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ORIGINAL ARTICLE

Towards navigation on the heart surface during coronary arterty bypass grafting

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Abstract
Object Coronary artery bypass grafting (CABG) is the standard treatment for advanced coronary artery diseases. In a preoperative MSCT, both wall plaque formations and resulting optimal anastomotic site are visible to the surgeon. During surgery, the identification of this position on the surface of the heart is of utmost importance for an effective revascularisation procedure. To assist the surgeon in this matter, a surgical navigation system for the open heart is desirable. This work focusses on an appropriate method for registration of a patient-specific map of the coronaries extracted from preoperative MSCT data with optical tracking data recorded intraoperatively at the ischaemic heart.
Methods The proposed registration process is based on mutually shared anatomical point landmarks and vessel paths on the heart surface utilised in an enhanced weighted ICP algorithm. Bypass grafting predominantly takes place at the ischaemic heart which is significantly distorted compared to its preoperative shape. To account for that, the method includes corrections for the effects of muscle relaxation and torsion of the ischaemic heart.
Results The registration process was tested retrospectively on real patient data recorded at the ischaemic heart during bypass grafting. After registration, the vessel paths and point landmarks recorded intraoperatively by the surgeon showed good accordance with the preoperative map of the coronaries.
Conclusion The registration method presented here is capable of matching the relevant parts of a preoperatively extracted map of the coronaries with intraoperatively recorded optical tracking data. Thus, it can be used as a basis for a surgical navigation system intended to assist the surgeon in the localisation of the optimal anastomotic site during CABG.

Keywords CABG · Registration · Decision support · Optical tracking system · MSCT

Introduction

Coronary artery bypass grafting (CABG) is the most commonly performed type of open heart surgery. Being the standard treatment for advanced coronary artery diseases, it is widely performed on patients with significant stenoses of the coronary arteries. In this revascularisation procedure, the blood flow to the affected ischaemic region is improved by a vessel graft, rerouting the blood flow around the stenosis. For heart surgeons, locating the diseased vessel and identifying the most appropriate anastomotic site for the bypass graft is of particular importance. Although bypass grafting on the beating heart is increasingly performed, CABG surgery is mostly performed during ischaemia while blood circulation is sustained by the heart lung machine [1]. It is beneficial for the patient to keep the duration of extracorporeal circulation as short as possible. Therefore, it is desirable to accelerate the localisation of the anastomotic site and thus reduce the ischaemic time of the heart.

In current clinical practice, the final positioning of the bypass graft on the target vessel is done by manually pal-

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pating the surface of the heart, which is often very time-consuming. Surgical dissection may be necessary in difficult cases, which requires additional time and involves the risk of damaging the heart structure. Moreover, CABG surgery at the ischaemic heart is performed under enormous time pressure. Therefore, a surgical assistence system which involves a preoperative planning step and offers decision guidance during surgery is desirable.

In a preoperative MSCT (multi slice computed tomography) image, luminal narrowing and wall plaque formations in the affected coronary and the resulting optimal distal anastomotic site are visible to the surgeon. During surgery, the major difficulty consists in identifying this optimal position on the surface of the heart which may be covered by epicardial fat. To assist the heart surgeon in localising the optimal anastomotic site and thus avoiding time-consuming palpating and dissection, a surgical navigation system for the open heart is proposed. Before surgery, a procedure planning step is intended, in which the optimal site for the bypass graft is determined on the basis of the MSCT information by collaboration of the operating heart surgeon and the cardiac radiologist. The position of this planned anastomotic site is then marked in the MSCT data for usage during surgery. In the operating room, the purpose of the assistance system is to provide a patient-specific map of the coronaries extracted from preoperative MSCT data in which the current position of a surgical pointing device (Cardio-Pointer) is visualised together with the planned anastomotic site and plaque information.

Such a surgical assistance system requires preliminary registration of pre- and intraoperative data sets. This work focusses on an appropriate method for registration of the 3D map of the coronary arteries extracted from preoperative MSCT data with optical tracking data recorded intraoperatively at the ischaemic heart. The registration is based on mutually shared anatomical point landmarks and vessel paths on the surface of the heart. The registration process includes a rigid coarse registration followed by an enhanced weighted ICP algorithm, as well as corrections for the effects of muscle relaxation and torsion of the ischaemic heart.

As the occuring deformation is highly specific to both the heart of the patient and the target vessel, the correction mechanism has to be different for each affected region. The left anterior descending artery (LAD) on the front side of the heart is an important target vessel for CABG and a bypass is grafted to it in the majority of surgeries. As a consequence, the LAD is specially considered as target vessel in this work.

Methods

In several surgical disciplines such as orthopaedics and neurosurgery, the usage of computer assisted navigation systems is common practice nowadays [2,3]. As to cardiac interventions, valuable research has been done in the field of minimally invasive surgery [4]. In the field of open heart surgery, the development of surgical assistance systems is still at the beginning.

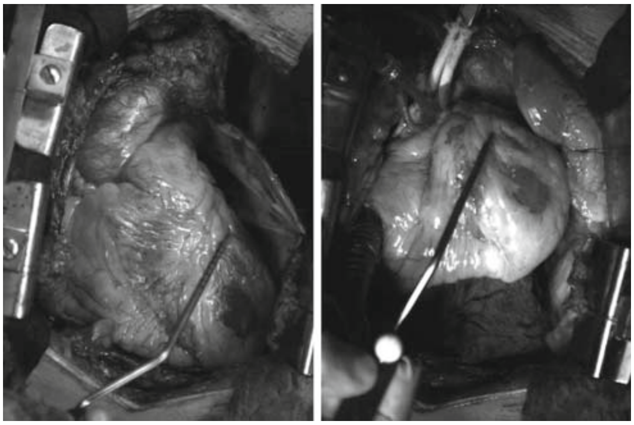

Fig. 1 Video images taken from same CABG surgery, illustrating the extensive deformation between the still beating heart (*left*) and the ischaemic, non-beating heart (*right*); The Cardio-Pointer tip points at the same point landmark on the beating and the deformed, ischaemic heart

The registration of pre- and intraoperative data sets provides the basis for computer assisted navigation systems in the majority of cases. In most disciplines, the shape and position of the surgical target do not change between data acquisition prior to the intervention and at the intraoperative site. Furthermore, many registration methods for surgical interventions rely on external fiducial markers while others use anatomical point landmarks [5,6]. When using external fiducial markers, the amount and type of landmarks can be chosen according to the requirements of the registration algorithm.

For CABG at the open heart, the situation is completely different: Bypass grafting predominantly takes place at the ischaemic, non-beating heart which is significantly deformed compared to its preoperative shape due to extracorporeal circulation. During surgery, the ischaemic heart experiences additional deformations and distortions due to appropriate positioning for bypass grafting (see Fig. 1). This means that the heart is extensively deformed prior to the grafting of each bypass in order to position the target vessel in the centre of the operating field. Moreover, in open heart surgery it is not possible to revert to external fiducial markers for registration as it is problematic to achieve an appropriate configuration of the markers and avoid shifting in their pre- and intraoperative positions at the same time. This is induced by median sternotomy and opening of the chest leading to a deformation of the rib cage.

As a consequence, the registration approach presented here (for a schematic overview of the registration process see Fig. 3) is based upon mutually shared anatomical landmarks and vessel paths on the surface of the heart. It is no easy task to find a sufficient number of such landmarks on the heart for registration, as the heart compared e.g. to the brain exhibits much fewer anatomical landmarks [7]. Due to fatty degeneration of the heart, many potential landmarks though visible in preoperative CT scans, cannot be seen on the surface of the heart during CABG surgery. This often results in the shortage of corresponding landmarks. Hence, a registration process for preoperative MSCT data and tracked position data from the ischaemic heart has to cope with both, the shortage of utilisable landmarks and the significant deformations of the ischaemic heart.

For the registration process described in the following, a minimum number of three anatomical point landmarks located in the relevant region of the heart surface and one part of the target vessel is sufficient. In this case that is three point landmarks on the LAD or neighbouring vessels and one visible part of the LAD vessel path which is visible in both, the preoperative MSCT data and the intraoperatively recorded optical tracking data.

Data acquisition

Prior to registration, pre- and intraoperative data have to be recorded. Preoperatively, an individual map of the patient's coronary arteries is generated. For this purpose, the centerlines of the coronary arteries as well as plaque positions are segmented from mid-diastolic (75 % RR) MSCT image data with a resolution of $0.4 \times 0.4 \times 0.5\ \text{mm}^3$. Additionally, prominent features which are likely to be observable during surgery are marked. Such potential point landmarks can be vessel bifurcations or crossing points of different vessels. Furthermore, on the basis of wall plaque formations visible in the MSCT data, the optimal distal anastomotic site can be determined for each target vessel by the heart surgeon in collaboration with the cardiac radiologist. Hence, in a preprocedural planning step, a 3D model of the coronary artery tree with marked 3D positions of plaques, potential landmarks and planned distal anastomotic sites is established for further usage during CAGB surgery.

Intraoperative data for the registration process are recorded by means of an optical tracking system. For this purpose, the surgeon is equipped with a trackable pointing device (Cardio-Pointer). The optical tracking system, the pointer and the mounting of the measurement system in the operating room can be seen in Fig. 2. After positioning of the heart, the identification of utilisable point landmarks, visible parts of the target vessel path and vessel paths in the area of the target vessel is done by the heart surgeon prior to data recording. While pointing at relevant landmarks, the 3D position of the Cardio-Pointer tip is recorded. Additionally, the course of registration-relevant vessels is retraced with the Cardio-Pointer, yielding 3D polylines (tracked vessel paths). For registration, only point landmarks and vessel paths mutually shared in the pre- and the intraoperative data sets are usable. The MSCT landmarks are assigned to the landmarks recorded with the tracking system by hand.

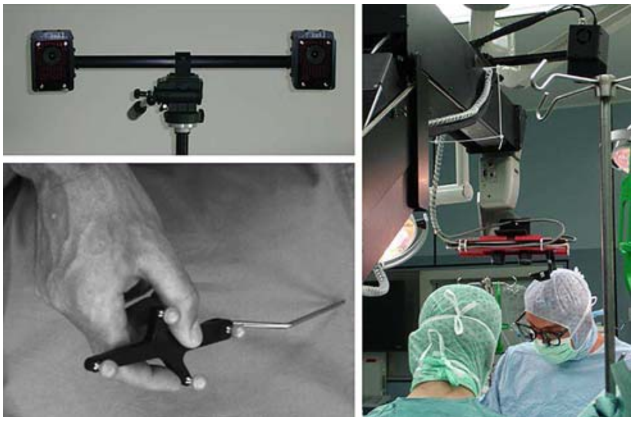

Fig. 2 *Left* optical tracking system and Cardio-Pointer; *right* optical tracking system and other equipment mounted on video robot arm

Registration process

A schematic view of the registration process can be seen in Fig. 3. After extraction of the 3D positions of corresponding landmarks and vessel paths from CT and optical tracking data, the registration algorithm consists of three steps:

1. Rigid registration of the pre- and intraoperative data sets using corresponding point landmarks
2. Applying an enhanced weighted ICP algorithm to refine the matching using corresponding vessel paths
3. Correction of major deformations and distortions due to positioning of the ischaemic heart for bypass grafting and thus further improvement of the matching.

Anatomical point landmarks, mutually shared in both data sets, are the basis for the first step. Such anatomical point landmarks can be crossing points of different vessels or vessel bifurcations [8]. Additionally, points with distinctive curvature in mostly undeformed areas of the surface of the heart can be used as point landmarks. Utilising them, a rigid body transformation is performed using Procrustes methods [9]. As the data available for registration are both limited in size and afflicted with outliers, establishing the right correspondences between the data sets is not easy. Even more challenging is the deformation occuring between the recording of the two data sets. Moreover, each of the data sets comprises data which the other data set does not. Therefore, it is important to achieve good alignment of the data sets in a step preceding the ICP. The rigid registration serves this purpose.

In the second registration step, vessel paths visible both on the heart surface and in the MSCT images are used to iterati-

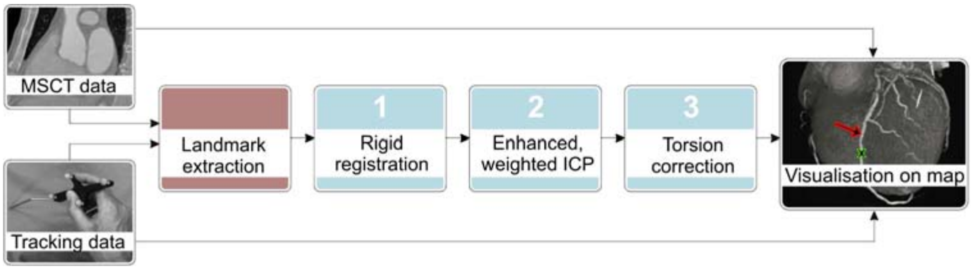

Fig. 3 Schematic view of the registration process: extraction of corresponding landmarks from preoperative MSCT data and intraoperative tracking data; Then rigid registration (*1*), subsequent enhanced, weighted ICP (*2*) and torsion correction (*3*); Finally, visualisation of current pointer position (*green cross*) and planned distal anastomotic site (marked with *red arrow*) in the coronary artery map

vely refine the matching. As mentioned above, the rigid transformation of point landmarks and vessel paths resulting from the first step is employed to initialise the enhanced weighted iterative closest point (ICP) algorithm. This algorithm is based upon the basic ICP algorithm [10]. At first, the closest point in the MSCT data set is determined for each vessel point in the rigidly transformed intraoperative optical tracking data set. Then, not overlapping data points are neglected for the most part. The basis of the neglection method is similar to the one described in [11], but was modified and extended specific to the data at hand. Both the CT and tracking data sets contain vessel path polylines and point landmarks. The enhanced ICP algorithm protects point landmark pairs from being neglected but it neglects correspondence-free points from the ends of the CT and tracked vessel paths whose position exceeds a threshold distance to the first (and last respectively) mutually shared vessel point in the same data set. This extension of the ICP algorithm prevents the unwanted influence of not corresponding data but at the same time allows for a small adjustment of the prealigned tracked data alongside the vessel path. Distinctive outliers are neglected as well. The non-beating heart is considerably deformed compared to the beating heart upon which the preoperative map of the coronaries and the MSCT data for registration are based. Concerning outlier neglection, it is important to distinguish between actual outliers and points which behave like outliers but are misaligned due to deformation. The latter are not to be discarded. Deformations occur on the one hand because the heart stops beating and the heart muscle relaxes and on the other hand because the ischaemic heart is manually brought into an appropriate position for bypass grafting. Due to the relaxation of the heart muscle, the vessel paths on the ischaemic heart may be skewed or diverged. To allow for such deformations, the ICP algorithm was enhanced to consider non-isotropic scaling. Therefore it is capable to stretch or tighten the space between vessel paths without stretching their length in the same way. This correction mechanism is only expedient for data sets with more than one corresponding vessel path.

If suitable, the data points on the vessel paths can be weighted individually. This has been done before [12,13], e.g. based on the distribution of distances, expected uncertainty of the errors or compatibility of normals [14]. Mostly, the intention of the weighting is outlier removal and thus improvement of the overall alignment. In this case, the intention for and thus the effect of individual weighting of the data points is different. As the transformation resulting from the ICP provides the basis for the torsion correction in the third step, the vessel paths are weighted accordingly. This means that the weighting coefficients are dependent on the amount of deformation which is expected for a pair of points. The expected deformation of course depends on the target vessel for whose accessibility the heart is positioned. In the case of the LAD, prior to bypass grafting on that vessel, the heart is manually deformed and positioned in order to expose the LAD in the centre of the operating field. To do so, the heart is distorted. Especially the upper parts of the heart, directly underneath the region where the major vessels connect the heart with the rest of the body, experience a severe deformation. The heart muscle is twisted in that upper region so as to bring the better part of the LAD into proper view. Lower parts of the heart are rather rotated in this process than actually twisted. As the LAD descends alongside the anterior interventricular sulcus to the apex of the heart, this manual positioning affects the LAD in most patients in a similar way: The upper part of the LAD is considerably deformed while the lower part of the vessel is rather shifted in its position and deformed to a much lesser extent. This means that, if anywhere, the shape of the LAD is maintained in the lower heart region. Hence, tracked vessel parts from the lower heart region are preferred in this registration step. As a consequence, larger weighting coefficients are assigned to those parts of the LAD which are recorded on the lower part of the heart and for which less distortion is expected. Smaller weighting coefficients are assigned to parts of the LAD which are recorded in the twisted and strongly deformed upper regions of the heart. Naturally, this weighting is patient-specific as only in few patients the LAD is fully

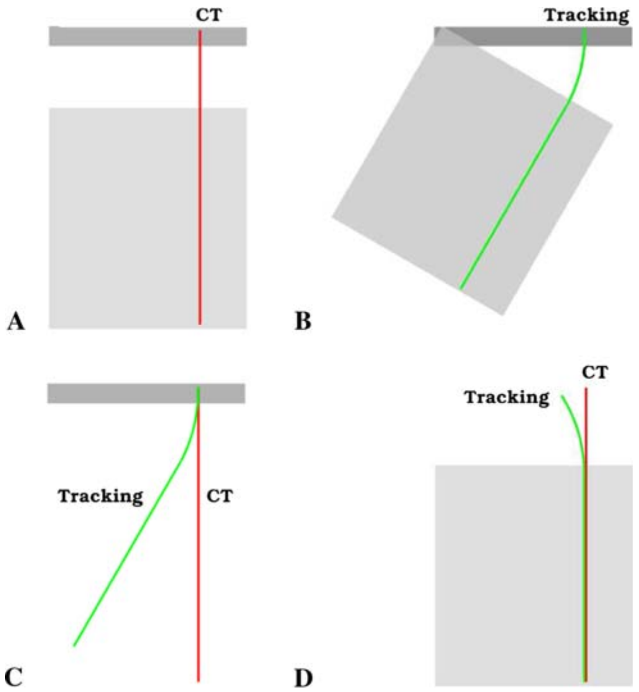

Fig. 4 Influence of the weighting (schematic): Vessel path extracted from CT images (**a**) and recorded with optical tracking system (**b**); Larger weighting of the *dark grey* areas results in **c**, larger weighting of the *light grey* areas results in **d** (**d** is preferred for subsequent torsion correction)

visible. In some patients, the bulk of the recorded points may lie in the upper area while in other patients only a small part of the LAD near the apex may be visible. Therefore, an appropriate weighting has to be chosen interactively during surgery on the basis of what parts of the vessel are actually visible on the surface of the heart. The influence of the weighting on the outcome of the enhanced weighted ICP is shown in Fig. 4.

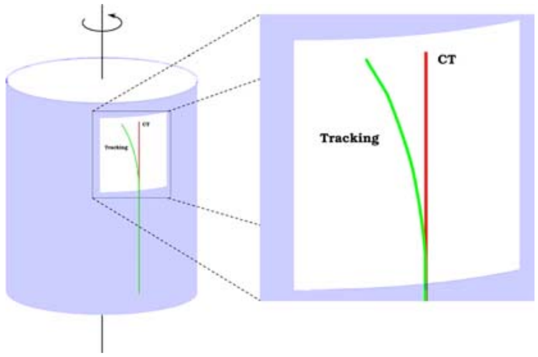

Fig. 5 Prior to torsion correction: a cylindrical surface resembling the heart with both CT (*red*) and tracking (*green*) vessel paths as resulting from ICP

As mentioned above, in the third step of the registration procedure, the torsion of the appropriately positioned ischaemic heart is corrected along the course of the relevant vessel. The torsion of the transformed optical tracking data resulting from the enhanced, weighted ICP compared to the vessel path segmented form the MSCT data is calculated along the vessel path with respect to a heuristically estimated torsion axis of the heart (see Fig. 5). The estimation of the torsion axis is based on the anatomy of the heart of the patient. In the upper region, where the major vessels connect heart and body, the heart is not moveable during surgery but remains in the same anatomical position as prior to surgery. Therefore, the upper point of the axis is chosen in the centre of a cross section of this area. The cardiac apex is chosen as lower axis point. The torsion angle of the tracking data in comparison to the CT data is calculated for each data point. Then, the variation of the torsion angle along the vessel is piecewise linearly approximated. This torsion angle approximation and an accordingly rescaled vessel length yield a further correction of the vessel tracking data.

The described registration process was developed on the basis of corresponding MSCT and tracking patient data sets from CABG surgeries. Apparently, any method for registration of MSCT data and data recorded at the open heart has to fulfil two requirements: First the capability to deal with a minimum number of corresponding landmarks and second a high flexibility regarding the patient-specific type and location of the landmarks. With the described process, registration of the LAD is possible for patients which exhibit a minimum number of three mutually shared point landmarks on or around the LAD and one part of the LAD vessel path.

Results

The described registration process was applied to corresponding patient data sets acquired preoperatively with the CT and recorded on ischaemic hearts during different phases of the bypass grafting procedure. The efficiency of the method was tested on registration of the relevant area around the LAD. The LAD runs on the front side of the heart, descending along the anterior interventricular sulcus down to the apex of the heart.

Corresponding data sets were recorded for six patients. A bypass was grafted to the LAD in all six CABG surgeries. In two of the patients, less than three mutually shared anatomical point landmarks could be found on the surface of the heart. Hence, the minimum number of sufficient landmarks for the registration was not available and the data sets were not further considered in the context of this work. In the other four patients, at least three reliable, mutually shared point landmarks were found in the relevant area. For all of these four patients, registration of the LAD was performed, achieving good results in each case.

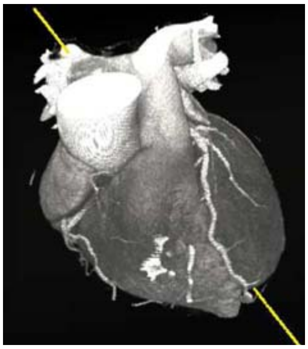

Fig. 6 Estimated torsion axis visualised in the CT map

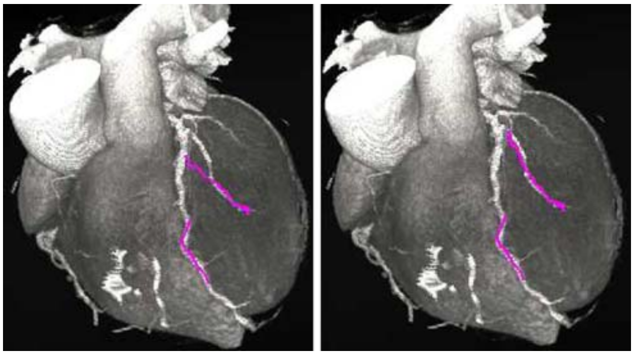

Fig. 7 Enhanced weighted ICP and subsequent torsion correction: Registration result without torsion correction (*left*); Registration result with torsion correction (*right*)

For the first step of the registration process, i.e. the rigid body transformation, different numbers and types of landmarks were used. In two patients, four point landmarks were visible, in the other two only three. As expected, the vessel bifurcations of the relevant vessel and its crossing points with veins were the most valuable point landmarks. Almost as well worked bifurcations and crossing points of vessel branches and parallel running vessels within the relevant area around the affected vessel. Distinctive curvature points turned out to be useful point landmarks as long as they were located in less distorted areas of the heart, i.e. in the case of the LAD located on the lower part of the vessel. For all patients, the resulting rigid body transformation provided a sufficient basis for the ICP algorithm.

The visible parts of the LAD, its branches and neighbouring vessels were used to refine the matching of the LAD vessel path. In two of the patients, the LAD was mostly visible during surgery. In the other two, the LAD was partly to mostly covered with epicardial fat and only a part of the vessel could be recorded with the Cardio-Pointer. In one of the patients, a diagonal branch of the LAD was visible. Therefore, in three patients only a part of the LAD vessel path was used for registration, while in one patient a second vessel path was used as well. When the ischaemic heart is brought into an appropriate position for bypass grafting on the LAD, the upper region of the heart, near the aorta and pulmonary artery, is distorted most. Therefore, smaller weighting coefficients were assigned to vessel parts in this area than to lower parts of the utilised vessel paths. On basis of the transformation resulting from the enhanced weighted ICP, the torsion correction was performed with respect to a heuristically estimated torsion axis of the heart (see Fig. 6).

Thereby, the result of the registration process was much improved. The improvement due to the torsion correction is shown in Fig. 7. In the registration process excluding the torsion correction step, the LAD (only the lower part of the LAD was visible on the heart surface) was matched correctly, but the upper part of its diagonal branch was mismatched due to the torsion applied to the ischaemic heart. Registration including corrections for this torsion led to a far better result.

After the completion of all three registration steps, the vessel paths recorded intraoperatively by the surgeon showed good accordance with the preoperative map of the coronaries. This is shown in Fig. 8 for all four patients.

To evaluate the performance of the registration algorithm, two values were considered: First, the RMS (root mean square) fiducial registration error [15] of all mutually shared corresponding landmark (LM) points was calculated. Second, the average distance of corresponding vessel paths taken from the preoperative MSCT data and the transformed intraoperative tracking data was calculated.

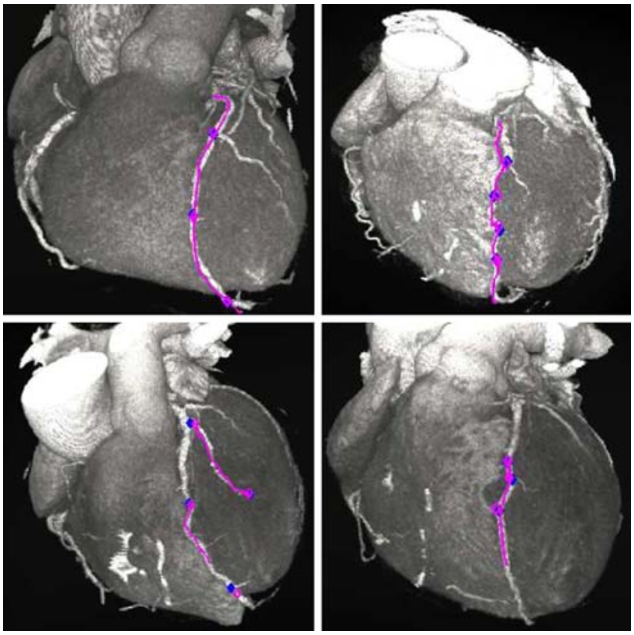

Fig. 8 After the registration process: For four different patients, the transformed tracking vessel path (*magenta*) as well as CT point landmarks (*blue*) and transformed tracking point landmarks (*magenta*) are visualised in the corresponding CT maps

Table 1 RMS errors for individual data sets

Data no.	Point LMs	Vessel paths	RMS of point LMs (mm)	RMS of vessel paths (mm)
1	4	2	3.5	2.3
2	4	1	2.8	1.6
3	3	1	1.1	1.4
5	3	1	3.2	0.5

Table 2 Overall errors and standard deviation of point landmarks and vessel paths

Point landmarks	
Overall number of point LMs	14
Mean RMS of point LMs (in mm)	2.7
Standard deviation of point LMs (in mm)	0.9
Vessel paths	
Overall number of vessel paths	5
Mean RMS of vessel paths (in mm)	1.2
Standard deviation of vessel paths (in mm)	0.4

The errors of the individual patient data sets are listed in Table 1. Table 2 shows the mean RMS and standard deviation for all landmark points and vessel paths.

For the four patient data sets, an average RMS of 2.7 ± 0.9 mm was obtained for the corresponding landmark points, while the average RMS distance of the vessel paths after registration amounted to 1.2 ± 0.4 mm. At first glance, it is striking that the average RMS distance of the vessel paths is much smaller than the average RMS of the corresponding landmark points. Two different reasons account for that behaviour. First, pairwise closest points are used to determine the RMS distance of the vessel paths. Therefore, the RMS distance considers the vessel displacement perpendicular to the vessel path but cannot include displacements alongside the vessel path. The RMS of corresponding point landmarks includes displacements both alongside and perpendicular to the vessel path. Second, the mutually shared point landmarks are used to determine the initial alignment of the data sets and their respective distance is minimised in that step. In the subsequent ICP, where the vessel paths are included in the registration, these point landmarks are almost certainly shifted from their positions for the sake of a better overall matching of landmark points and vessel paths.

Conclusion

The registration process described in this work is capable of matching preoperative and intraoperative data from relevant parts of the surface of the heart. 3D positions of vessel centerlines and anatomical point landmarks are extracted from preoperative MSCT data and matched with corresponding 3D positions of intraoperative data recorded with an optical tracking system. This allows for the visualisation of optical tracking data in a patient-specific map of the coronaries extracted from MSCT data prior to surgery. The registration mechanism facilitates the visualisation of the optical tracking data and thus the current pointer position in that map. Therefore, the registration can be utilised as the basis for a surgical assistance system which enables the navigation with the Cardio-Pointer on the relevant parts of the surface of the heart.

Luminal narrowing and wall plaque formations are displayed in the MSCT. This information would be available both for preprocedural planning of the optimal position for the bypass graft and for decision guidance during surgery. As not only the pointer position on but also the plaque formations within the target vessel can be visualised in the map of the coronaries, such a system can assist the operating heart surgeon in the localisation of the optimal anastomotic site and the identification of this site on the surface of the heart. This may decrease the need for time-consuming palpation of the surface of the heart and dissection of the vessel of interest and therefore augment both quality and speed of CABG surgery.

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