An Image Processing Environment for Guiding Vascular MR Interventions*

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Abstract. MRI offers potential advantages over conventional X-ray techniques for guiding and evaluating vascular interventions. Image guidance of such interventions via passive catheter tracking requires real-time processing of the dynamically acquired MR slices and advanced display facilities inside the MR examination room. Commercially available clinical MR-scanners currently do not provide this functionality.
This paper describes a processing environment that allows near-realtime MR-guided interventions. Two stand-alone workstations connected to our MR-scanner offer a flexible and fast tool for guiding the interventionist without affecting the stability of the MR-scanner. The paper describes and discusses our approach, including image processing techniques. Results of a phantom balloon angioplasty experiment are presented.

1 Introduction

Magnetic resonance imaging (MRI) offers several advantages over conventional X-ray imaging, and has therefore received interest recently for guiding and monitoring interventional procedures such as biopsies and thermal tumor ablation. Since harmful contrast agents are not required for MR imaging of vasculature, and functional information can be provided, for instance with regard to flow and capillary perfusion, it is potentially also an attractive modality to guide intravascular interventions [1].

Two approaches for image guidance of intravascular MR interventions have been advocated, *viz.* active [2] and passive tracking. In the latter approach, the catheter is located by processing of the dynamically acquired MR images. This method requires dedicated intravascular devices that are visible in the MR slices,

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but do not contain any conducting material. In order to show the feasibility of MR-guided balloon angioplasty with passive catheter tracking, we developed MR-compatible guide wires and catheters that are locally impregnated with dysprosium oxide [3]. These areas of increased susceptibility cause artifacts depicted by small signal voids in the MR image.

During an MR intervention slices are acquired dynamically, *i.e.* every image is processed and displayed immediately after acquisition. Hence, image processing techniques should allow fast (within 1 sec.) localization of device markers in MR slices. However, commercially available scanners do not support any complex image processing of dynamic scans. Therefore, near-real-time image processing was achieved by building an image processing environment separated from our MR-scanner (Philips Gyroscan ACS-NT15), and connected via Ethernet.

Several other groups followed a similar approach using add-on systems for attaining real-time MR imaging ("MR fluoroscopy") [4–8]. Most of the reported systems were developed to achieve real-time reconstruction or low-level processing of image data, and hence often require specially designed hardware that is dedicated to these tasks. Although these systems can receive, reconstruct and display multiple images per second and thus achieve considerably higher refresh rates, they focus on specific fast sequences like EPI and spirals, where –in contrast with our sequences that supply images at a rate of maximally one per second– reconstruction is a fundamental bottleneck.

Our environment has been developed with the intent to enable passive catheter tracking by rapidly feeding the acquired images to image processing algorithms. Since, we focus on a direct clinical application, the system was designed such that it guarantees stability during *in vivo* MR interventions. It offers sufficient performance for our purposes and flexibility with regard to image processing functionality to be developed. It employs the graphics hardware of low-cost, non-MR-dedicated workstations for fast visualization.

2 Environment

An image processing environment for MR-guided intravascular interventions should meet three requirements:

1. The scanner stability must be preserved. Major modifications to the scanner software are thus not acceptable.
2. The environment must have a high degree of flexibility, allowing new visualization and device tracking algorithms to be easily implemented without affecting the stability of the system.
3. An in-room, MR-compatible display close to the scanner bore is required. Remote control from outside the examination room must be possible.

To preserve the stability of the MR-scanner, a Direct Reconstructor INterface (DRIN) was installed on our scanner. This minor and safe extension to the reconstructor software uses a TCP/IP protocol and allows connected clients to receive either modulus, phase, real and imaginary images in both spatial and frequency domain, including the associated acquisition parameters. We use the local network to connect our systems to the scanner reconstructor.

2.1 Hardware

Our image processing environment consists of two O2 (Silicon Graphics, Inc.) UNIX workstations. One –the "master"– is located in the operator room adjacent to the MR examination room and is equipped with an R10000 processor acting as a client of the DRIN server. The console is a standard color monitor. The workstation ("slave") located in the MR room is a diskless R5000 O2, which boots from the master via Ethernet. It displays on a 13" inch 18-bit 1280 × 1024 color LCD (Presenter 1280, Silicon Graphics).

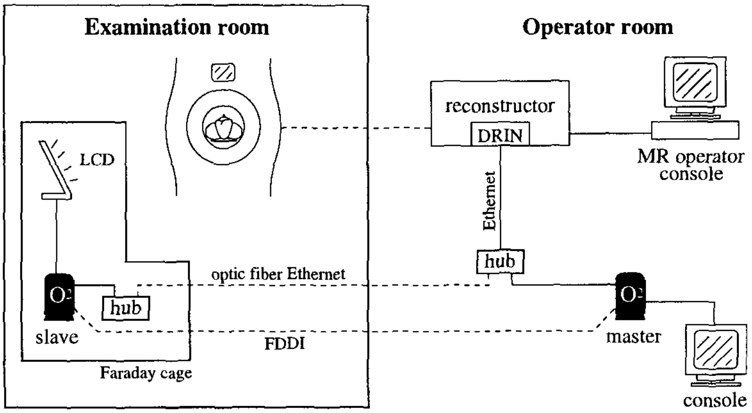

Fig. 1. Hardware environment; O2 workstations communicate via optic fiber connections. Raw image data are first transmitted to the master via Ethernet, and next to the slave via FDDI.

Radio-frequency radiation emitted by the LCD and the slave was avoided to interfere with the MR signal by Faraday caging them (fig. 1). Data communication with the master was established via optic fiber connections. An optic Ethernet connection (10 Mb/s) between both workstations allows booting of the slave with remote control from the master. Image data are transferred from the master to the slave via a much faster optic fiber connection (Fiber Distributed Data Interface (FDDI), 100 Mb/s), which guarantees minimal data transport delay between both systems. Although the slave might also login at the DRIN server for retrieving image data, this would considerably increase Ethernet load, thereby decreasing performance.

2.2 Software

In order to achieve the required stability, flexibility and performance, the implementation was performed by event-driven, object-oriented programming with a Tcl/Tk [9] user interface. Several C++-objects were implemented that encapsulate data receiving from DRIN (DrinClient, see fig. 2), communication between the O2 workstations (Server and Client), image storage (Storage), and visualization (Display). The DrinClient object receives the acquired images in data

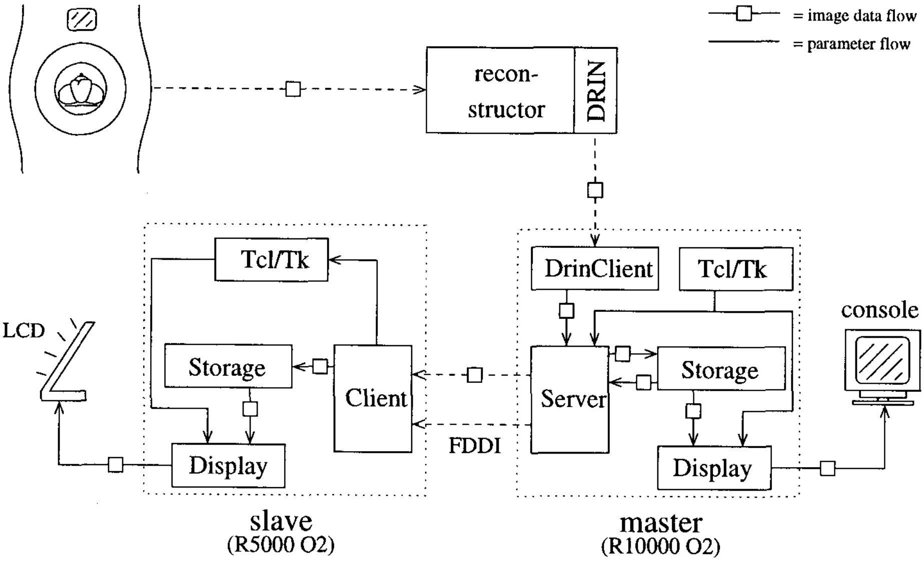

Fig. 2. Software environment; data packages from DRIN are received by the DrinClient object and immediately sent to the slave via the Server–Client FDDI connection. Display parameters are also transmitted via this connection.

packages of 8 KB from DRIN. These packages are immediately transmitted to the TCP/IP-based Server object, which distributes them to the connected Client objects.

The event-driven approach of Tcl/Tk ensures fast and appropriate handling of interrupts from communication ports. Inter-object communication is also entirely performed by the event mechanism. Since all tracking and visualization algorithms are encapsulated within the object Display, extensions and modifications to these algorithms do not involve other objects, thus conserving their stability. This guarantees flexibility and stability of the software. The graphics hardware of the O2 systems is exploited by using the OpenGL library [10].

Events are handled in sequence of priority. In order to achieve a minimal delay between data acquisition and visualization in the MR examination room, events related to image data transfer from DRIN to the slave have a high priority level. Display and storage of newly received images on the master have lower priority and are thus only started after the completion of data transfer to the connected clients.

The slave is controlled from the master by the operator. Therefore, modified display parameters (*e.g.* for window-leveling, zooming) are copied immediately to the slave via the Server–Client connection. This guarantees identical displaying on both systems. The Tcl/Tk script interpreter also permits on-the-fly execution of script code on both systems for changing the operation of the systems, which makes them highly flexible and facilitates development, testing and experimenting.

2.3 Image processing

An MR-guided intervention procedure is preceded by a series of scans for (i) localization of the stenosis and specification of the scan planes, (ii) quantification of the pre-operative flow through the stenosis, and (iii) a 2D phase-contrast (2DPC) acquisition with a geometry identical to the dynamic scan series. This 2DPC image brightly depicts the vasculature that the interventional devices are likely to pass (fig. 3a). It is therefore suitable to indicate the positions of the located devices. We call this a "roadmap", similar to the contrast-enhanced roadmap image for conventional X-ray interventions.

The actual intervention is carried out using a dynamic gradient echo technique. Images show small regions of marker-induced decreased signal intensity (fig. 3b). Subtraction of a previously acquired reference image can improve visualization of the device markers (fig. 3c). This operation is available in the graphics hardware of the O2 systems. Motion artifacts reduce the quality of the subtraction, but can be overcome partly by the selection of a new reference image by the operator after a substantial patient movement.

For guidance of the interventionalist during the positioning of the intravascular devices, information on the locations of the markers as contained by the subtraction image should be combined with the morphologic information of the vasculature. Therefore, we first color the roadmap (fig. 3a) red. Next, the subtraction image is inverted, thus yielding white markers, which is finally merged with the roadmap image by applying alpha-blending [11]. We call the result the "overlay" image. All required image processing operations were implemented using the graphics hardware, and thus are very fast.

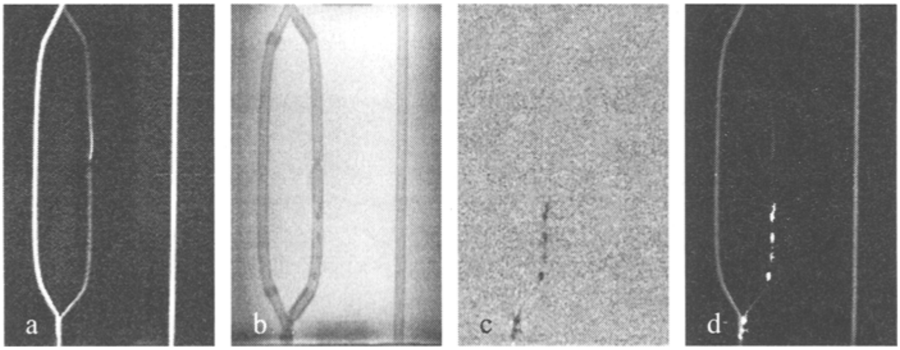

Fig. 3. (a) 2DPC image of a flow phantom, which serves as a roadmap during the intervention; (b) dynamically acquired modulus image containing five dysprosium markers in the lower part of the middle tube; (c) result after subtraction of a reference image; (d) overlay image; in reality, the vasculature is colored red and the markers are white.

3 Results

Our imaging set-up provides near-real-time image guidance of MR interventions with a refresh rate of one image per two seconds. Acquisition of each MR image takes approximately one second. Image data transfer between DRIN and the master takes 0.7 second. The latency introduced by the data transfer to the slave is negligible as a result of the division of the image in small data packages and the fast FDDI connection. Image processing and display takes approximately 0.3 second for a 1024^2 overlay image. Modulus images of a dynamic scan series can also be displayed by the LCD at the scanner front within 0.5 seconds after acquisition, but any image processing of these images is not possible.

Image guidance using the overlay technique was tested during an *in vitro* interventional MR procedure. A 6 mm flexible plastic tube loop with a dilatable stenosis was connected to a flow system and taped onto the forearm of a volunteer. This experiment allowed us to practice a clinical application of MR-guided balloon angioplasty in patients with an obstructed hemodialysis access graft under realistic conditions with regard to patient positioning and sterility issues (fig. 4).

4 Discussion and conclusions

We have demonstrated that near-real-time imaging for MR-guided interventions can be achieved with a stand-alone, non-MR-dedicated workstation containing graphics hardware. Delays introduced by the described image processing and visualization do not considerably decrease refresh rates as compared with those currently achieved for dynamic scan series on a commercially available MR-scanner, whereas these scanners do not provide dynamically available advanced image processing functionality for accomplishing intravascular interventions.

Scanner stability, which is an essential condition for a clinical application, is conserved by the high degree of independence of the developed environment. Flexibility is also achieved by this approach, where development and implementation of visualization and tracking algorithms do not involve the scanner software, and thus do not require modifications by the manufacturer. The environment seems also suitable for the development and testing of new image processing algorithms required for new imaging techniques like perfusion, diffusion and functional MRI.

Visualization inside the MR examination room was accomplished by placing a diskless slave workstation and a LCD in the MR suite, encapsulated in a Faraday cage in order to avoid RF interference. Although visualization inside the examination room from the outside by means of a projector is emerging as a good alternative, it was not considered an appropriate solution for our purposes because of the required image resolution and the specific construction of our MR suite. A second computer outside the MR suite is required for booting of the diskless slave, and for control by an operator. Current image processing is entirely performed by the graphics hardware of both systems.

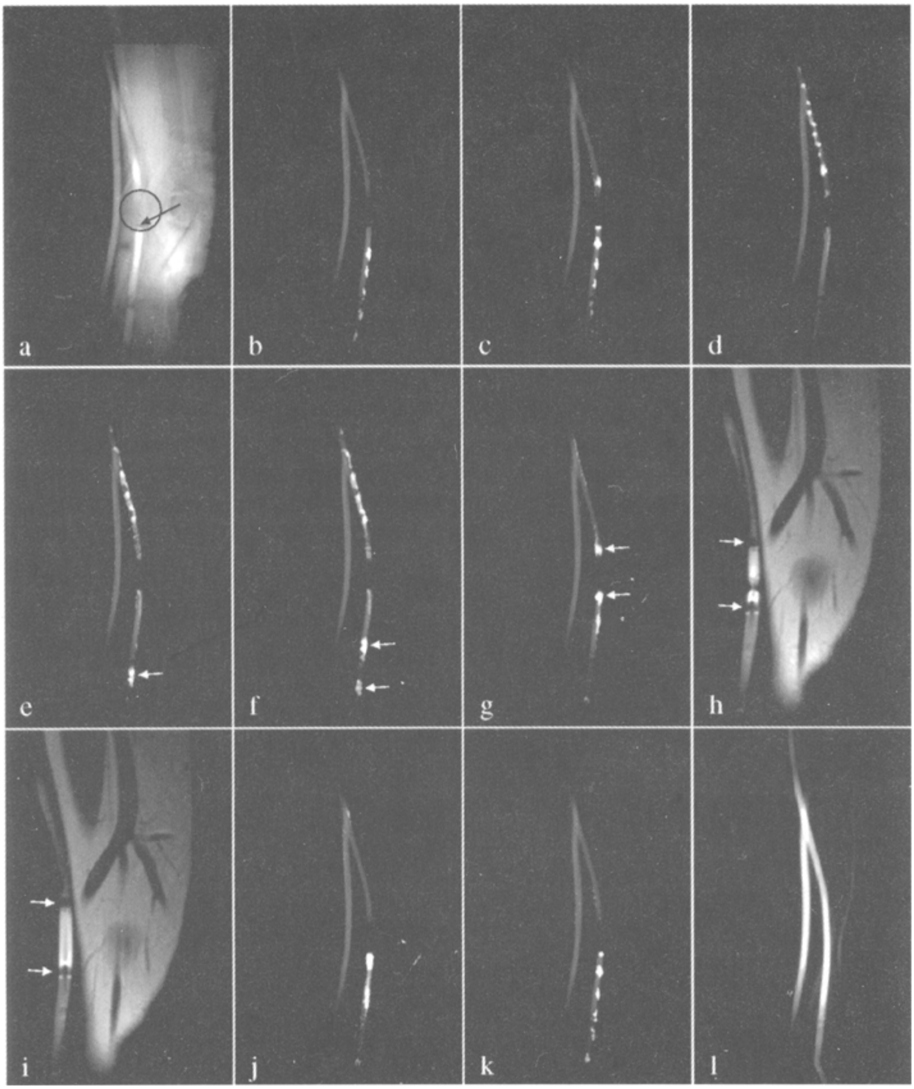

Fig. 4. Results of an *in vitro* MR-guided balloon angioplasty. (a) First modulus image of the dynamic scan series depicting the phantom (two tubes) taped onto a forearm; the stenosis (arrow) in the right tube, which is superimposed on the arm, causes a signal void distally (circle). (b-d) Introduction of the guide wire (seven markers); in the region of the signal void, markers are not visible. (e-g) Introduction and positioning of the balloon catheter (arrows) across the stenosis; the guide wire has been moved further distally in (g). (h,i) Balloon inflation with Gd-DTPA doped water causes the stenosis to dissolve (visualization performed by a spin-echo sequence with a different geometry); markers are indicated by arrows. (j,k) Catheter and guide wire are withdrawn. (l) Post-operatively acquired 2DPC image with recovered tube lumen.

The overlay technique provides morphological information of the patient's vasculature as well as the location of the stenosis and the marker positions of the invasive devices. Therefore, it sufficiently supports image guidance of MR interventions in simple vasculature such as in human limbs. However, three-dimensional coordinates of the tips of these devices are not yet explicitly calculated. This is essential for steering the scanner by automatic modification of the scan plane in order to allow vascular interventions in regions of complex three-dimensional vasculature like the brain. Therefore, advanced tracking algorithms are required, which are currently being developed in our group. As a consequence of the object-oriented programming of the image processing environment we described, incorporation of these algorithms without affecting stability is straightforward. The extra computational capacities of the master might be used by these tracking algorithms, while the slave can focus on rapid visualization.

Our image processing environment has convincingly demonstrated its potential for guiding balloon angioplasty procedures in phantom experiments, and allowed us recently to start the *in vivo* application of MR-guided balloon angioplasty on clinical patients with a hemodialysis access graft obstructed by a stenosis. We expect to successfully perform an MR-guided intervention on a patient within some months.

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