4.5.4 3–D ecography to MR registration

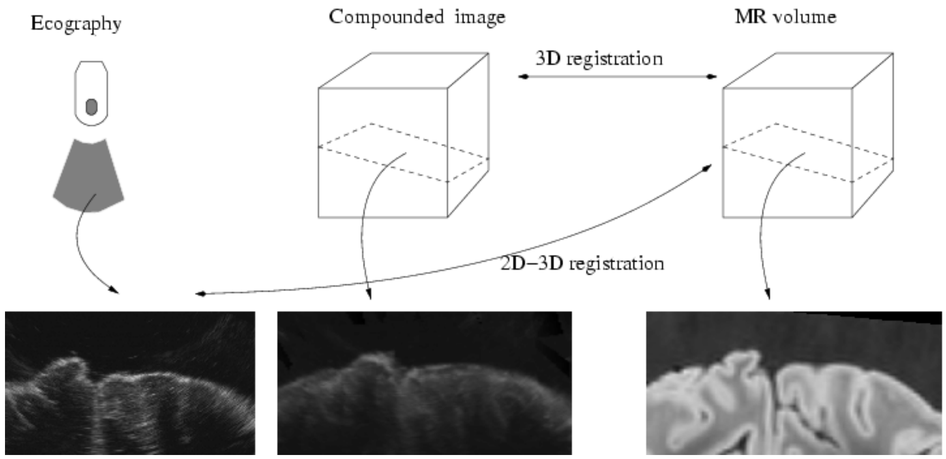

Figure 4.35: Scheme of the coordinates systems from the video image to the registered MR volume

The experiments described so far have been working with ultrasound images only. The goal was to spatially compound a correct *us* volume from frames captured while moving the transducer in a free-hand format. Having the whole content of the brain scanned is normally not feasible for normal neurosurgery operations, because the perforation hole in the skull is minimal, and the resulting field of view contains only a small adjacent area.

However, it is part of the operating protocol to have an MR scanner of the patient before the operation. Then, the following issue arises: if we could have some estimation of the position of the ecographic image in the head, then we could relate it to the preoperative MR volume, and perhaps it could be feasible to correct the contents of the latest to account for the intraoperative sinking of the brain.

Figure 4.35 shows the scheme of this process. We need some procedure to relate preoperative MR volume images to the position of individual slices given by the tracker. We have already seen in section 4.5.1 that this could be made by means of a bite-block attached to the teeth of the patient and locatable both in the MR scanner and in the tracker coordinates. This procedure, however, is not retrospective: the MR has to be acquired with the patient wearing the dental landmarks.

Initially, we planned this correspondence to be made in the operating theatre by means of some registration procedure. Since in normal operations only a small part of the brain can be imaged with ecographies, the registration would use instead the shape of the head acquired with the ecographer, or perhaps a set of manually pointed landmarks. This was not possible, of course, with the brain in vitro.

Then, the alternative approach was to register the ecography volume with the MR image similarly to the registration of any pair of 3D images. After the correspondence

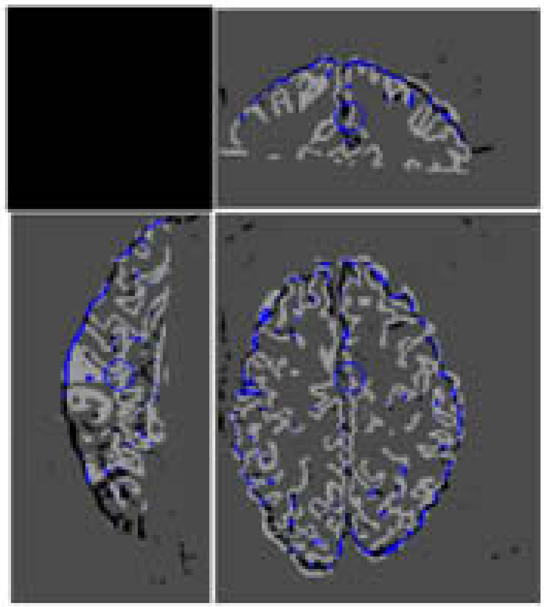

Figure 4.36: Orthogonal view of creases after registration; overlapping features appear in blue, MR creases in white and *us* creases in black.

had been computed, the coordinates of the individual slices could be related first to the ecography volume and then to the MR image.

For the purpose of volume ecography to MR registration, there was a good chance that the algorithm already tested for CT to MR registration could work. The only novelty was, this time creases would not be set to detect the skull but to detect the brain convolutions, so-called gyri and sulci.

Achieving a proper segmentation of the sulci is itself a recurrent subject amongst literature. Early papers [18] propose a manual identification by means of an adequate visualisation of the shape, and then the extracted landmarks are employed for brain registration [17]. Automatic segmentation can be achieved by a variety of methods: [6] iterates a deformable surface model to find the central layer of the thick surface of the white matter. Similarly, in [63] the author proposes a boundary model to segment the arachnoid (the membrane which follows the brain structure). A morphological process, followed by watershed segmentation, is proposed in [49] with the aim of automatically label the whole sulcal structure. Finally, [24] identifies the boundaries as voxel not clearly belonging to any tissue after running a classification algorithm.

Our aim was simpler than achieving a perfect segmentation of the sulci. We only needed the segmentation to show enough structures common to both images to make the comparison possible. This was not difficult for the MR image, but for the 3D US the segmentation had to cope with high levels of noise, and also to missing and overlapping features. The creaseness operator proved to work well under these conditions, and the only additional operation required was to discard features out the borders of the brain (after masking with a dilated threshold of the image).

We believe the registration to be very accurate for the three experiments, furthermore after considering the quality of the images. See in figure 4.36 that creaseness images were a good choice for the purpose of registration: most creases in the US image (in black) actually match (in blue) those corresponding in the MR volume (in white). This occurs specially at the top slices where the US image gave better signal.

Check as well in figure 4.37 that the original volumes are also visually aligned. Despite the gaps in the image, the shape of the two images is very similar. We have chosen views at the extreme location in the brain to show the most unfavourable case, as misalignments would appear here more clearly.

Note that sulci appear much less clearly in the *us* image than in the MR image. The reason is that small sulci appear as white areas instead of depicting black, empty areas, because the signal is partly reflected back at these points.

There is another interesting visualisation, which makes use of the whole system of transformations: it is possible to locate each B-frame into the MR volume, and thus to present its corresponding MR slice. See in figure 4.38 the accuracy demonstrated despite various possible sources of error in the positioning:

- M_U^R Calibrating the position of the transducer with respect to the receiver.
- M_R^T Position and orientation errors of the magnetic tracker.
- The error in the registration of the *us* volume to the MR image.

The accuracy of this registration inspired another application: to use the MR image as the reference image to correct possible inaccuracies of the tracker. This idea is explored in the next section.

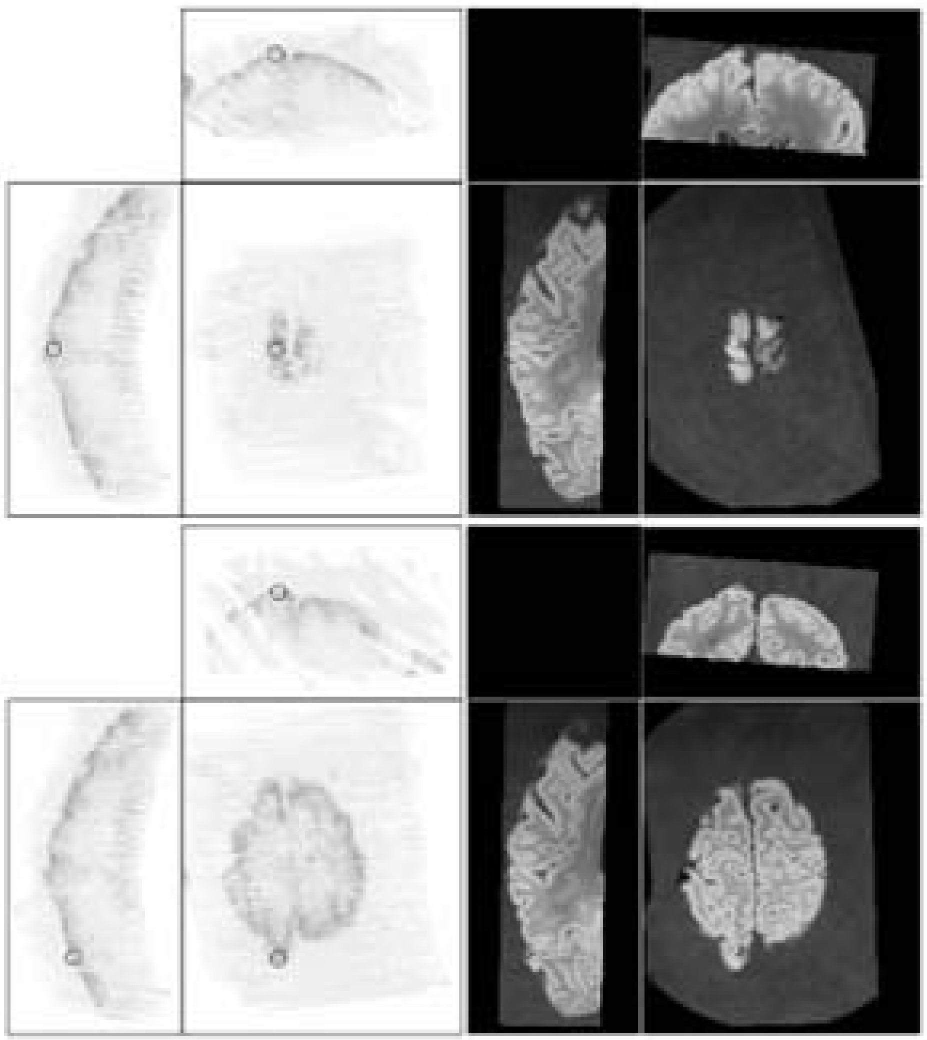

Figure 4.37: Two corresponding views of US (left) and MR (right) after registering the two volumes.

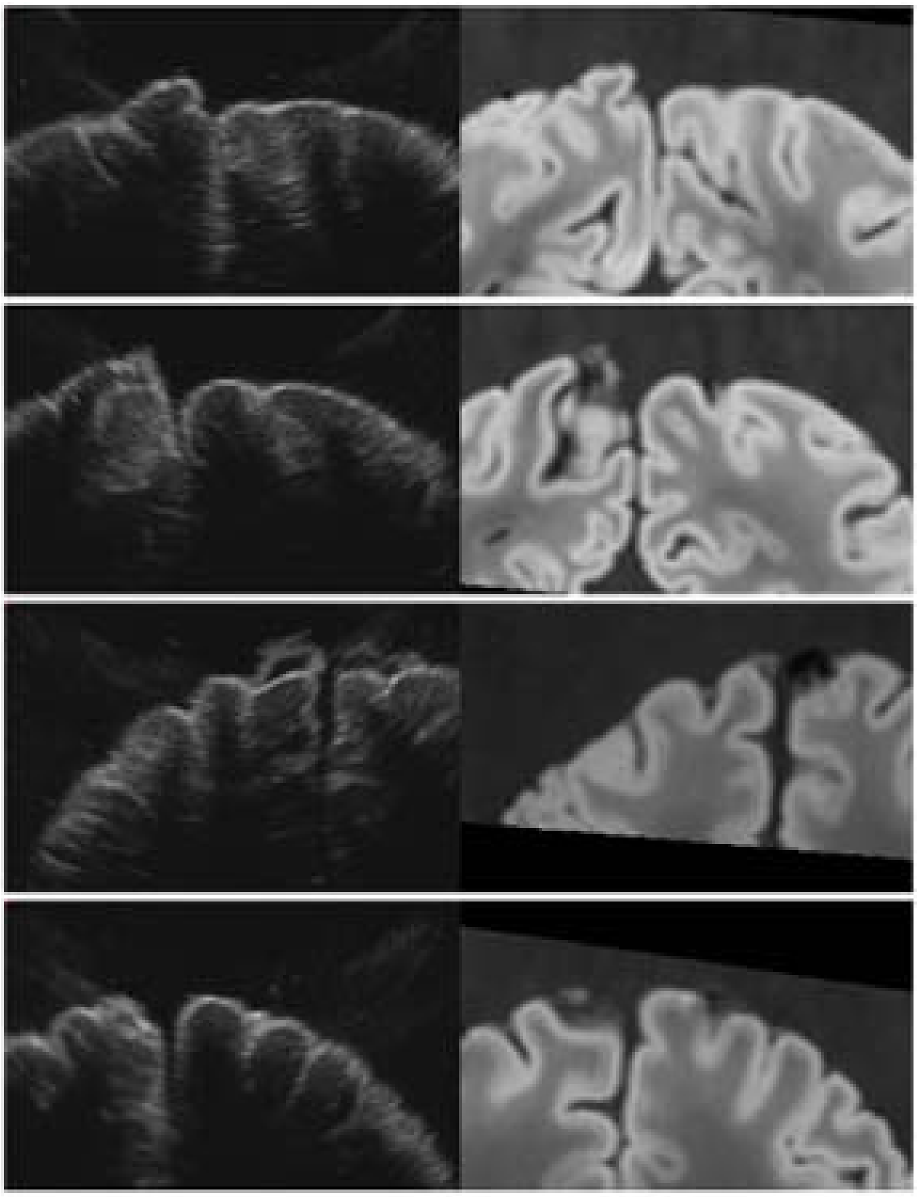

Figure 4.38: The accuracy of the registration is better estimated after presenting the original ecography slice (left) together with the corresponding slice in the MR volume (right). (experiment C)

4.5.5 Live ecography to MR registration

In the previous section we have managed to relate the coordinates system of the ecographies to the MR volume, by means of an automatic algorithm. We have seen in a previous section that the position of the transducer could be corrected after a 2D–3D registration with the compounded cuberille. We propose to perform a similar process but this time employing the MR image as reference.

The purpose of the registration process in this section, rather than correcting the position, is to demonstrate that the possibility to modify the contents of the MR volume according to the information given by the live video frame. For that case, and contrary to that now assumed, the position of the transducer would be taken as the reference, and our assumption would be that the contents of the brain have shifted their position and thus the MR image is no longer valid.

Of course it would have been interesting to produce some sort of deformation in the in-vitro brain, and then see if we could update the previous MR volume to agree with the data currently provided by the *us* sampling. But this modification was not possible without a permanent damage of the specimen, which was out of the question because we did not own it.

A number of papers have studied the problem of the sinking of the brain; only in the past three years, citations include about 30 papers. Here our goal is again simpler: to achieve some indication that a 2–D ultrasound to 3–D MR registration is feasible if a proper initial guess is given.

One restriction of our algorithm is that there has to be a number of structures common to both image for the registration to succeed. Since we will be using the same algorithm as in section 4.5.3, if the contents are too dissimilar the initial search will fail and the algorithm will not converge. Of course, this restriction could be cancelled if another strategy would be designed for this initial search. This is currently beyond our goal for this chapter, but still it is interesting to see how well the algorithm is able to match the two images.

Once the set of transformations (one for each frame) has been computed, the MR volume should be deformed accordingly. This is a case very similar to that reported for 2D in appendix D, already used for local deformations of retinographies. The only difference, in addition to the 3D, is that now the landmarks are not regularly distributed along the image, so the interpolation scheme would need to search for each voxel the nearest landmarks, and weight the contributions accordingly. Also, before applying the deformation possibly some filtering should be applied to the list of transformations to discard those non coherent with their neighbours.

We have run the same algorithm as in previous section, this time to register 2D ecographies to MR volumes. We must point out that features appearing in both images, despite corresponding to the same region, are often very dissimilar and, more disturbingly, not following a regular fashion.

For instance, void spaces forming the sulci appear in dark when distance is large, but in bright white if the distance is small. Again, extracting the creaseness helped a lot to normalise the images; to eliminate the effect explained above, both valleys and creases were used for landmarks.

Figure 4.40 depicts the result of the registration process for a number of samples.

The algorithm works reasonably well, specially when the image has many features. Other times, same as it happened with the 2D to 3D US registration, the algorithm can't find a suitable matching and converges instead to a region with creases.

We have labelled the registration for all B-scan in the three experiments, following the same criteria as section 4.5.3. This time the statistics are worse, for often there were not enough common features to permit convergence. Still, the numbers follow a pattern similar to those of the previous sections: smaller fields of view achieve worse results. For all cases, at least 1 of every second frame was properly registered.

We present two sets of samples, 4.41 and 4.40, for successful and not successful registration of experiments A and C. See that the algorithm is able to find even small overlapping features, which is the usual case because *us* and MR images are very different. On the other hand, sometimes there is not enough information to permit a proper match, or it is misguided by some large artifact. This latest case is specially difficult to solve, because there is no way to distinguish it from a proper convergence. As a future work, an automatic classification criteria could employ the morphological thinning operator to discard large size surfaces from other true, wire-like, creases.

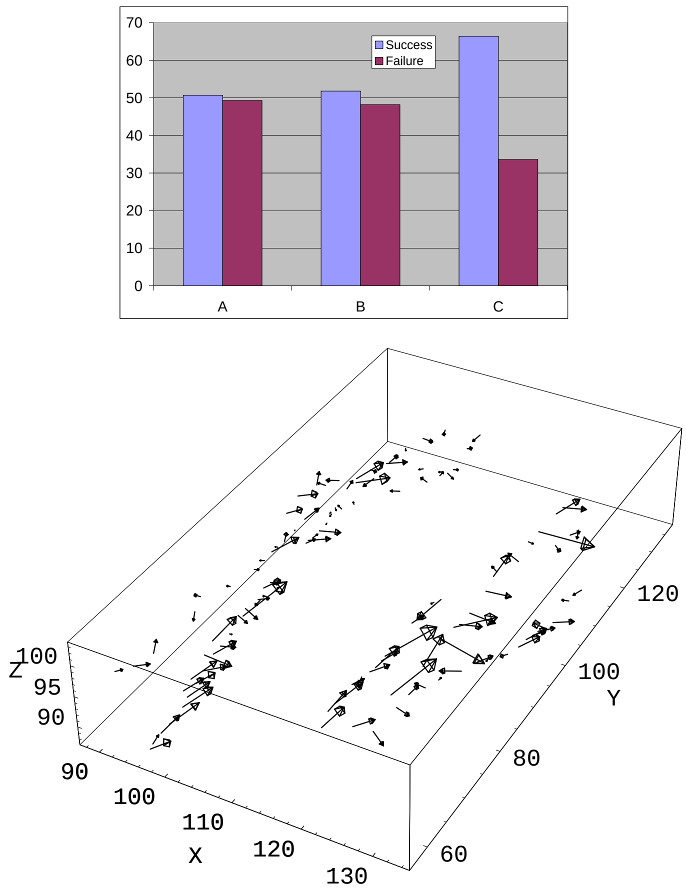

Figure 4.39: Top: Percentage of successful and failure registrations for experiments A, B, C. for *us* to MR . Compare with table 4.28 in page 175. Bottom: the values of the transformations, depicted as an arrow with the origin on the middle point of the B-frame and the target on coordinates after applying the correction.

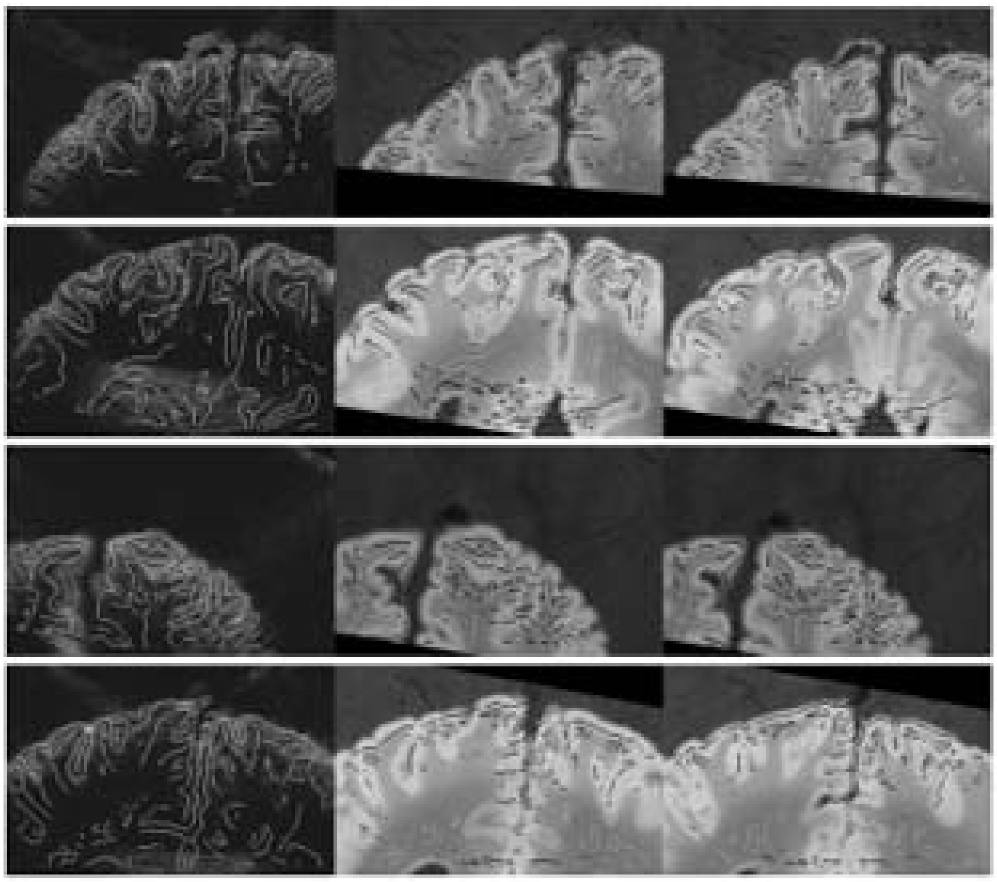

Figure 4.40: The accuracy of the registration is better estimated after presenting the original ecography slice (left) together with the corresponding slice in the MR volume before registration (middle) and after registration (right).

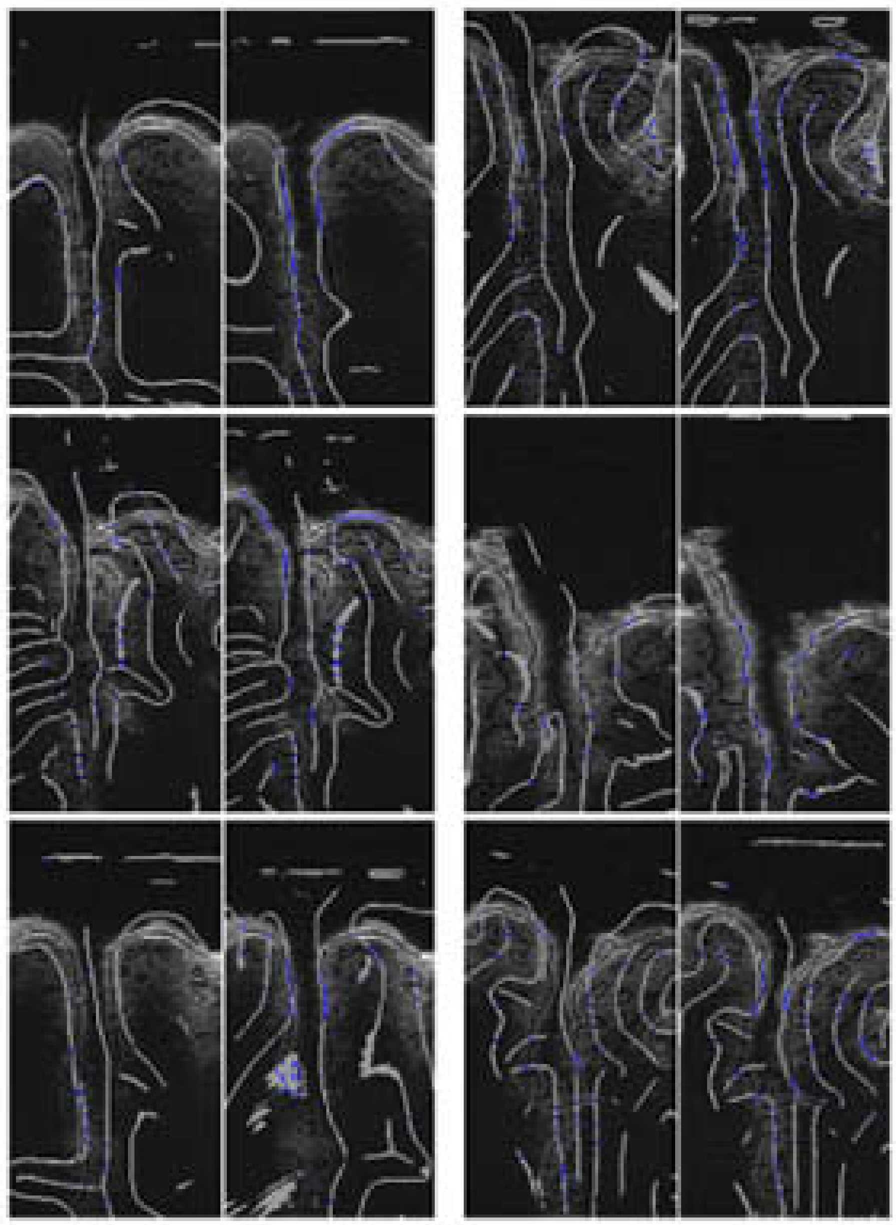

Figure 4.41: 2-D to ecography volume registration with the 6.5 MHz transducer. Each picture depicts ecography with the creases overdrawn, without registration (left sub-image) and after registration (right sub-image). Lines in blue show proper matching. First two rows: successful registrations. Last row: wrong registrations, due to large crease surfaces. (see text for details)

4.6 Conclusions

The measure of intraoperative brain deformation is today an active area of research. The reason for its popularity is that potential benefits are enormous, and also that the necessary equipment is available.

Our contribution to this subject, being the work of only one person in one year, has consisted primarily on several proposals and ideas, some not fully explored yet due to lack of time. Not a small part of the total work has been devoted to items which are absolutely necessary but of a more technical than innovative nature, and therefore they have not been fully described here. This is the case of the design and implementation of the software to grab the video images and track the transducer. The code of this software lengthened 27000 lines, written in Microsoft Visual C++.

Another technical issue which needed special attention has been the calibration of the ultrasound device. Although the literature regarding this is wide, finding a scheme which would work with our equipment has been lengthy: we have built various phantoms for this purpose (one a novel approach), and we have investigated the influence of several statistical issues regarding the final accuracy: the scaling of the variables, and the condition number of the problem matrix Σ (page 232). As the result of this investigation, we have obtained a phantom and a protocol to achieve a calibration with predictable accuracy.

A major drawback in the progress of our investigation has been the lack of an ecography device available at a reasonable basis. For this reason, most experiments were performed in a very short scheduling. One initial result was the demonstration of live correspondence between the ecographic video sequence and the MR volume image of the same patient. The transformation between both coordinate systems was achieved by means of a dental marker, which has been an interesting proposal in order to enhance the information available to the surgeon during the intervention.

The next goal has been to set a system similar to the previous one without the need of the dental marker. Instead of it, we planned to employ as anatomical landmarks the sulci of the brain, because they are visible in both modalities. To investigate this idea we borrowed an in-vitro adult human brain and scanned in the free-hand paradigm. Also, we imaged the volume it in an MR device. After, the first step has been to compound the sequence of *us* images to build a volume image and register it to the MR volume. The registration has been made with the algorithm already studied in chapter 2. We ran it unmodified except for the parameters of the creases, which were set now to detect the sulci. The accuracy achieved has been very satisfactory for all datasets. One object, however, must be raised: the registration made use of the whole volume as it has been fully scanned, but this is unfeasible given the small diameter of most craniotomies and the restricted field of view of the transducer. Therefore, it remains as a future work to investigate the convenience of the algorithm for this restricted area.

A novel proposal we made was the correction of the errors in the position of the transducers given by the locating device. The idea is to self-register each individual frame to the compounded volume using a 2D–3D version of the creaseness-based algorithm. The creaseness operator proved again to be able to detect similar landmarks appearing in the *us* frames and volumes, so only a few modifications had to be made:

the initial search would be done in 2D in order to avoid local maxima, and the large creaseness volume had to be stored in a 1 bit/pixel format to permit its storage in memory.

The same procedure has been applied to register the B-scans to the MR volume, but now our goal has been different, for we wanted to correct the MR volume according to the values of the registration. In effect, intraoperative ecographies would depict the shift produced in the brain by the intervention, and the MR volume could be updated accordingly. We have run the registration algorithm for all the datasets, and validated the results manually. Now, the next step would be to update the MR image. For this purpose, the centre of each registered frame can be considered as a landmark with an initial and a corrected position. Then, given the list of landmarks, the MR image can be updated with a 3D version of the algorithm presented in appendix D.

The interpolation scheme would be slightly different because the landmarks are not distributed uniformly along the volume. In addition, some sort of filtering would be necessary to discard incoherent transformations. Finally, it remains as future work to investigate if the algorithm could cope as it has been designed with large values of misregistrations produced by the sinking of the brain, or perhaps some broader search should be added.