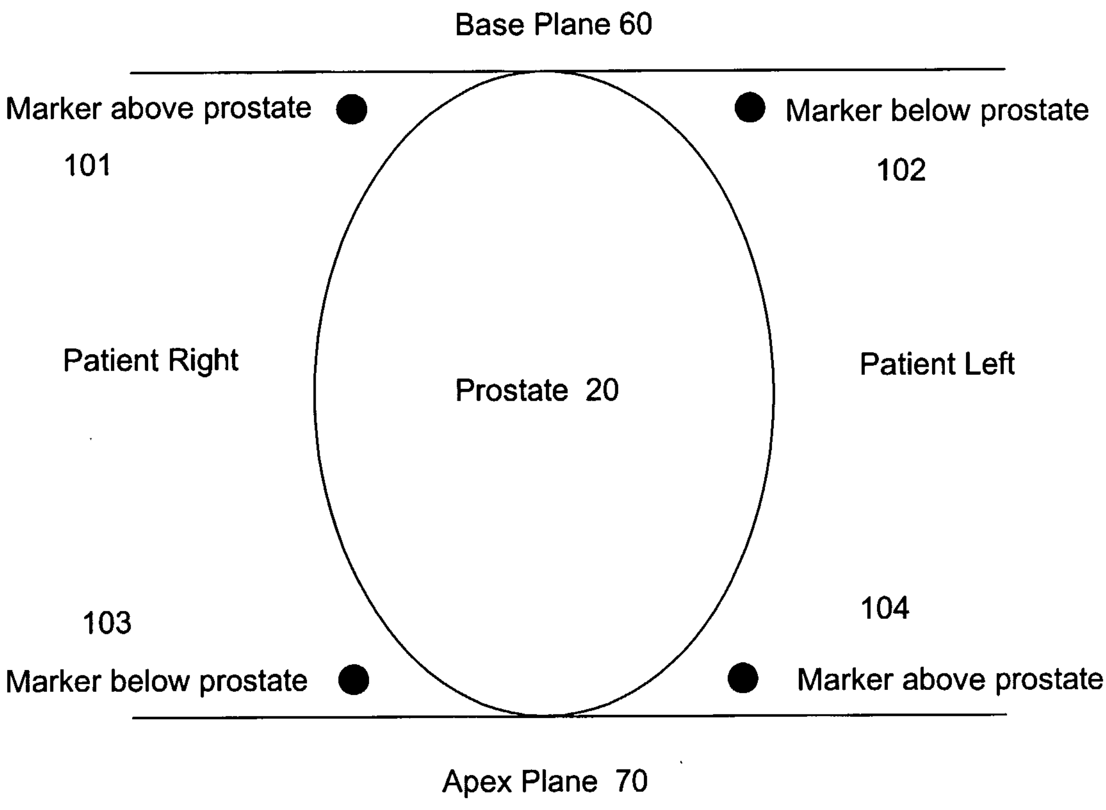

Fig. 2a

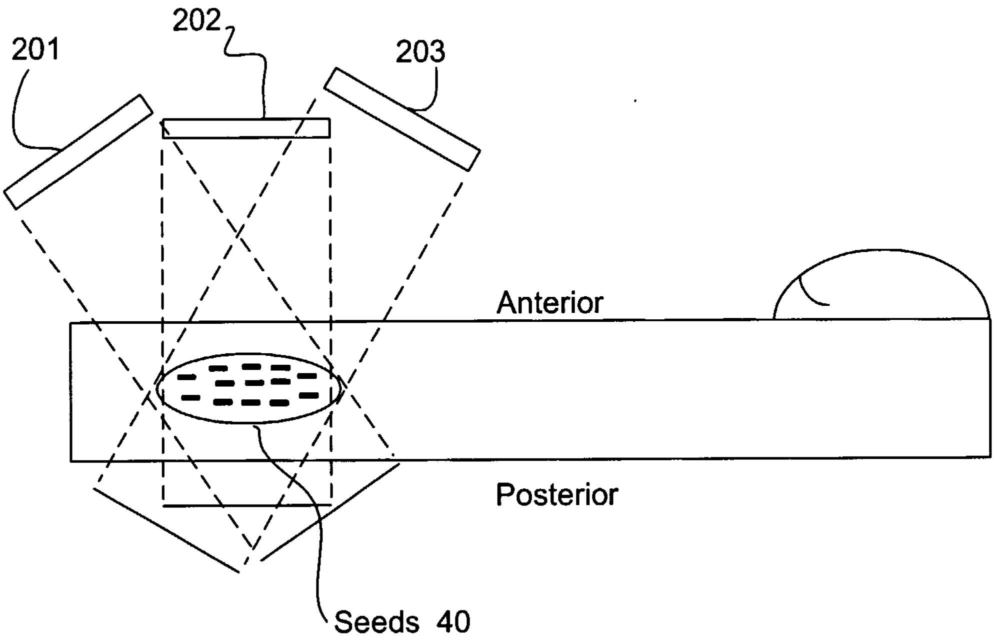

Fig. 2b

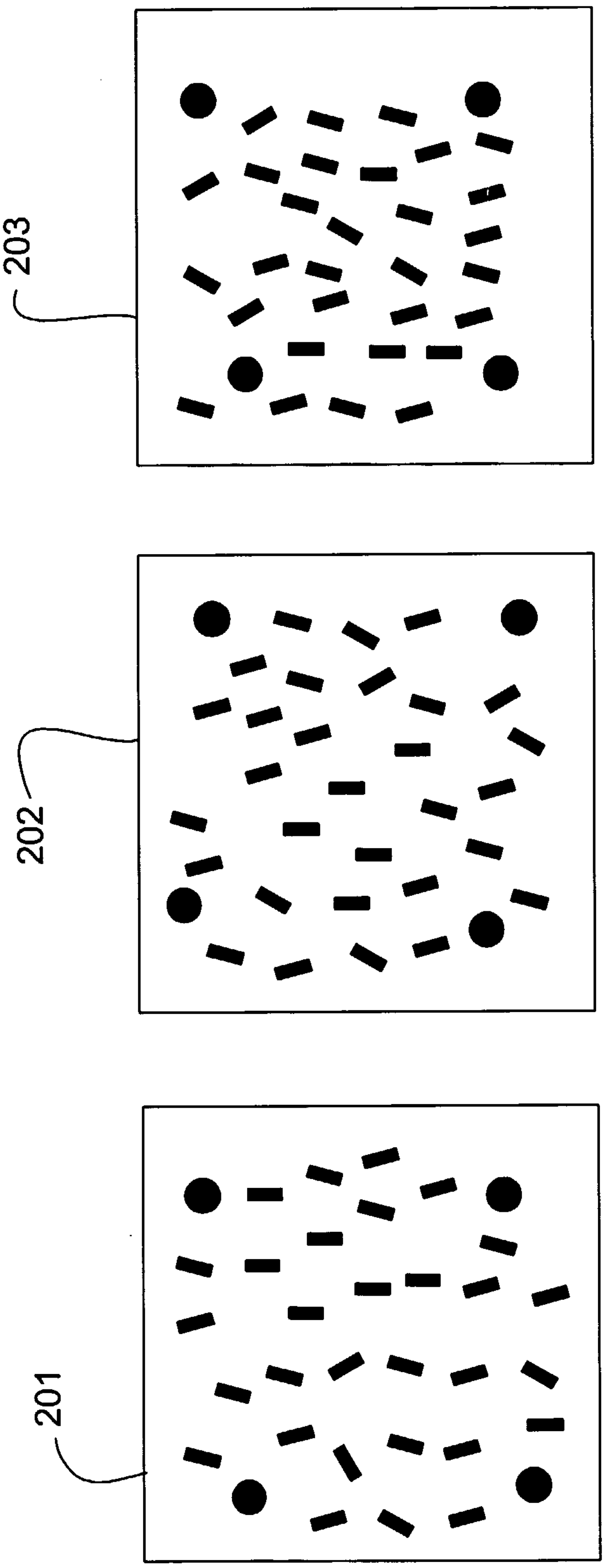

Fig. 2c

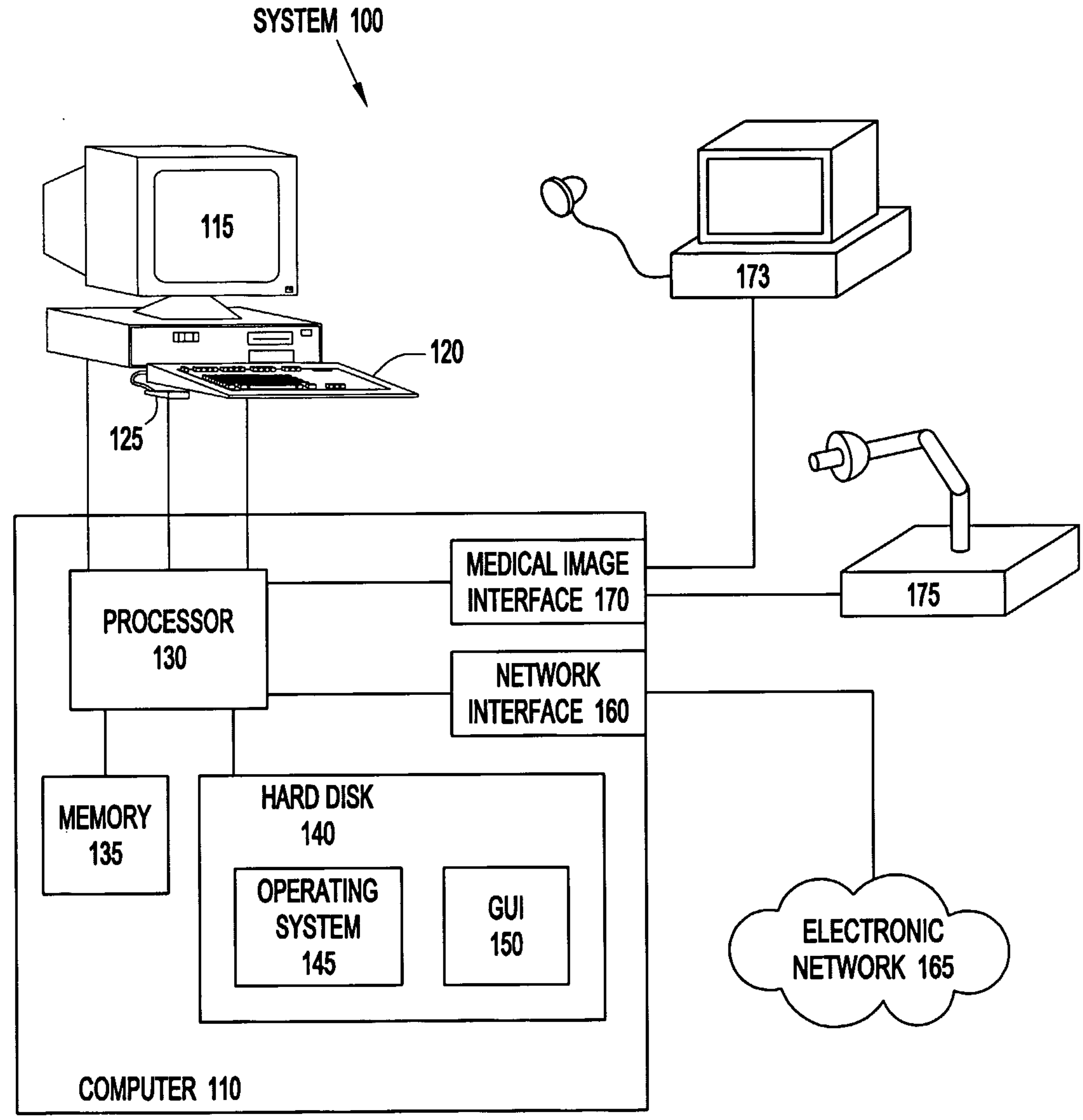
SYSTEM 100
115
120
125
173
175
MEDICAL IMAGE INTERFACE 170
PROCESSOR 130
NETWORK INTERFACE 160
MEMORY 135
HARD DISK 140
OPERATING SYSTEM 145
GUI 150
ELECTRONIC NETWORK 165
COMPUTER 110

Fig. 3

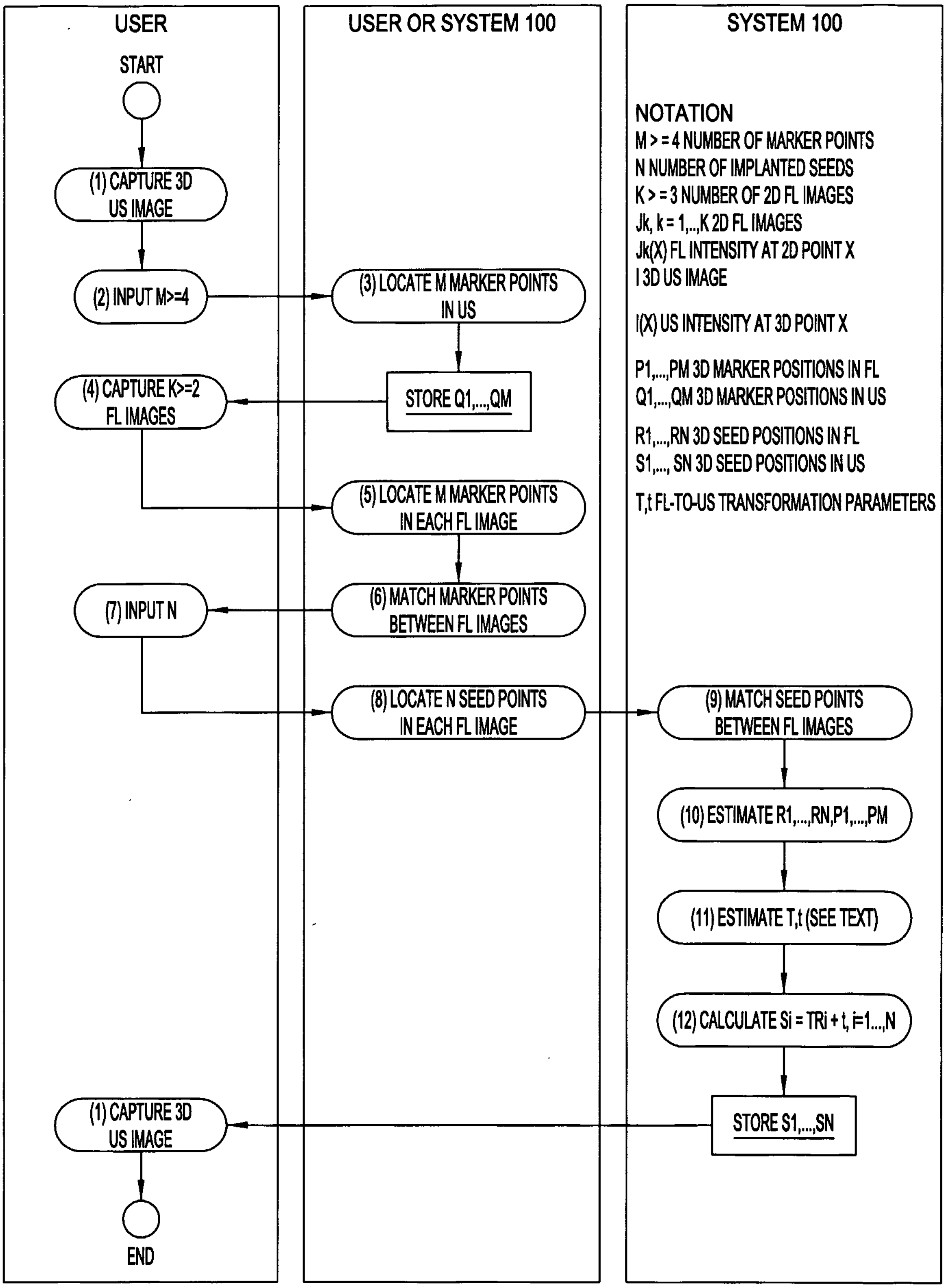
USER
USER OR SYSTEM 100
SYSTEM 100
START
(1) CAPTURE 3D US IMAGE
(2) INPUT M>=4
(3) LOCATE M MARKER POINTS IN US
STORE Q1,...,QM
(4) CAPTURE K>=2 FL IMAGES
(5) LOCATE M MARKER POINTS IN EACH FL IMAGE
(6) MATCH MARKER POINTS BETWEEN FL IMAGES
(7) INPUT N
(8) LOCATE N SEED POINTS IN EACH FL IMAGE
(9) MATCH SEED POINTS BETWEEN FL IMAGES
(10) ESTIMATE R1,...,RN,P1,...,PM
(11) ESTIMATE T,t (SEE TEXT)
(12) CALCULATE Si = TRi + t, i=1...,N
STORE S1,...,SN
(1) CAPTURE 3D US IMAGE
END
NOTATION
M > = 4 NUMBER OF MARKER POINTS
N NUMBER OF IMPLANTED SEEDS
K > = 3 NUMBER OF 2D FL IMAGES
Jk, k = 1,..,K 2D FL IMAGES
Jk(X) FL INTENSITY AT 2D POINT X
I 3D US IMAGE
I(X) US INTENSITY AT 3D POINT X
P1,...,PM 3D MARKER POSITIONS IN FL
Q1,...,QM 3D MARKER POSITIONS IN US
R1,...,RN 3D SEED POSITIONS IN FL
S1,..., SN 3D SEED POSITIONS IN US
T,t FL-TO-US TRANSFORMATION PARAMETERS

FIG. 4

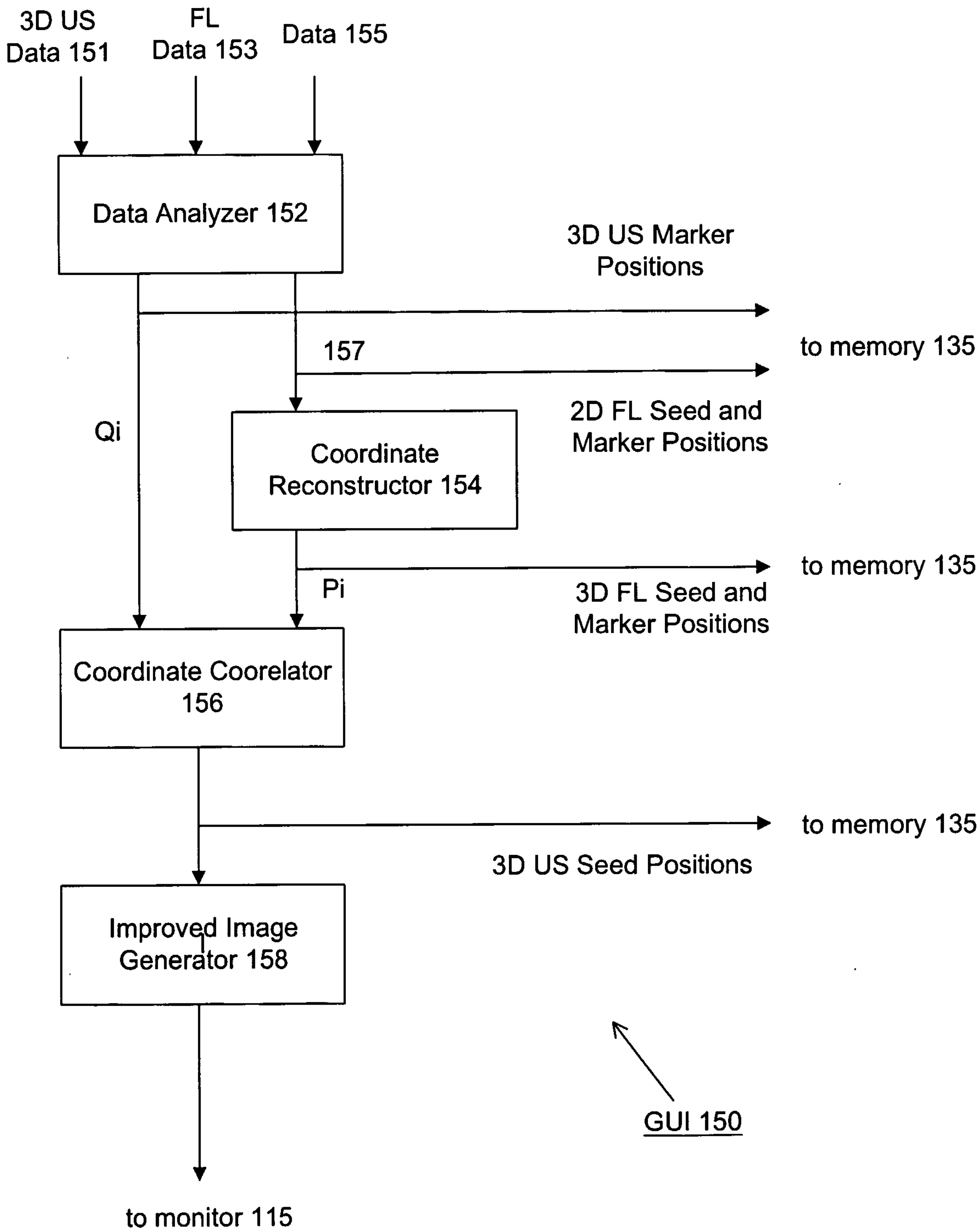
3D US
Data 151
FL
Data 153
Data 155
Data Analyzer 152
3D US Marker
Positions
157
to memory 135
2D FL Seed and
Marker Positions
Qi
Coordinate
Reconstructor 154
to memory 135
Pi
3D FL Seed and
Marker Positions
Coordinate Coorelator
156
to memory 135
3D US Seed Positions
Improved Image
Generator 158
GUI 150
to monitor 115

Fig. 5

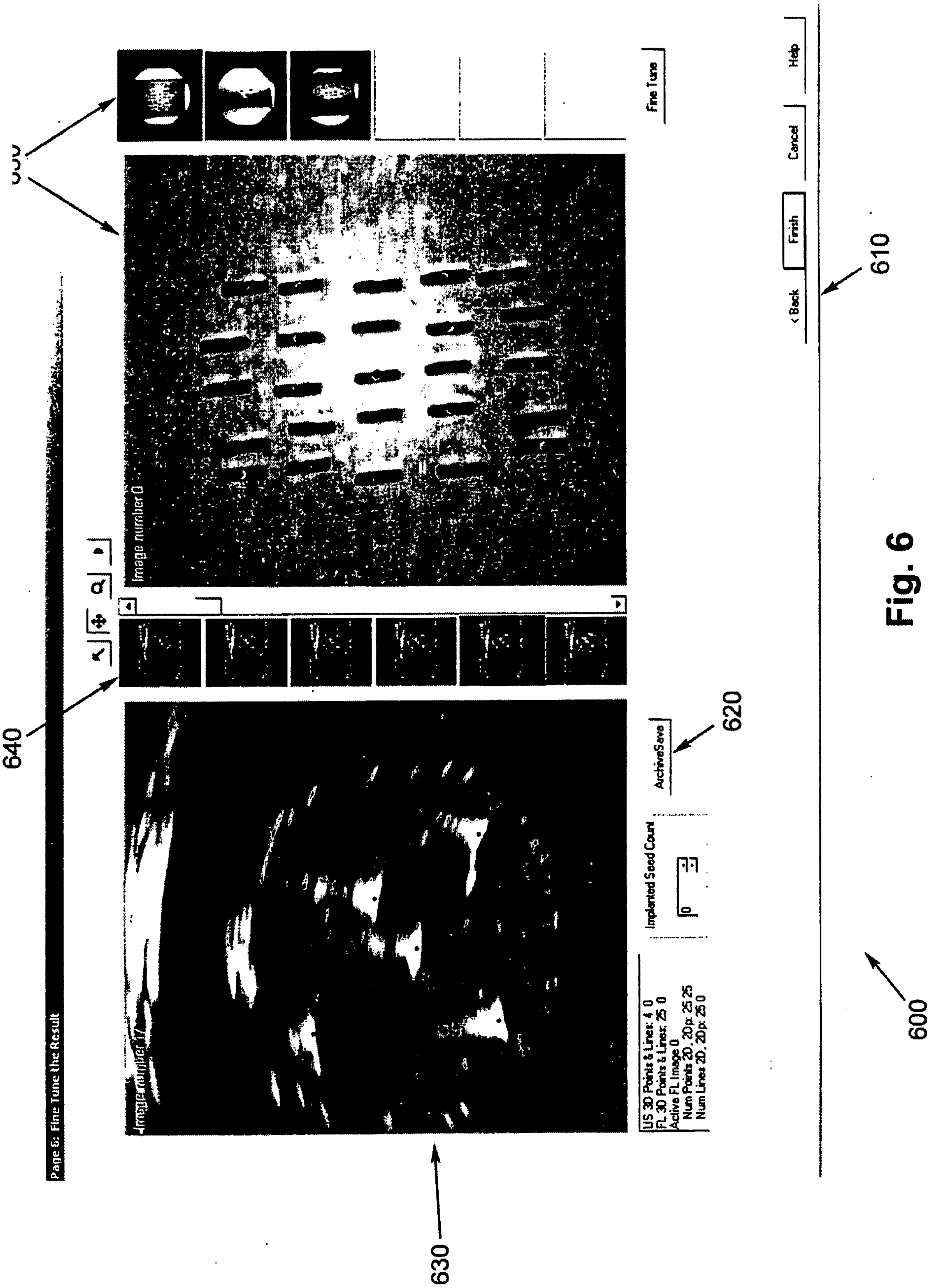
Page 6: Fine Tune the Result
Image number 0
Fine Tune
ActiveSave
Implanted Seed Count
< Back
Finish
Cancel
Help
600
610
620
630
640

Fig. 6

专利名称(译)	超声透视和超声融合的种子定位系统和方法		
公开(公告)号	EP1392171A2	公开(公告)日	2004-03-03
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[标]申请(专利权)人(译)	瓦里安医疗系统公司		
申请(专利权)人(译)	瓦里安医疗系统公司.		
当前申请(专利权)人(译)	瓦里安医疗系统公司.		
[标]发明人	THORNTON KENNETH B		
发明人	THORNTON, KENNETH, B.		
IPC分类号	A61N5/10 A61B6/00 A61B6/12 A61B8/08 A61B8/12		
CPC分类号	A61N5/1048 A61B6/12 A61B6/5247 A61B8/0833 A61B8/0841 A61B8/4416 A61N5/1027 A61N2005/1012		
优先权	09/875031 2001-06-07 US		
其他公开文献	EP1392171A4		
外部链接	Espacenet		

摘要(译)

种子定位系统和方法，其中使用基于计算机的系统（100）使用超声（US）确定放射治疗种子相对于受影响组织（例如前列腺）的区域的三维（3D）位置和透视（FL）成像，（173,175），以便可以计算放射治疗剂量。在一个实施例中，本发明可用于确定植入的近距离放射治疗种子的3D位置。本发明的替代实施例可用于确定除近距离放射治疗种子之外的植入物体的3D位置。种子定位系统和方法包括图形用户界面（150），其用于在其操作中帮助种子定位系统的用户。