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Cardio Navigation: Planning, Simulation, and Augmented Reality in Robotic Assisted Endoscopic Bypass Grafting

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Background. **The aim of this study is to optimize the set-up and port placement in robotic surgery and enhance intraoperative orientation by video overlay of the angiographic coronary tree.**

Methods. **In three mongrel dogs and two sheep an electrocardiogram-triggered computed tomographic scan and coronary angiography were performed after placing cutaneous fiducials. The regions of interest (ie, heart, ribs, coronaries, internal thoracic artery) were segmented semiautomatically to create a virtual model of the animal. In this model the target regions of the total endoscopic bypass procedure along the internal thoracic artery and anastomotic area were defined. Algorithms for weighing visibility, dexterity, and collision avoidance were calculated after defining nonadmissible areas using a virtual model of the manipulator. Intraoperatively, registration of the animal and the telemanipulator was performed using encoder data of the telemanipulator by pointing to the fiducials. After pericardiotomy, the reconstructed coronary tree was projected into the videoscopic image using a semiautomatic alignment procedure. In dogs, the total endoscopic bypass procedure was completed on the beating heart. The first human case applying preoperative planning, intraoperative registration, and augmented reality was subsequently performed.**

Results. **The rigid transformation linked the patient's preoperative frame and the robot coordinate frame with a root mean square error of 9 to 15 mm. The predicted port placement derived from the model initially varied from the one chosen due to an incomplete formulation of the weighing procedure. After only a few iterations, the algorithm became robust and predicted a collision free triangle. Video overlay of the angiographic coronary tree into the videoscopic image was feasible.**

Conclusions. **Surgical planning and augmented reality are likely to enhance robotic surgery in the future. A more complete understanding of the surgical decision process is required to better formalize the planning algorithms.**

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Total endoscopic coronary artery bypass grafting using the left internal thoracic artery to the left anterior descending coronary artery has become possible using surgical telemanipulators [1]. Initially performed on the arrested heart, the development of endoscopic stabilizers has enabled total endoscopic bypass procedure on the beating heart [2, 3]. Although this procedure can be performed with a low conversion rate in selected patients, operating on the beating heart in an endoscopic environment is still associated with a number of patient and system related problems. Despite the use of vacuum assisted stabilizers, residual motion of the heart is usually present in the anastomotic area [4, 5]. Limitations for manual control and tracking as well as system related delays complicate endoscopic bypass grafting [6, 7]. Orientation with regard to the target vessel or the appropriate target site can be difficult, given the limited and angled view of the operative field.

In addition, positioning a surgical robot at the patient and determining the best access port location can be a challenging task. Surgical manipulators are designed to have a flexible structure to adapt to the operating room environment, and thus they have a high number of degrees of freedom to position. In minimally invasive cardiac surgery, they are subject to spatial constraints defined by anatomical structures that limit the number of accessible entry ports. Hence, we present a method for preoperative planning of port placement for an endoscopic bypass grafting procedure. Second, we propose a method for intraoperative target site localization using a cardio-navigation system.

Patients and Methods

The overall method sequence is illustrated in Figure 1 and requires four main steps: (1) data acquisition and

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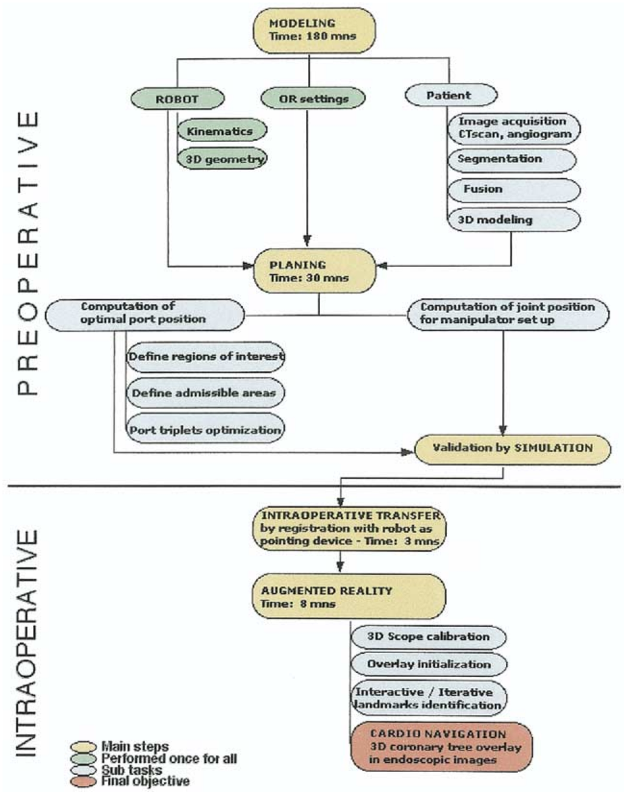

Fig 1. Schematic illustration of the cardio-navigation process (CT = *computer tomography;* OR = *operating room.)*

modelling: gathering information about the patient, the robot, and the environment; (2) planning port placement and robot position: determining the best incision sites (ports) based on intervention requirements, patient anatomy, and tools specifications, and then determining the best relative position of the robot, the patient, and the operating room; (3) transfer: transfering the results to the operating room by registration and positioning; and (4) execution and augmented reality: executing planned results with visual assistance, monitoring, and predicting possible complications (see Appendix for definitions of terms that are commonly used in the field of computer-assisted surgery and navigation).

Data Acquisition

Standard (mono or biplane) angiographic data are complemented by preoperative computed tomographic (CT) imaging of the chest and the heart. Prior to performing two CT scans, superficial radio opaque landmarks are positioned on top of bony structures (ribs, sternum) to enable intraoperative registration (see Appendix). A gated and injected scan is focused on the heart where large coronary structures can be located and where a high resolution image of the heart is obtained (slices thickness, 1 mm). A large nongated scan is performed to capture the overall anatomy of the patient (slices thickness, 10 mm).

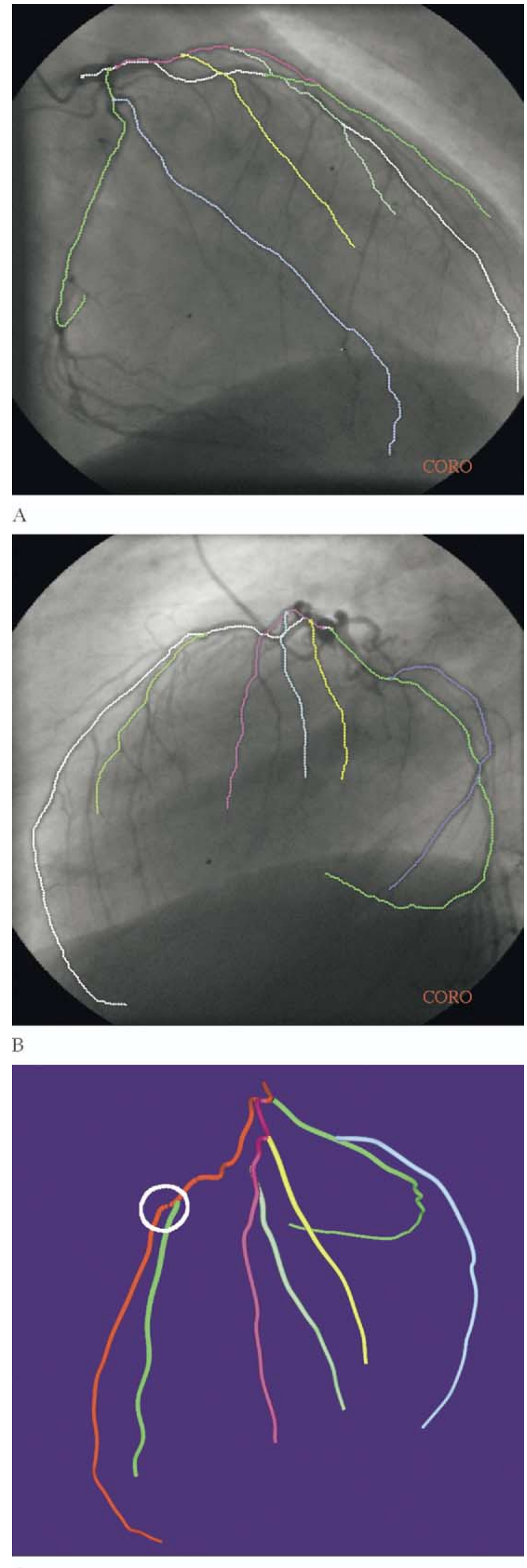

Fig 2. Coronary angiography. Right anterior oblique view (A) and left anterior oblique view (B) with segmented coronary artery center lines. (C) Three-dimensional (3-D) reconstruction of the coronary tree and localization of the stenosis on the 3-D tree.

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Patient Modelling

For patient modelling (see Appendix), regions of interest (ie, heart, coronaries, internal thoracic artery, ribs, skin, sternum, diaphragm) must be isolated from the original scans, a process called segmentation (see Appendix). Part of this process is performed on the CT scan. Based on this segmentation, 3-dimensional (3-D) reconstruction of organ models is used to transform volumetric data into surface data upon which the planning is based.

Interactive semiautomatic identification and labelling of the coronary tree in the angiography is performed by the surgeon [8]. After segmentation in two different views synchronized at the same time in the heart cycle, a 3-D model is reconstructed. This 3-D coronary tree is fused with the model obtained from CT scans, which later serves as a map for cardio navigation.

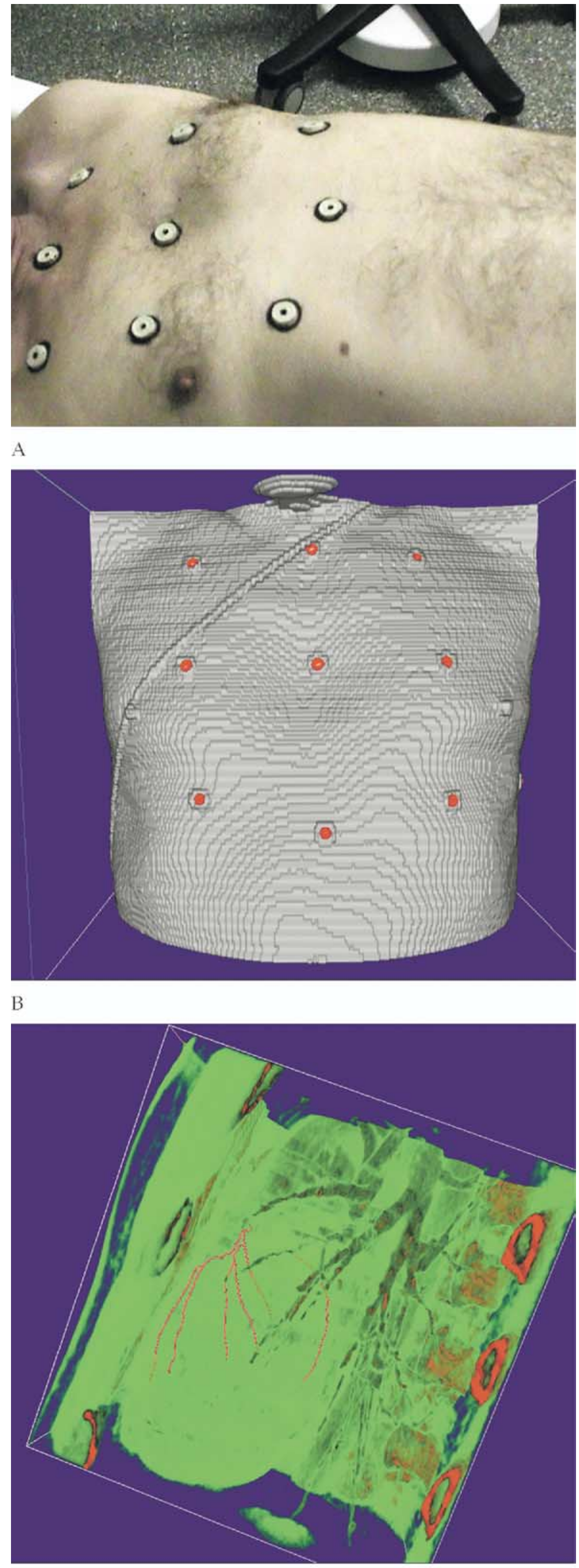
Robot Model

The joints position, orientation, and velocity (robot kinematics, see Appendix) complemented by the physical shape of the robot constitute a robot model. A detailed description of the generation of such a model is provided elsewhere [9, 10]. The robot modeling is performed once for all patients. Both patient and robot models were combined in the same frame of reference to allow the computation of interactions between the robot and the patient.

Planning

The goal of planning is twofold: using patient and robot models. First, compute an optimal port location to assess all structures of interest with the most reach ability, dexterity, and the best visibility. Second, position the 30 degree of freedom manipulator arms to allow access through the optimized port set up while avoiding collisions and singularities. Based on the patient model, a description of the intervention formalizing surgical knowledge is integrated into the algorithm that determines the location of the best ports. The surgeon defines in the patient model regions of interest, such as the course of the internal thoracic artery and the anastomotic site. Relative weights are assigned to each target point (eg, the surgeon can choose to provide more priority on preserved dexterity at the anastomotic site as opposed to the proximal internal thoracic artery). This will lead to a computation of a port placement in favor of manipulation at the anastomotic area. The general sequence of the intervention is then translated into mathematical criteria [11]. The most advantageous triplet for the patient is generated using an exhaustive optimization process.

The second part of the algorithm then computes the positioning of the different joints of the robot that will maximize separation between the arms to avoid most collisions between the manipulator arms and minimize the number of necessary set-up joint adjustments [12]. During this phase, environmental obstacles such as the operating room table and approximations of the patient's body beyond the information of the CT scan (head, lower body) are taken into account. A visual interpretation of the resulting

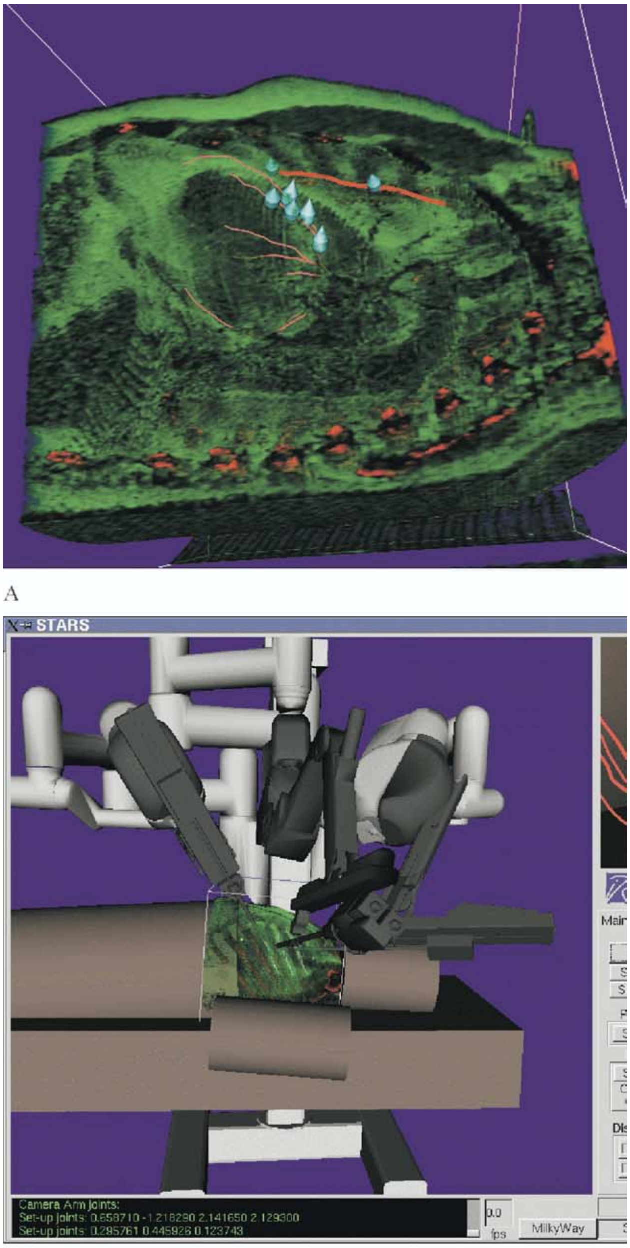


A

B

C

Fig 3. (A) Fiducials (see Appendix) markers positioned prior to the contrast computed tomographic (CT) scan on the patient's chest. (B) Segmented fiducials and patient skin from CT data. (C) Fusion of regions of interest isolated on the CT scan with the 3-D left coronary tree reconstructed (compare with Fig 2C).



A

B

Fig 4. Choice of targets sites for the procedure (A) and result of planning (ports placement and robot arms positioning) and graphical interface (B).

computation shows a simulation of the positioned arms placed in the ports in the patient model sweeping through the work space, demonstrating the range of motion and any residual potential for collisions [13].

Transfer

Transfer is the most critical and important step of our approach because it describes the process of bringing the overall information derived from the modeling and planning into the operating room by setting it in precise and accurate correspondence with the patient. This requires that the coordinate frames of the CT scan, the patient, the robot, and the operating room environment are transformed into a single frame of reference, a process called registration. For this purpose, a mathematical transformation is computed to link the positions of the radio-opaque fiducials as identified in the CT scan with the positions of the same fiducials on the patient's skin within the operating room. For this last purpose, the da Vinci manipulator (Intuitive Surgical Inc, Sunnyvale, CA) is used as a positioning sensor to point at the fiducials on the patient's chest [14]. The selected ports are then indicated on the patient using the arm of the robot as a localization device. This method avoids the use of an additional navigation system. Once ports are cut, the arms are positioned on top of the patient as planned.

Execution with Augmented Reality

The objective here is to project and overlay preoperative data (3-D angiography) in the endoscopic view to facilitate orientation and identification of target vessels and suitable anastomotic sites. Before a rough initialization of the 3-D tree overlay can be performed, the parameters of the endoscope must be extracted through calibration [15]. The initial projection then needs to be corrected for patient deformation and organ shift. This is achieved by an interactive approach that allows the surgeon to select and mark any visible vessel bifurcations or arteries. Based on this selection, an algorithm will then adapt the 3-D tree to the image, in accordance to the real field of view [14, 16]. Once the model overlay fits the heart surface currently seen in the visual field of the surgeon, any subsequent motion of the endoscope will lead to an automatic adjustment of the 3-D tree model in the new visual field.

Validation and Verification Protocols

The span of the cardio-navigation system is quite large, which required a formal validation and verification protocol before a human trial could be performed. Thus, the computer algorithms were tested and tuned on phantom validations [12]. Then animal cases were performed to calibrate the weights used in the planning algorithms (according to real anatomic data) and to tune the cardio-navigation overlay process on live in vivo data [17]. For the mathematical formulations of the processes see references 8 to 17.

Animal and Patient Data

Three male foxhound-beagle dogs (25 kg) and two sheep were used for validation of the latest software version. Details of the anesthesia management are provided elsewhere [18]. In the dogs, the endoscopic total endoscopic bypass procedure was completed on the beating heart using cardio navigation coupled with the Da Vinci surgical system. The first human trial was performed in October 2003 on a 72-year-old man with single-vessel disease of his left anterior descending coronary artery with 90% proximal stenosis. In all cases, the Da Vinci surgical system was operated in a special application

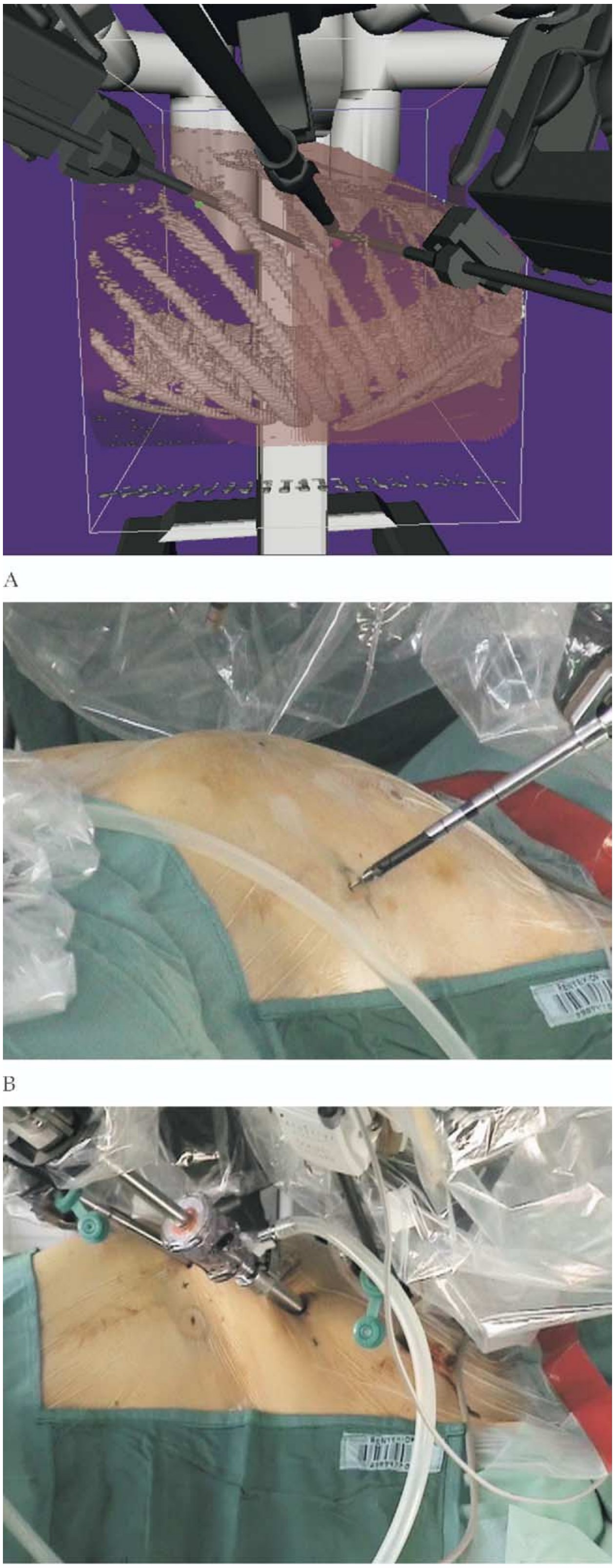


Fig 5. *(A) Result of optimal port placement on patient's model. (B) Effective transfer of the computed ports on patient in the operating room using robot tool tip as pointing device. (C) Chosen ports on patient and robot positioning.*

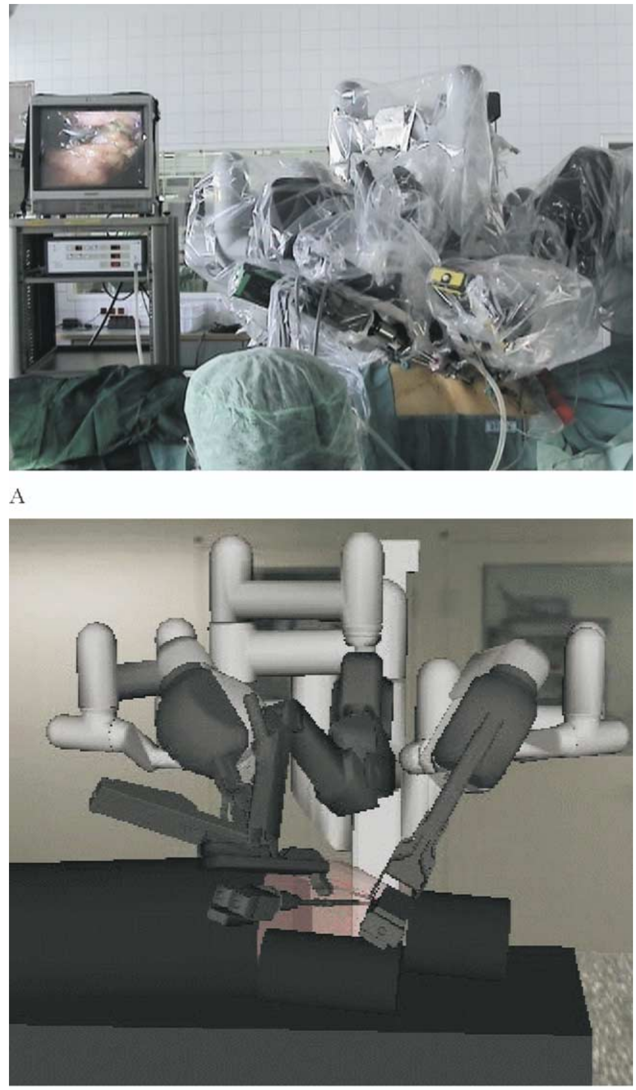


Fig 6. *(A) Effective robot set-up in the operating room (B) compared with planned results.*

programming interface mode that enables precise readings of the state of the robot and the endoscopic images.

Results

Preoperative Processing and Planning

The results of segmentation of the center lines of the coronary arteries to reconstruct the patient's coronary tree is illustrated in the left and right anterior oblique views during the same heart cycle (Fig 2A, 2B). The stenosis is underlined on the corresponding 3-D reconstruction of the left coronary tree, further used when localizing the anastomotic site (Fig 2C). The CT scan with fiducials on the patient thorax is shown in Figure 3A. The surface model of the patient chest, the segmented bones, and the left internal thoracic artery are shown in Figure 3B. The result of merging the 3-D

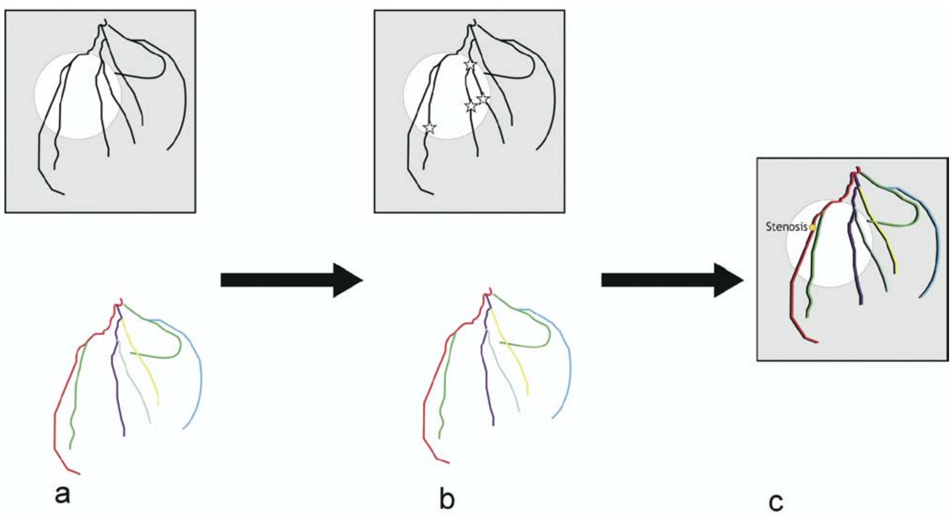


Fig 7. Schematic illustration of the matching algorithm. (Top views) Limited endoscopic view of coronary anatomy through scope (indicated by light circle *as the visible field). (Bottom) Modeled three-dimensional representation of angiography. (a) Initial representation of reconstructed angiogram after surface registration. Note that the reconstructed angiogram is projected far from the true location of the coronary tree visible through the endoscope. (b) In the endoscopic view, visible structures such as bifurcations and vessels are marked (landmarks). (c) The marked landmarks are matched by computation to the reconstructed coronary tree (landmark matching), and the tree is then moved accordingly. As a final result, the true anatomy and the reconstruction are superimposed within the endoscopic image.*

coronary tree and the CT scan is shown in Figure 3C. This step is more time consuming and is currently a 2-hour process.

For further planning, target cones were positioned on the heart and on the left internal mammary artery to identify surgical targets and bound the surgical volume (Fig 4A). Optimal placement of the ports and the corresponding collision-free position of the robot (Fig 4B) were subsequently obtained and confirmed in the animated model prior to surgery. In the first two animals the predicted port placement derived from the model initially varied from the one chosen by the surgeon due to an incomplete formulation of the weighing procedure. After only a few iterations, the algorithm became robust and predicted a collision-free triangle in subsequent animals as well as in the clinical case.

Transfer

Intraoperative registration of the preoperative model (Fig 5A) with the patient and the robot was a 3-minute process and allowed to position the planned ports on the patient within 2 minutes. The fiducial-based registration proved to be a simple and efficient registration technique. Ten fiducial markers as identified on the CT scan were manually pointed by one of the robotic arms (see Fig 5B). The rigid transformation linked the patient preoperative frame and the robot coordinate frame with a root mean square error of 9 to 15 mm. This registration precision error was mostly due to the patient deformation on the operating room table.

The planned ports (expressed in the robot coordinate frame) were then transferred on the patient's skin by manipulating the end effector as a pointing device according to the directions provided by the computed results (see Fig 5C). The remote center of the robot arms were positioned on the ports, and the arms postures were tuned according to the computed planned and validated values (Fig 6A, 6B). During the procedure, no collisions occurred and no set-up joint reconfiguration had to be performed. Given the accuracy of the transfer, a good "seeding-value" was provided for the initial overlay of the coronary tree within the endoscope.

Augmented Reality

After pericardiotomy interactive calibration of the endoscope was performed in 3 to 8 minutes. The initial overlay of the 3-D coronary tree was directly provided to the surgeon on the stereoscopic views of the heart surface based on the initial registration. Figure 7a shows a schematic illustration of the process. To update this overlay and correct the residual visual error introduced by the heart shift due to operative conditions (Co2 insufflation, single lung ventilation) and patient breathing, the surgeon now indicated and marked the visual clues recognized in the visual fields as seen in Figure 7b. The algorithm then automatically provided an update of the 3-D tree overlay that best fit the marked points and the initial overlay. The algorithm processed iteratively and could take into account as many clicked landmarks as available. Figure 7c shows the overall 3-D tree map in which the surgeon's visual field of view was localized. The internal registration error was in the range of 9.3 to 19.2 mm. The overlay precision was in the range of 30 to 53 pixels. The internal registration error is an indicator deduced from the displacement applied to the coronary model after the interaction stage and measures the correction

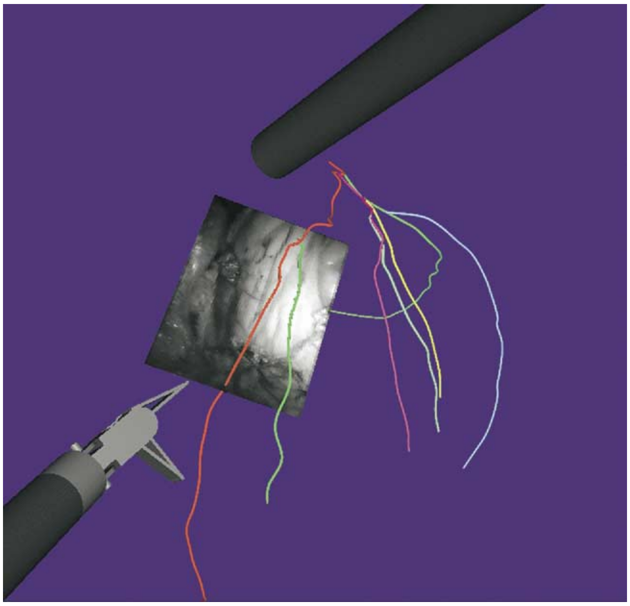


*Fig 8. The local view (*black and white patch*) of the actual endoscopic view seen at a given time by the surgeon is positioned on the global map of the heart, thus illustrating the global positioning system behavior.*

necessary to compensate the cumulated errors and heart displacement. The overlay precision is computed from the interactive registration process after the pointing of landmarks on the video images (post interaction). It depends on the point of view and is given here for a standard view. For the overlay usefulness in a standard video image format (image size, 768 × 576 pixels), this precision must be better than the distance between two neighbouring arteries, which usually largely exceeds 50 pixels. In Figure 8, the endoscope position with regard to the real image patch and the overall modeled 3-D tree gives an idea of the tool power to overcome the reduced visibility field in endoscopic surgery. Upon moving the endoscope, the coronary tree overlay was updated accordingly. The total endoscopic bypass procedure was completed on the beating heart as previously reported.

Comment

This is the first report of a planned and navigated endoscopic procedure in cardiac surgery. By using weighed algorithms, the ideal port placement for a robotic instrumentation system was calculated based on preoperative data sets and a successful registration process. Finding the ideal port triplet represents a complex problem as not only anatomic variations such as size and shape of the chest and intrathoracic organs, but also as technical aspects of the manipulator (set-up joint position, relative position of the robot to the patient, motion constraints of the arms and instruments) that ultimately determine the range of motion and available dexterity. The proposed method formalizes the surgical knowledge and transforms it into a computer database of criteria that can be used to guide the procedure. This database is able to learn and can propose port locations that enable a maximum of dexterity and visualization while avoiding collisions and additional set-up joint changes throughout the case.

The registration process uses the robot as a positioning device making use of its built-in position encoders. Hence, no additional navigation system is required. The transfer is simple and its duration is compatible with surgical time constraints. Besides a standard CT scan, no additional preoperative examinations are required for planning and creating the patient model. Angiographies of any source can be used as the applied matching algorithms are generic and robust. With more advanced CT technology, angiography may become obsolete for the planning process.

Identification of the left anterior descending coronary artery can be obscured by overlaying tissue or an intramyocardial course. Looking through an angled scope has led to confusion in some cases in which a dominant diagonal branch was mistakenly grafted instead of the left anterior descending coronary artery. A preoperative CT scan alone, although helpful in alerting the surgeon to an intramyocardial course [19], provides limited use without navigation. The proposed overlay procedure is meant to facilitate orientation in an analogy to a global positioning system. By projecting the angiographic tree into the videoscopic image at the time of surgery, an augmented reality scenario is created integrating preoperative and intraoperative data directly into the surgical site.

As with any global positioning system, the overlay is updated in real time as surgeons move the endoscope. The applied alignment algorithms were designed to be robust. Therefore it is not required to actually identify the left anterior descending coronary artery; the surgeon only has to identify any coronary that is visible and point to any bifurcations seen in the endoscopic image. Then the program will compare this landmark information and look for compatibility within the segmented coronary tree. In the next step, additional information such as areas with severe calcification or the exact location of a stenosis may be overimposed in the endoscopic image. The same software platform that is now being used for planning may also be used in the future to simulate parts of the operation using an individual patient data set. Patient modeling can not be done online yet, and planning is currently a 2-hour process. The rapid evolution in medical image processing will allow online reconstruction of the patient in the near future. The modeling phase will then be completed at the time of the examination. Planning, transfer, and augmented reality will all be performed in the operating room without significant procedural delay, which will open the door for image-guided surgical therapy.

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Appendix

Definitions

Fiducial: radio opaque landmark visible and identifiable in radiographic medical examinations for segmentation purpose.

Segmentation: delineation of meaningful anatomic (sane or malign) structures in medical imaging examinations.

Patient modeling: three-dimensional construction of a numerical model of the patient's organs upon which computations can be performed (eg, computation of port location, computation of potential collisions between internal instruments and organs, and so forth). This process uses digital medical images and the results of the segmentation.

Robot kinemactics: the set of information required to compute the position of the tool tip (extremity) of the robot in space and time from mechanical engineering.

Registration: a process to transform and align different data within a unique reference frame. A rigid transformation is computed to link the patient's preopreative frame with the intraoperative robot and coordinate patient frames in the operating room.

INVITED COMMENTARY

The median sternotomy has remained the primary incision for all cardiac operations. Therefore, surgeons rarely have been concerned with chest wall topography as related to specific cardiac regions. Nevertheless, spatial projections of intercostal entry points onto cardiac surgical sites vary widely. The thorax is a complex semirigid, paraboloid cage that encloses a dynamic organ (ie, the heart). Until now alignment of robotic instrument entry points with cardiac operative sites has been difficult, even on an arrested heart and with the use of visual cues through a small incision. Comparatively, the elastic abdominal wall can be mobilized to align instrument entry points with multiple operative targets. In robotic cardiac surgery exact placement, the operative "triplet" (3-dimensional [3-D] camera and two instrument arms) amplify these complexities. Heretofore, the frustration of trocar placement and instrument vector alignment with the operative plane has been an impediment to wide-

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