Virtual Reality in Medical Imaging for Image-Guided Surgery

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This presentation discusses relatively recent advances in the use of techniques from medical imaging and simulation to facilitate minimally invasive surgery. The descriptions in this paper are based on original work done in the EC-sponsored EASI-project (European Applications in Surgical Interventions).

Introduction

With medical imaging equipment one can generate images of the inside of the body. The images can be used for diagnosis, but also for planning and simulation of radio-therapy, surgery and other types of interventions, as well as for guidance and navigation while intervening according to the pre-operative plan. Several registration techniques are available to transfer the pre-operative virtual plan onto the real patient on the operating table, so that planned positions, orientations and sizes can be found back. The position and orientation of surgical tools are measured so that they can be overlaid interactively onto images, showing the tools to the surgeon in relation to the patient's anatomy and pathology. Such guidance greatly facilitates minimally invasive surgery, it improves surgical accuracy and speed, it reduces surgical risks, and it improves the surgeon's confidence.

A further step is the integration of intra-operative imaging (e.g. with microscopy, endoscopy, ultrasound, X-ray, CT and MR) to update pre-operative images for changes which have occurred, either as a result of surgery itself, or because of flexible anatomy.

For microsurgery where a very high precision is needed, it is advantageous to augment the surgeon's dexterity with the help of telemanipulators, to minify movements, to filter any remaining microtremor, and to limit the force (or degrees of freedom) of surgical instruments. Simulation of surgery is gaining acceptance for training of surgeons in the non-destructive use of laparoscopic and endoscopic surgical tools.

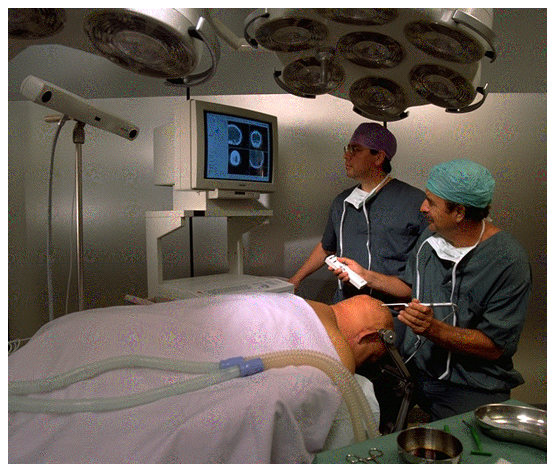

Figure 1: Image-guided neurosurgery: image-to-patients registration

During the last few decades various three-dimensional medical imaging techniques have become available, such as Computed Tomography (CT) and Magnetic Resonance (MR) imaging, with which various parts of the human body can be accurately depicted. The resulting images can be used as an aid in diagnosing pathology and for planning of medical treatment.

Conventionally, diagnosis is performed in a visual way: clinicians compare what is seen in patient images with knowledge of anatomy and pathology. Planning of treatment is performed similarly. Prior to surgery, surgeons use the images to mentally project the three-dimensional patient's anatomy and they determine the surgical plan on the basis of this.

In recent years, advances in computer technology and a significant increase in the accuracy of imaging have made it possible to develop systems that can assist and augment the clinician much better in the full path of diagnosis, planning and treatment.

In the European Applications in Surgical Interventions (EASI) project, research, development and clinical evaluation in the area of image-guided surgery were performed. The project focused on two application areas: image-guided neurosurgery of the brain (EASI-Neuro), see Figure 1, and image-guided vascular surgery of abdominal aortic aneurysms (EASI-Vascular), see Figure 2. The goal was to improve the effectiveness and quality of surgery and to reduce the overall cost of treatment.

Figure 2: Image-guided vascular surgery: overlay of aorta from CT to X-ray

EASI-Neuro concerned surgical procedures such as the retrieval of brain biopsies for tissue analysis, resection of brain tumours, endoscopic ventricular surgery and the treatment of neurovascular aneurysms. Advanced tools were developed for planning, visualization and tracking, while using the EasyGuide intra-operative navigator and EasyVision clinical workstation as starting platforms.

EASI-Vascular was concerned with image-guided treatment of abdominal aortic aneurysms (AAAs), a life-threatening dilation of the abdominal aorta. Rupture of an AAA leads to instant death in the majority of the cases. Conventionally, these aneurysms are treated with open surgery via the abdomen. Relatively recently, a minimally-invasive technique has been introduced for the endovascular placement of an aortic prosthesis via the femoral arteries. The EASI-Vascular project focused on planning of the dimensions (length and diameter) of the prosthesis from pre-operatively acquired 3D CT images and on image-guided prosthesis placement.

Project Approach

First, the needs of the clinical users were analysed with respect to the various steps involved in image-guided surgery (pre-operative imaging, pre-operative planning and intra-operative navigation). For the applications of interest, the desired improvements and possible new surgical procedures were formulated in a clinical specification.

From the clinical specification, a functional specification was derived in which each of the required functions and its required performance was specified in detail. This functional specification was translated into a technical specification in which the hardware and software tools to be developed were specified. Based on the technical specification, prototype image-guided surgery planning and navigation systems (called demonstrators) were built and installed at clinical sites for clinical validation. On the basis of results of the ongoing clinical validation the demonstrators were continuously improved.

Neurosurgery

The clinical procedures addressed in EASI-Neuro are craniotomy (opening of the skull for e.g. tumour resection), biopsy (the retrieval of small brain tissue samples), insertion of shunt catheters into the ventricles (draining of CSF) and endoscopic surgery. For all of these procedures the clinical users want to accurately plan the procedure on the basis of pre-operatively scanned CT or MR images. This may involve segmentation and visualization of critical structures such as blood vessels, tumours, ventricles, gyri and sulci. Furthermore, the users want to accurately follow the pre-operative plan during surgery while getting feedback about any deviations from the plan.

Basic platforms for EASI-Neuro

The EasyVision CT/MR pre-operative planning station and the EasyGuide™ intra-operative navigator were used as starting platforms (see Figure 3). New software and hardware tools were added to improve functionality, resulting in the EASI-Neuro demonstrator.

Figure 3: EasyVision workstation (left) and EasyGuide™ navigator (right)

Figure 4: Phantoms for the detection of scanner-induced geometric distortions in CT (left) and MR (right) images

Developed tools for EASI-Neuro

Tools were developed for correction of scanner-induced distortions in CT/MR images, for planning and guidance in frameless stereotactic biopsy, for craniotomy and path planning in tumour resection, and for image-guided endoscopic surgery.

Geometric correction

The first step in image-guided neurosurgery is pre-operative CT or MR imaging. Geometric distortions may be present in the images due to, for example, imprecisely reported table speeds or gantry tilts (CT) or imperfect magnetic fields (MR). Such scanner-induced distortions may influence the accuracy of image-guided navigation. Special phantoms were designed for measuring distortions in CT and MR images (see Figure 4) and methods were developed for correcting the images (any patient-induced MR distortions are not corrected for).

Use of these phantoms on scanners of various manufacturers revealed that distortions of several mm are no exception, both for CT and MR. We are evaluating how much the overall navigational accuracy can be improved by correcting for such scanner distortions.

Frameless stereotactic biopsy

When diagnostic imaging indicates the possible presence of a tumour, often a biopsy is retrieved. This is conventionally done by using a stereotactic frame, see Figure 5 (left). In the operating theatre, the base of a reference frame is attached to the patient.

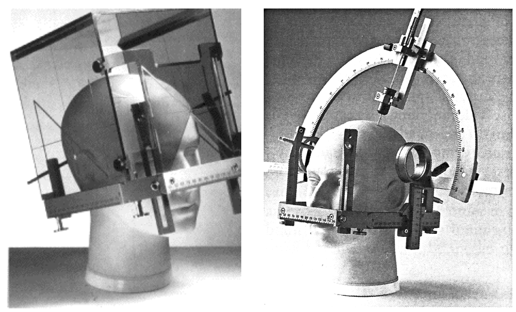

Figure 5: Leksell frame with scan plates (left) and arc (right) (photos courtesy Elekta)

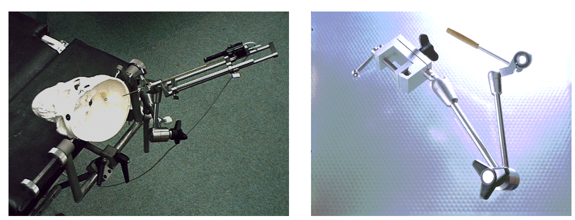

Figure 6: EasyTaxis™ surgical arm

The patient is then transferred to the radiological department for CT or MR scanning. After scanning, the patient is brought back to the operating theatre, where the arc is mounted to the base, see Figure 5 (right). The needle's insertion point, orientation and insertion depth are measured from the scanned images and are transferred onto the arc of the stereotactic frame. Then a needle is inserted and the biopsies are taken.

The conventional frame-based stereotactic procedure is patient unfriendly, time consuming and suboptimal for hospital logistics. We therefore developed a frameless procedure that is described below.

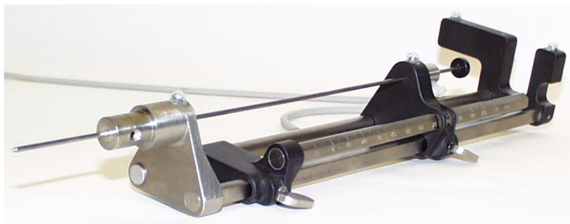

Figure 7: Needle guide

The patient is first scanned (CT/MR) with fiducials markers attached to the skin and is then transferred to the operating theatre. There, the EasyGuide navigator is used to register the patient to the preoperative images. The biopsy entry and target points are planned with a special biopsy planner tool, which allows evaluation of the path from entry to target. The needle is positioned and oriented according to the planned path by using a special biopsy needle guide which is mounted in a surgical arm attached to operating table or Mayfield clamp.

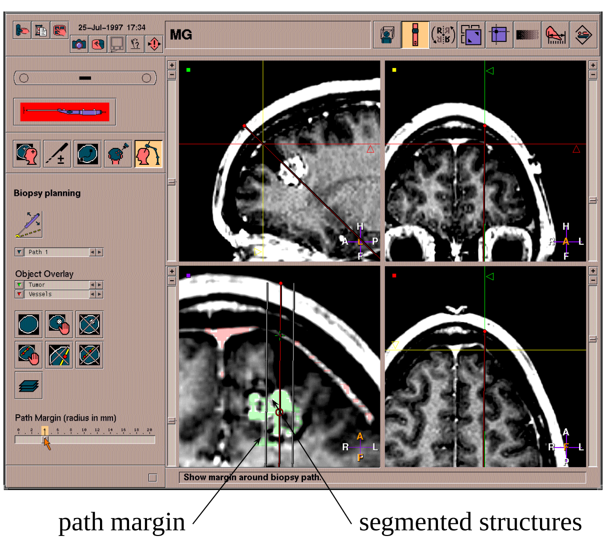

Figure 8: Planner tool

The alignment software in the biopsy planner tool helps the user to find the correct position and orientation quickly and accurately. The surgeon first puts the tip of the biopsy needle guide on the planned path (+ marker). The surgeon then aligns the guide's orientation with the planned path (x marker). The alignment matches the defined path position and orientation when both the + and x markers are shown at the image center position, indicated by the crosshair. The positions of the markers are calculated in the biopsy needle guide coordinate system, which establishes a natural feedback: left, right, up, down on the screen is also left, right up down for the biopsy needle guide.

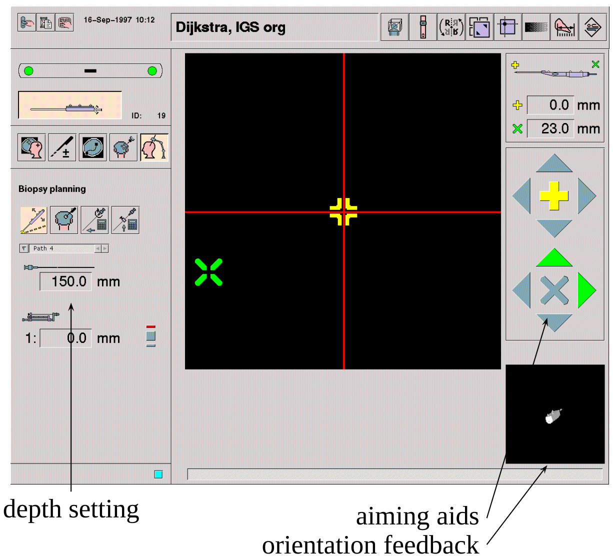

Figure 9: Tool to align guide onto planned path

As the needle is tracked, the progress of the needle insertion can be shown in relation to the preoperative images. The surgeon can simulate the retrieval of a biopsy by moving the guide's depth stop as if a needle was inserted. The pre-operative images are shown at the needle tip position. When all is satisfactory the real needle can be inserted into the guide and the biopsies can be retrieved.

Clinical studies have shown that the procedure can be performed in a very short amount of time (about 40 minutes in the OR) with accuracy better than 2mm.

Craniotomy and path planning for neurosurgery

We developed a craniotomy planner tool for tumour resection that allows the surgeon to accurately determine the tumour position (the target), to compare alternative positions and shapes/sizes of the craniotomy (the entry point) and to verify the path from the entry point to the tumour.

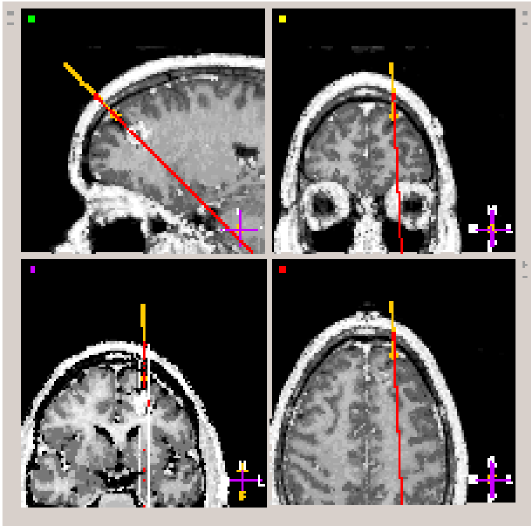

Figure 10: Tool to simulate a biopsy and to navigate while taking a biopsy

This tool uses advanced segmentation techniques to discriminate the tumour and surrounding critical structures (e.g. major blood vessels and gyri and sulci of healthy brain tissue) and advanced visualization techniques to show what is encountered on the path.

The pre-operative plan can be transferred onto the patient by using the tracked pointer of the EasyGuide navigator. During surgery, deviations from the plan can be visualized on the navigator display.

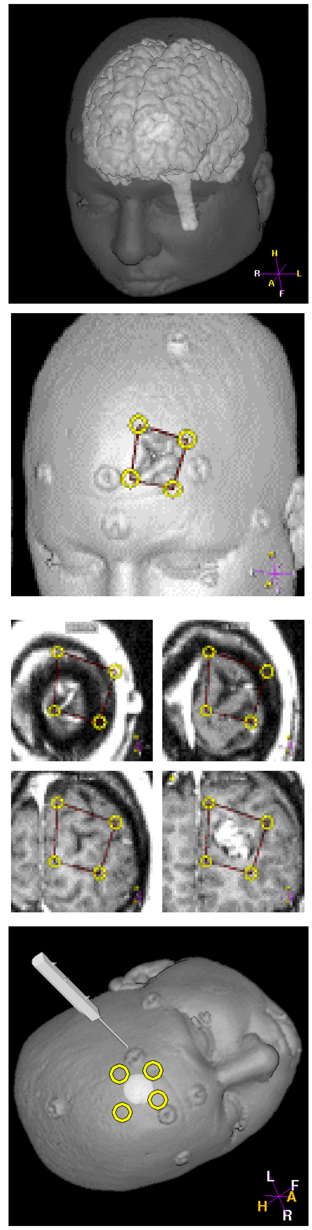

Figure 11: Plan a tumor resection on virtual patients images and transfer the plan onto the real patient

Endoscopic procedures for EASI-Neuro

A mountable pointer has been developed to enable tracking of the position and orientation of the endoscope during endoscopic surgery of the ventricular system. The pointer can be placed at any position on the working cannula of the endoscope.

The geometry of the endoscope-pointer combination can be learned with a specially developed tool. The EasyGuide navigator displays the orientation and position of the endoscope on the pre-operative images. Special tools have been developed to grab and display video images from the endoscope.

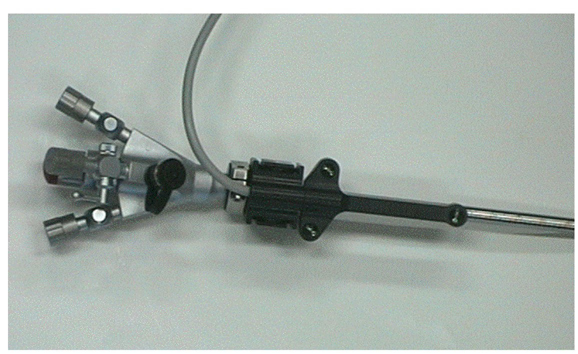

Figure 12: Endoscope with mountable pointer

Clinical validation results for EASI-Neuro

Advanced tools were developed for planning of a craniotomy and a surgical path to a selected location in the brain and for planning and performing frameless brain biopsy.

The surgical plan is based on CT/MR images that have been acquired pre-operatively. These images may contain geometric distortion which influence the obtainable surgical accuracy. Tools were therefore developed to measure and remove scanner-induced distortions.

Finally, tools were developed to enable tracking of various surgical instruments (pointers, endoscope, catheters).

The tools were thoroughly validated at National Hospital London, where they were used in 404 operative procedures. The 11 clinical users highly appreciated the tools: for instance 96% of the users was of the opinion that usage of tools has significant advantages over conventional techniques.

Especially the tools for frameless biopsy were highly appreciated. A true frameless procedure could be performed in less than 40 minutes with an accuracy of about 1.5-2.0 mm, which compares favourably with conventional frame-based methods.

Vascular surgery

User needs for EASI-Vascular

EASI-Vascular concentrates on the treatment of aneurysms of the abdominal aorta. An abdominal aorta aneurysm is a life-threatening weakness of the aorta wall which results in a swelling and possible rupture of the aorta. The attention in this project is focused on the Transfemoral Endovascular Aneurysm Management (TEAM) procedure, which is a relatively recent technique to reinforce abdominal aneurysms by placing a endoprosthesis (often Y-shaped) inside the aorta while passing through a small insertion in the femoral artery. The prosthesis is hooked from inside the aorta into its wall. For patients satisfying certain selection criteria, the minimally-invasive TEAM procedure can replace the rather invasive conventional procedure in which the abdomen is completely opened to replace the aorta by a prosthesis.

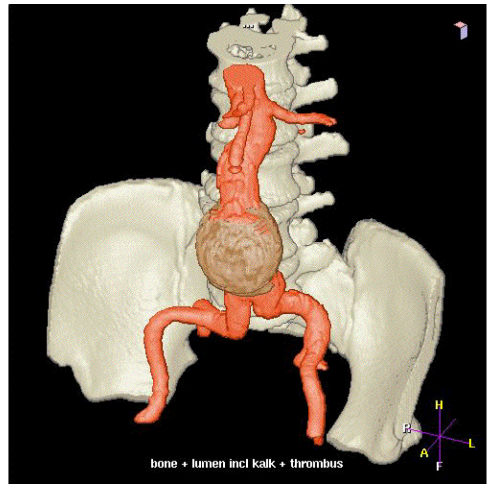

Figure 13: Aneurysm of the abdominal aorta

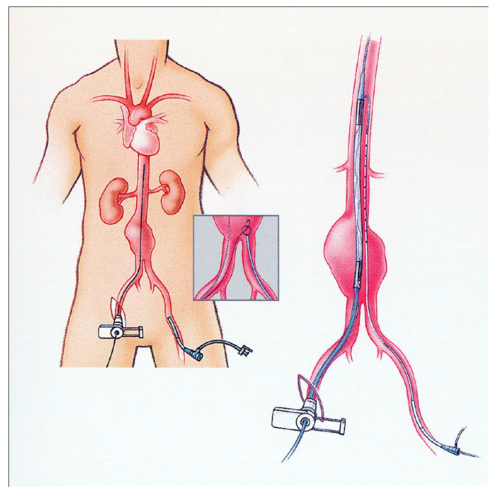

Figure 14: The TEAM procedure (illustration courtesy EVT)

A careful pre-operative planning is necessary to see whether the patient satisfies the selection criteria, to evaluate the suitability of the access trajectory and to determine the dimensions of the required endoprosthesis. We have also evaluated whether intra-operative surgical guidance could improve the accuracy of positioning the prosthesis as planned.

Basic platform for EASI-Vascular

Contrary to EASI-Neuro, EASI-Vascular had no navigation products that could serve as a starting platform. The demonstrator was therefore developed based on an EasyVision CT/MR clinical workstation with additional hardware and experimental software.

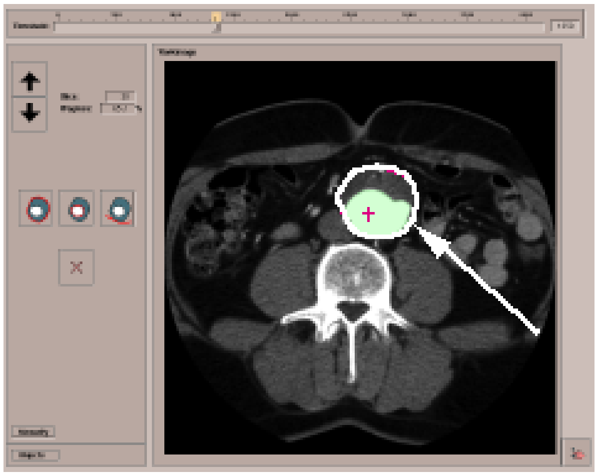

Figure 15: Automatic segmentation of the lumen from the CT data

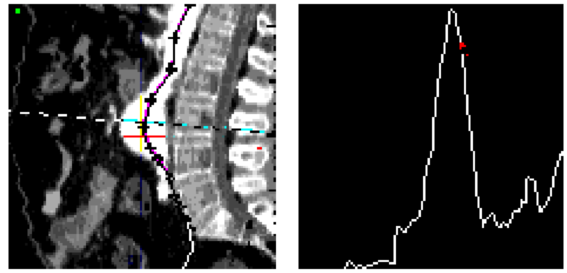

Figure 16: Semi-automatic tracking of the central lumen line (CLL) and estimation of the lumen area along the CLL from reformatted images perpendicular to the CLL

Pre-operative planning for EASI-Vascular

To evaluate the access trajectory and attachment sites, a (semi-) automatic algorithm was developed that segments and tracks lumen and thrombus in CTA images from the insertion point in the groin up to the renal arteries (see Figures 15 and 16). The algorithm automatically calculates the diameter of the aorta along the central lumen line and determines the diameter of the best-fitting endoprosthesis.

Intra-operative navigation for EASI-Vascular

To aid the clinical user in the placement of the endoprosthesis, a navigation system has been developed that registers intra-operative fluoroscopic X-ray images with pre-operative CTA images. This allows the visualisation in the intra-operative X-ray images of structures which are clearly visible in the CTA images (such as the lumen), but which are not visible in the X-ray images. Briefly summarized, the registration method operates as follows. A vertebra is segmented from the 3D CTA images. A projection of this vertebra is constructed and automatically registered to the corresponding vertebra in an intra-operative 2D X-ray image. The registration is performed by using a similarity measure based on pattern intensity. This similarity measure performs better than other measures, such as the normalised cross-correlation and mutual information.

The registration only remains valid as long as the patient has not moved with respect to the X-ray imaging system. Therefore an automatic motion detection method was implemented. In clinical practice, such motion occurs regularly, due to both intentional and unintentional repositioning of the operating table and/or the X-ray device. When motion has been detected, the registration is declared invalid and the registration algorithm is restarted.

Clinical validation results for EASI-Vascular

A method was developed for image-guided placement of an abdominal aortic prosthesis. The prosthesis is inserted through a small incision in the femoral artery. Intra-operative guidance is supplied on the basis of registering intra-operative 2D fluoroscopic X-ray images to pre-operatively scanned 3D CT images. After registration, information that was retrieved from the CT data and that is not clearly visible in the X-ray (e.g. the aorta) can be overlaid on the X-ray.

In the last phase of the project, attention was shifted towards planning: determination of patient eligibility and sizing of the patient-specific prosthesis. Tools were developed for automatic segmentation of the lumen in the aorta and for automatic estimation of the prosthesis dimensions. A preliminary clinical validation showed that the dimensions can be accurately estimated.

The EASI-Vascular demonstrator has been clinically validated at the Utrecht University Hospital (AZU). Up to now the system has been evaluated in 11 procedures (of circa 20 in total since July 1996). Discussions with the surgeons have repeatedly led to important redesigns. Therefore quantitative results are not present in the same abundance as they are in the EASI-Neuro part of the project.

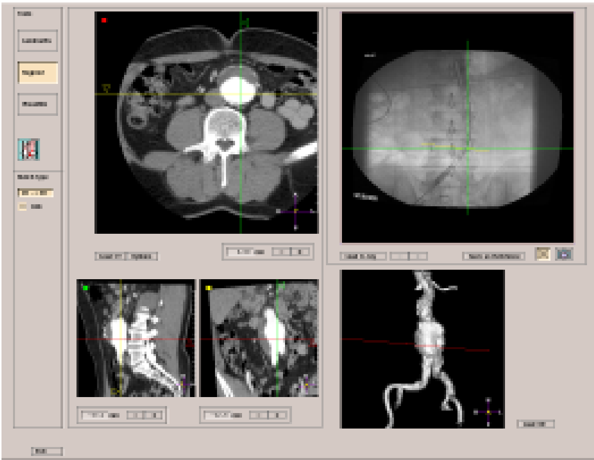

Figure 17: Linking of pre-operative CT with intra-operative X-ray images

The vascular surgeons are very pleased with the planning tools for pre-operative assessment of patient eligibility, for measurement of the dimensions of the required prosthesis, and for planning its attachment site. The vascular surgeons' enthusiasm for intra-operative guidance is much less. From a technical viewpoint, the developed intra-operative guidance method proved to function well in practice. Intra-operative localization (based on matching intra-operative X-ray to pre-operative CT) was realized with an accuracy of circa 1 mm in the directions parallel to the plane of the X-ray projection, and circa 2-3 mm in the perpendicular direction. However, the accuracy specified by the surgeon was 1 mm in all directions, for accurate determination of position and orientation of the tip of the endoprosthesis. This could not be reached with only a single direction of X-ray projection. Further improvement of the localization performance can be reached by using two or more directions of X-ray imaging.

However, if one relies on similarities between the pre-operative imaging and the intra-operative situation, then it is not sufficient to only improve the intra-operative localization accuracy. For instance, when the aorta's shape changes, and/or when its relation to the vertebrae changes significantly, the resulting lack of similarity severely reduces the usefulness of the pre-operative images.

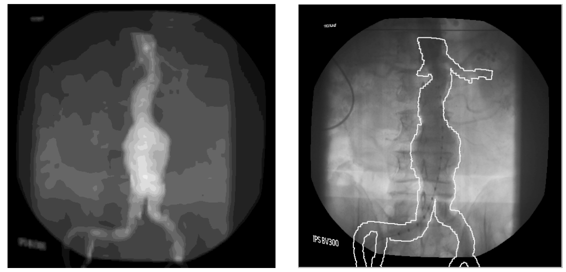

Figure 18: Overlay of aorta with aneurysm (segmented from pre-operative CT images) onto intra-operative X-ray image

Conclusions and future plans

In the course of the EASI project, advanced methods and tools were developed and validated for planning and performing image-guided surgery on the basis of pre-operatively acquired imagery.

Future research, development and clinical co-operations will focus on further increasing the accuracy of surgery, by combining intra-operative images (CT, MR, US, Video) with pre-operative images.

The competition in this field is heavy and the market has not taken off as quickly as was estimated several years ago. In order to limit the development costs, several companies merged their image-guided surgery activities in the Surgical Navigation Network (SNN). Philips joined SNN in October 1998. The aim of SNN is to come to an open-standard, multi-vendor, modular, plug-and-play image-guided surgery platform.

Philips Medical Systems introduces the achievements of the EASI project and other related work as much as possible into SNN.

PMS is currently focusing more attention to the combination of intra-operative imaging (e.g. mobile CT, interactive MR, X-ray, ultrasound and video) and image-guided navigation.

Acknowledgements

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EASI project partners

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EASI project web site

http://home.planet.nl/~frans.gerritsen/EASI/EASI.html

Biography

Frans A. Gerritsen was born in 1953 in Balikpapan (Borneo, Indonesia). He has been working in the field of image processing since 1975. He obtained his Ph.D. degree in Applied Physics from Delft University of Technology in 1982 on the subject "Design and Implementation of the Delft Image Processor DIP-1", a pipelined array processor tuned for image processing. Between April 1981 and 1984 he worked at the NLR National Aerospace Laboratory in Amsterdam in the fields of Digital Cartography, Remote Sensing and F-16 Mission Planning.

In April 1984 Frans joined Philips Medical Systems (PMS), where he worked in the fields of Magnetic Resonance system architecture and reconstruction software. In 1986-91 he was one of the pioneers laying the groundwork for what later became the EasyVision family of clinical viewing/analysis workstations.

Since 1991 he is the chief of the EasyVision Advanced Development group. At PMS this group is responsible for working with affiliated contract research and clinical application sites to develop and validate innovative and robust prototypes of future EasyVision products.

In the period 1992-1994 Frans was responsible for managing the contribution of PMS to the EC-sponsored COVIRA project, with R&D in the field of computer vision technology in radiological workstations. In the period 1996-1998 he was project manager for the EC-sponsored EASI project, with R&D in the field of surgery planning and intra-operative navigation for minimally invasive neurosurgery and aortic surgery.

Frans is a member of the board of the Dutch Society for Pattern Recognition and Image Processing (NVPHBV) and editor of its web-based newsletter.