Virtual Navigator Automatic Registration Technology in Abdominal Application

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Abstract—**Real-time Ultrasound (US) image fusion with a pre-acquired second imaging dataset - Computed Tomography (CT), Magnetic Resonance Imaging (MRI) and/or CT/PET - has become widely used in recent years for both diagnosis and image-guided interventional procedures. Liver and kidneys are the main focused anatomical districts, related to abdominal application.**

There are still nowadays some drawbacks, regarding the adoption of the fusion imaging technique in everyday practice especially regarding its ease of use and the time needed in order to obtain a precise real-time fusion between US and the second imaging modality.

The present work is a preliminary study on the feasibility and practical use of an Automatic registration algorithm for CT-US real-time fusion imaging. Data obtained by tests performed on a Doppler phantom, for the assessment of the precision of the registration procedure and in-vivo Automatic registration tests, are presented.

I. Introduction

In recent years real-time Ultrasound (US) image fusion with a pre-acquired second imaging dataset - Computed Tomography (CT), Magnetic Resonance Imaging (MRI), and/or CT/PET [1,2] has become widely used in both diagnosis and image-guided interventional procedures, with liver and kidneys as the main focused anatomical districts of abdominal application. [3-11]

There are two major drawbacks up to today regarding the adoption of the fusion imaging technique in daily clinical practice: first, the necessity to manually perform the registration procedure between US and the pre-acquired second imaging volume dataset; second, the necessity to maintain the patient steady after the registration procedure. The latter was recently solved by the introduction of a proper Motion Control Sensor [12-14], which counteracts the patient's voluntary or involuntary movements after the registration procedure, the former is the topic of the present work.

Slow adoption of the fusion imaging technology in daily clinical practice can be also imputed to the complexity of the user interface and practical workflow of the fusion imaging tools, but they are continuously and daily improved in terms of features and ease of use to overwhelm this difficulty.

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The present work is a preliminary study on the feasibility and the performances – in terms of precision and requested time- of an Automatic registration algorithm for CT and US real-time fusion imaging. Data obtained by in vitro tests performed on a Doppler phantom, assessing the precision of the registration procedure, and in vivo Automatic registration tests on liver district, are presented.

II. Materials and Methods

A. Study population

Nine subjects (6 males, 3 females; age range: 53-87, mean age: 68), scheduled for percutaneous thermal ablation of liver lesions, underwent CT - US fusion obtained using Automatic registration.

B. Methods of examination

CT examinations were carried out by a HiSpeed CT (GE Medical Systems, Milwaukee, Wisconsin, U.S.A.), slice thickness = 5 mm (2.0x2.0 mm in-plane resolution), CT images were acquired in expiratory breathing phase, as percutaneous thermal ablations are generally performed in this condition. Subsequently, real-time image fusion of US and pre-acquired CT data was performed using an US system (MyLab Twice, Esaote S.p.A. Italy) equipped with Virtual Navigator (VN) option [15]. CT data were transferred in DICOM format to the US system through a DVD support or a LAN connection, query/retrieving hospital PACS system (IMPAX 6, Agfa Healthcare NV, Mortsel, Belgium).

Automatic registration algorithm tests were first carried out and tested for precision through dedicated in vitro tests, performed with a US Doppler phantom (Model 453, Dansk Fantom Service, Frederikssund - Denmark). The phantom CT scan was performed injecting a proper CT contrast agent (Iomeron 350, Bracco S.p.A., Milano, Italy) in the blood-mimicking fluid present in the Doppler phantom, in order to be visible on the CT acquisition. This CT evaluation can be considered equivalent to the one used for the in vivo tests, for the purposes of this work.

For in vitro tests a US linear Array probe (Operating Bandwidth: 3- 11 MHz; CFM-PW Frequencies: 3.1-3.6-4.2-5.0-6.3 MHz, LA332, Esaote) and a reusable tracking bracket with sensor mounted (639-031, Civco Medical Solutions, Kalona, Iowa, USA), were used.

For in vivo tests a US convex Array Probe (Operating Bandwidth: 1- 8 MHz; CFM-PW Frequencies: 1.9-2.1-2.3–2.6–3.3 MHz, CA541, Esaote) and a reusable tracking bracket with sensor mounted (639-041, Civco Medical Solutions, Kalona, Iowa, USA), were used. The appleprobe

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design of these probes allowed a dual-possibility hand grip, pinch and palmar grip, in order to provide a neutral wrist position. This represented an operator's additional comfort, considering that the whole treatment procedure could be prolonged, especially during the phases of planning, execution and monitoring of the treatment. [16]. The linear probe instead of the convex probe was selected to perform in vitro tests due to US Doppler Phantom limited width, which didn't allow the convex probe to fit its surface and to obtain a compete coupling between the transducer and the US Doppler phantom surface.

Virtual Navigator fusion procedures were allowed by an electromagnetic tracking system, composed by a transmitter and a small receiver, mounted on the US probe. The transmitter's position, which is the origin of the reference system, was fixed by a support and the receiver provided the position and the orientation of the US probe in relation to the transmitter in the created 3D space. The electromagnetic field source tip was oriented to point to the phantom, in order to address the highest intensity of the created field to the US scanning area. A non-metallic table was used to reduce interferences as much as possible. Before starting, a check of the accuracy of the electromagnetic field was performed: the same point coordinates were measured twice by a dedicated registration pen with the electromagnetic sensor mounted in two different spatial orientations. An accuracy of 0.2 cm or less was considered acceptable.

C. *One plane registration procedure*

After importing the CT phantom data on the US system in DICOM format by DVD support, the system was ready to start the fusion procedure between CT and real-time US data.

One plane registration was performed selecting the same plane in axial view both on US scan and on CT dataset. After this selection, the system roughly registered the two imaging modalities. Therefore, moving the US probe, real-time US scans of the Doppler phantom and simultaneous navigation within its CT volume were achieved.

This procedure is mandatory in order to give the US system the information about the examined Doppler phantom orientation and position within the electromagnetic field and respecting the second modality volume dataset (CT).

In vivo registration procedure for fusion of CT and US dataset was carried out similarly. In case of real patient this operation had to be performed in the same patient's respiratory phase of the CT acquisition, in order to reduce the possible sum of errors.

D. *One point registration procedure*

After the one plane registration procedure, the one point registration procedure is performed. One point registration consisted in real-time selection of the same point on US scan and on CT volume dataset. During in vitro tests, the region of interest is selected moving the probe on the phantom and then the same point was placed on the US scan and on the CT segmentation of the tubes.

In vivo tests were carried out similarly, selecting the same point on the US scan and on the segmentation of the CT vessels, trying to pick a target where the hepatic vascular pattern presented a bifurcation.

One point registration corrected the spatial error in the three coordinates (X, Y, Z), even if the operator's error, related to the point identification/selection accuracy, and the initial angular error, related to the probe position (always considering the same patient's respiratory phase – expiration), were still present [17]. If the operator proceeded with the manual registration procedure, a fine-tuning adjustment, referring to anatomical points different from the previous ones, was necessary in order to achieve a further improvement of registration.

E. *Automatic registration algorithm*

The Autoregistration algorithm works simultaneously on both the US and the second imaging modality volume. It is based on matching the vessels visible in both modalities. In order to do this, both volumes have to be translated in a common coordinated system. The main task to address is the extraction of the vessel tree from the second modality. The data can look in very different ways (i.e.: MR scans which are not normalized as CT scans) and the algorithm should perform on every dataset more or less in the same way.

The second main task is the matching part of algorithm: it should be enough precise and at the same time adequately fast, so that the Automatic registration step can be repeated during the examination if something which requires a new registration (i.e., the patient moves) occurs.

The registration algorithm workflow can be described as follows: first the initial transformation is build, afterwards the regions of interest (vessels) are extracted from both US and second imaging modality volumes; the working volumes, containing only the extracted and filtered vessels, are re-sampled and prepared for the downhill simplex algorithm; the matching finishes when the downhill simplex does not provide any further position, which maximizes the common part of the vessel trees.

F. *Automatic registration procedure*

After the one point registration, the Automatic registration algorithm was used, in order to fine tune the remaining spatial and angular error. The spatial error, partially corrected by the one point registration procedure, is represented mainly by the error generated in the point identification, error dependent by operator's accuracy or by more reliable organ movements. The angular error origins during the previous manual registration procedures, where the US probe couldn't stand perfectly perpendicular on the patient's body, in order to completely reply the CT scan plane shown (mainly the axial one).

When performing Automatic registration procedure during in vitro tests, a US volume of the Power Doppler signal in the same selected region of interest of the one point registration was acquired. Then the US volume was automatically matched by the US system with the segmentation of the tubes detected within the CT volume. At

the end, visual control of the correspondence of anatomical-mimicking structures on US and CT in axial, coronal and sagittal views during fusion navigation and size measurements of recognizable structures in the phantom were used as assessment of the accuracy of the registration procedure (Fig. 1).

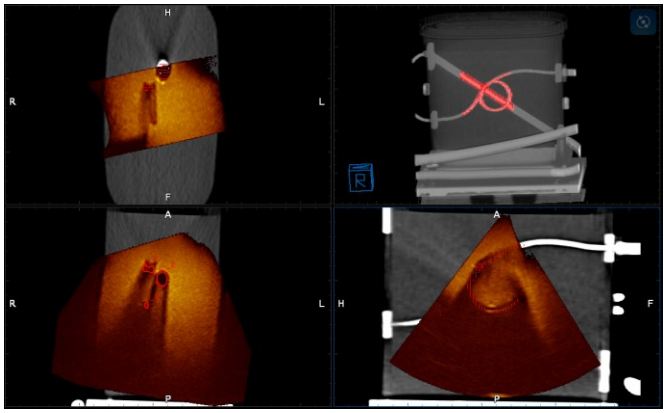

Figure 1: Automatic registration procedure between US and CT with the 3D Power Doppler show. The image shows the phantom CT dataset in tridimensional views in grey. In white are highlighted the equivalent vessel circuits and in red the automatically segmented part. In overlap (orange) the ultrasound volume position after the automatic registration algorithm. The red segmented vessel is coincident with the black part of ultrasound volume that represents the vessel after the processing. The red label identifies the vessel bifurcations.

The in vivo registration procedure for fusion of CT and US dataset was carried out similarly. Automatic registration with hepatic anatomical markers (vascular tree) was carried out acquiring a US three-dimensional Power Doppler volume of the hepatic vascular tree (Fig. 2), that is in the same selected region of interest of the one point registration procedure. Then the data were matched automatically by the US system and finally it showed the US Power Doppler volume together with the CT segmentation (Fig 3; Fig. 4).

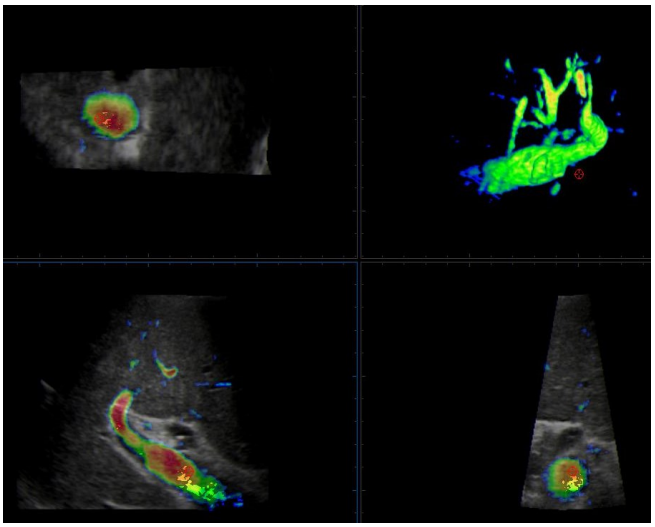

Figure 2: Automatic registration algorithm - US Power Doppler 3D view of portal vein three. Where, in the quadrant in the upper left corner is present the coronal view of the portal vein branch, down left the axial view and down right the sagittal view of the acquired ultrasound Power Doppler volume of the portal vein. In the upper right quadrant the Power Doppler volumetric representation of the portal vein with its branches is represented.

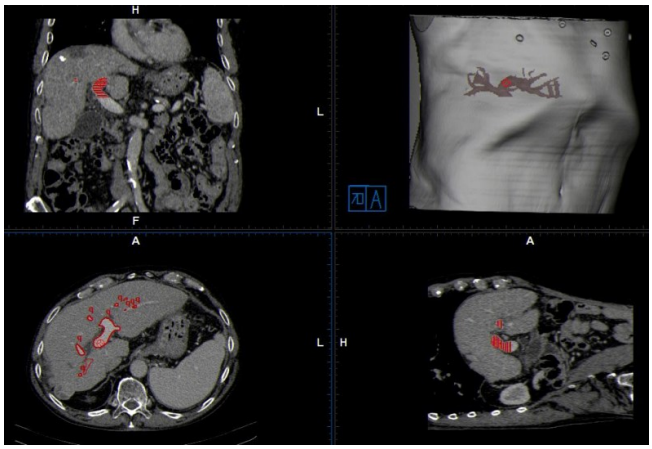

Figure 3: Automatic registration algorithm - CT 3D view of portal vein tree after segmentation process. Where, in the quadrant in the upper left corner is present the coronal view of the portal vein branch, down left the axial view and down right the sagittal view of the CT of the portal vein. In the upper right quadrant the CT volumetric representation of the surface of the abdomen of the patient, with the volumetric segmentation of the portal vein with its branches represented as immersed in the CT volumetric rendering.

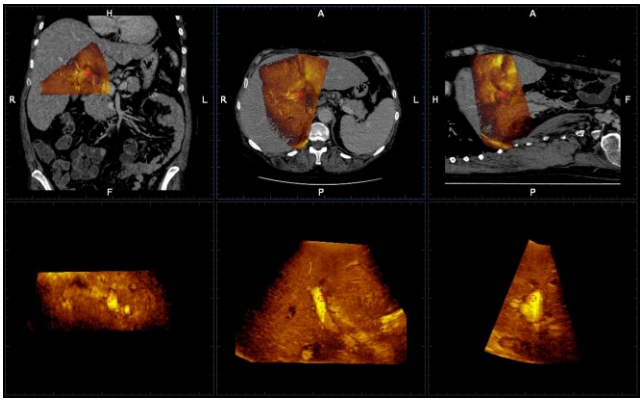

Figure 4: Automatic registration US-CT of a liver. In first line in grey from left to right are displayed the coronal axial and sagittal and coronal views of CT with over-imposed in orange the ultrasound volume after the automatic registration procedure. In second line, from left to right, the coronal, axial and sagittal views of the acquired ultrasound volume. In bright are highlighted the portal vessel branches.

Visual control of the correspondence of anatomical structures on US and CT in axial, coronal and sagittal views during fusion navigation and measurement of the same anatomical point, i.e. portal vein bifurcation, were used as assessment of the error of the registration procedure (Fig. 5). The distance of the same anatomical point visualized with the two modalities was measured in the sagittal, axial and coronal views, and the Euclidean distance was computed. We tested if there was a statistical difference among these distances measured before and after the automatic registration, using Wilcoxon test. Time was recorded for each phase of the study; finally , the manual fine tuning procedure has been compared with the automatic registration procedure.

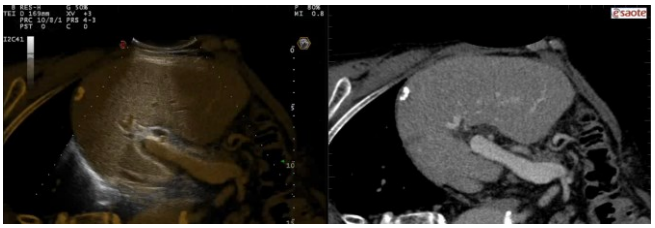

Figure 5: Post Automatic registration visual check of the final accuracy of the fusion imaging considering images overlap between the two imaging modalities (left: US real-time fusion with CT; right: CT second modality reference image).

III. RESULTS

Six tests to assess the registration precision between CT and US datasets were performed on the Doppler phantom. Volumes of the straight and circular tubes were acquired. Three tests were performed positioning the selected point of the one point registration on the straight tube, while three tests were performed placing the point at the level of a "false tube bifurcation". False bifurcation is generated by the Doppler signal of adjacent tubes shown on the US volume as one single vessel with bifurcation (Fig. 6). The three tests with the Automatic registration point selected outside the "bifurcation" failed. The other three tests were successful with the measurement of respectively the axial, coronal and sagittal views of three points for each registration. Results for each of the three cases are shown in Table 1, with also the error reduction in the three planes and the Euclidean error reduction after the Automatic registration.

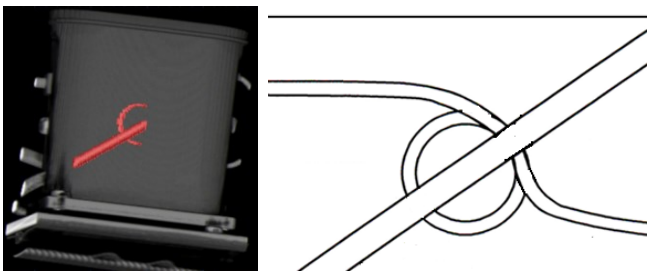

Figure 6: Left: fusion imaging between the CT of the Doppler phantom and the US Power Doppler of the Doppler phantom: false bifurcation generated by the Power Doppler signal of adjacent tubes shown on the US volume as one single pipe with bifurcation. Right: graphical representation of the internal pipe organization of the Doppler phantom where the straight and the curved pipes are adjacent but not intersecting each other.

TABLE I. IN VITRO AUTOMATIC REGISTRATION RESULTS

Error (mm)	Test A	Test B	Test C
Initial error **Axial –Sagittal- Coronal**	8 - 13 - 6	11 - 7 - 8	9 – 9 - 9
Final error **Axial –Sagittal- Coronal**	3 - 1 - 3	2 - 3 - 2	3 - 3 - 2
Absolute error reduction **Axial –Sagittal- Coronal**	5 - 12 - 3	9 - 4 - 6	6 - 6 - 7
Euclidean error reduction Pre-post automatic registration	16.4 - 4.4	15.3 -4.1	15.6 - 4.7

The maximum registered error with Automatic registration procedure was 3 mm. This value can be reasonably considered the minimum registration error achievable during in vivo CT-US fusion imaging procedures. In the clinical cases, the respiratory activity had a significant impact on the registration error, as previously reported in literature [18,19]. For in vivo cases, after the Automatic registration procedure, an error range 1- 5 mm was achieved for all the patients, except for one patient, where the maximum error was 6 mm, mainly due to particularly poor image volume dataset, which didn't show any major portal vein bifurcation. The median values and 95% confidence intervals along with the p-value of the improvement after automatic registration are reported in Table 2.

TABLE II. IN VIVO AUTOMATIC REGISTRATION RESULTS

Error (mm)	Median initial error	95% CI initial error	Median final error	95% CI final error	p-value
3D	18.1	13.8 - 20.8	6.0	4.2 - 7.0	0.004
Axial	9.0	8.0 - 12.7	4.0	2.1 - 4.0	0.004
Sagittal	11.0	8.1 - 12.0	3.0	2.1 - 4.0	0.004
Coronal	10.0	5.5 - 12.9	3.0	2.0 - 3.9	0.01

The mean time for One Plane Registration was 23±6, for One Point Registration was 55±18, for Manual Fine Tuning 152±106 and for Automatic Registration was 98±58 .

IV. DISCUSSION AND CONCLUSION

Our results demonstrated that Virtual Navigator Autoregistration is feasible, fast, and allows for a precise registration of US and CT images On Doppler phantom tests, if the selected point of the one point registration is placed within the main central tube where no bifurcations are present, there were several positions where the Automatic algorithm found local minimal values which hampered the final target, that was the finding of a global minimum value and resulted in the failure of the final registration procedure.

For in vitro tests, the Automatic registration algorithm was able to work properly only in cases where the Power Doppler volume was acquired comprising the tube false bifurcation.

The Automatic registration worked properly in all the in vivo cases where the portal vein three was acquired as a Power Doppler volume, obtaining a final error within the range 1-6 mm.

Fusion imaging Autoregistration capabilities reduce the time needed for the practical manual alignment of the same view on the two (or more) interested imaging modalities. This can lead to increased confidence, repeatability and easiness related to boosted fusion imaging use for increased clinical confidence, second modality visual check and repeated use also during follow up sessions.

The proposed Automatic registration algorithm has shown to be able to work on difficult patients, being not imaging dependent, while working on Power Doppler signal, which have a higher sensitivity. In difficult patients where the Power Doppler signal is poor, US Contrast media can be administered (if there are no major contraindications) in

order to increase the Doppler signal within the focused vessels. The proposed Automatic registration algorithm can be theoretically applied in all organs that show a vascularization tree. Proper automatic segmentation on the CT vessel with automatic threshold average increases the chance to gain always the maximum vascularization, obtaining a whole map of the organ vessel. This lets perform the automatic registration on a different position, gaining always the maximum accuracy in the scanning regions. After the one plane registration procedure, which anyway is characterized by a major registration error, the one point registration procedure reduces most of the spatial error of the registration procedure, whose precision is higher depending on how accurate is the selection of the same point in the two imaging modalities. Alignment of the two modalities based on the same point reduces the possibility to find local minimum due to the fact that the research area is limited. In addition, if a local minimum exists, it will represent the maximum accuracy in the point surrounding region.

There are pitfalls related to the proposed algorithm; the first is that a vessel bifurcation is mandatory to reach an optimal/final result. On a pipe a partial overlapping or a vessel rotation on its axis could happen. Furthermore, vessel size between the two datasets and US Power Doppler signal due to persistency, smoothing level, possible movements and general acquisition errors could lead to a wrong alignment of the US and CT vessel; this because the overlapping region with the vessel tree has more than one best fit. Consequently, this solution is not available for anatomical application as muscle skeletal, prostate, gynecology due to lack of clear vascularization landmarks. Until today, the vessel recognition of the Automatic segmentation works only on white vessel signals, so CT portal phase or particular MR sequences are required. CT poor in terms of contrast resolution is not usable or gives a partial result (vessel segmentation too small). Organ Deformation due to breathing induces an error that until today is not compensated, but an average accuracy is always guaranteed.

In conclusion, automatic registration seems to be a feasible, fast and precise method to obtain fusion between US and CT images for liver application. This method hold the potential of offering a faster and easier way to obtain a precise registration. Further studies are necessary to confirm our preliminary results.

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