White Paper

Fusion Imaging

Techniques and Applications

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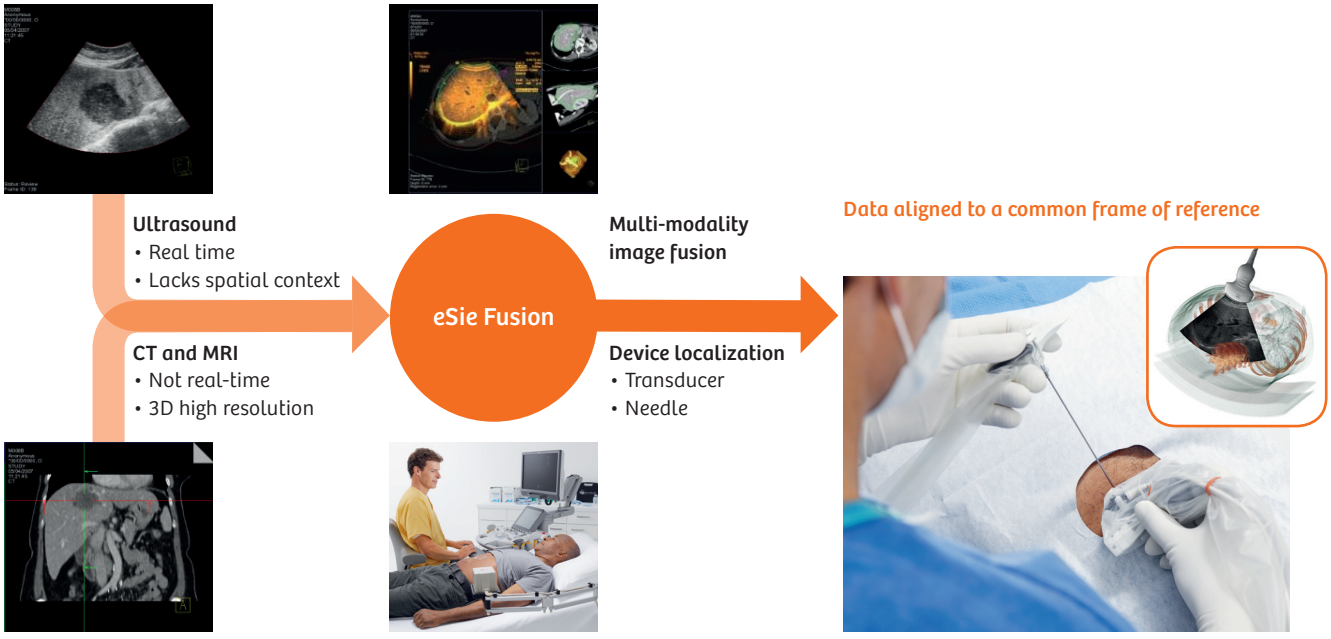

Figure 1. Multi-modality image fusion brings image and sensor data from different modalities into a common frame of reference

1. Introduction

Multi-modality fusion – Definition

Needle-based interventional procedures such as biopsy and ablation are typically performed under ultrasound guidance. This supports cost-effective and versatile real-time visualization of the needle/ablation applicator and the target lesion. Computed Tomography (CT) or Magnetic Resonance Imaging (MRI), the common alternative modalities for procedure guidance, may not be real-time, but can offer 3D visualization of the target as well as provide additional information not otherwise available during the biopsy or ablation procedure. eSieFusion™ Imaging combines these two powerful advantages of different modalities to one exam, at the same time, with the ACUSON S3000™ Ultrasound System.

eSieFusion consists of matching or "aligning" the two imaging datasets (CT or MRI) with ultrasound, spatially to each other. The core concept of fusing image data and sensor data into a common reference frame is illustrated in Figure 1.

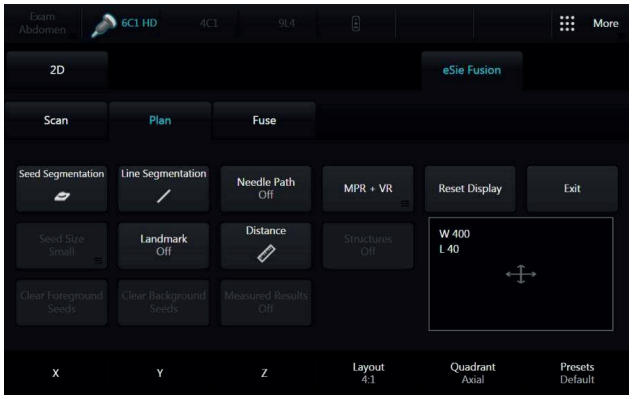

Figure 2. eSieFusion imaging workflow menu layout

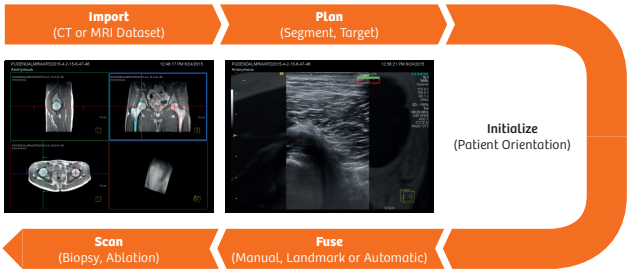

Figure 3. Overview of steps required to use fusion imaging for guidance

2. Workflow and Applications

How to use multi-modality image fusion?

Selecting the eSie Fusion button on the touch screen launches the workflow menu, shown in Figure 2. The process requires a series of short steps, commonly performed in just a few minutes. These are illustrated in Figure 3. First, the **import** of prior images from MRI or CT. Then, **planning**, which allows identification of biopsy or ablation targets, as well as planning of needle trajectories. This includes **initialization**, to establish patient orientation with respect to the imported dataset. Next, **fusion** aligns the CT or MRI and live ultrasound, and begins the **scan**, or patient examination. This is explained in more detail below.

The Plan tab on the touch screen provides tools to plan the needle path or trajectory. **Segmentation markers** use Siemens proprietary Knowledge-based Workflow technology to detect and outline an area of interest in 3D so that it can be marked and viewed simultaneously in all imaging planes on the CT/MRI and the real-time ultrasound.

Markers are particularly useful in alignment fine-tuning, and aid in lesion correlation when there are multiple lesions or lesions that are difficult to visualize.

A **Landmark** is a single color-coded marker used to mark a corresponding point that can be viewed in all imaging planes on the CT/MRI and ultrasound. These tools are illustrated in Figure 4.

The Needle Path Off button can be used to add a cylindrical path from a user-selected skin entry point to a target point. During the guidance, a graphical indicator of the intersection of this cylindrical path with the ultrasound plane will be displayed to provide guidance for the needle. This is shown in Figure 5.

A Distance tool is also provided to measure and record user-selected distances between two landmarks or points of interest.

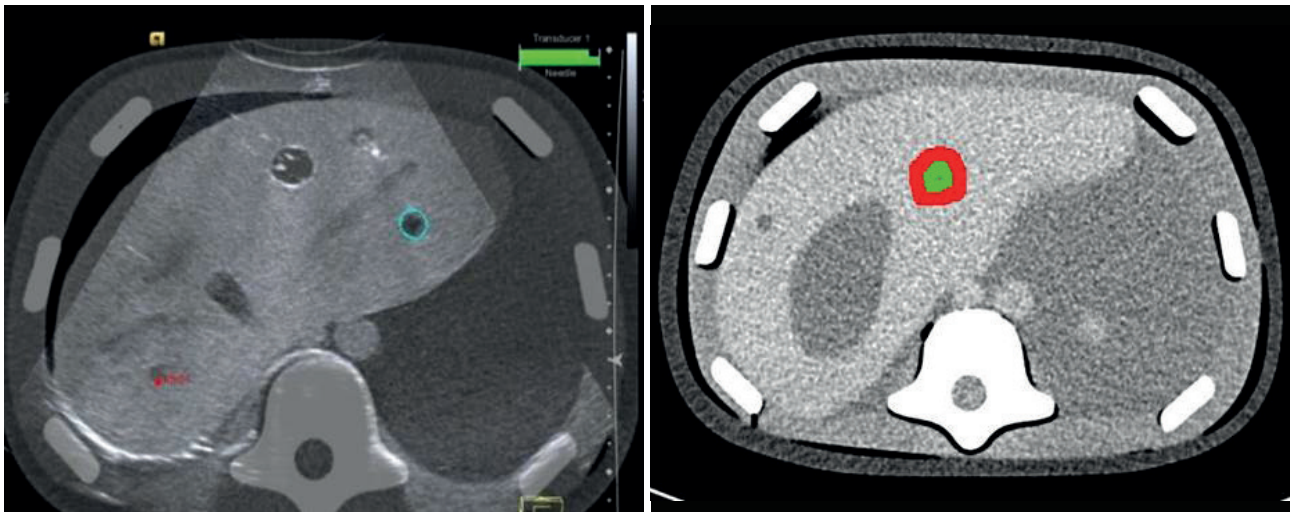

Figure 4. Plan tool available with eSieFusion imaging to help with fine tune alignment and assist in difficult to see lesions. On the image on the left, the blue circle indicates line segmentation. The red dot is an example of a Landmark. On the image on the right, seed segmentation is demonstrated as the green/red circle.

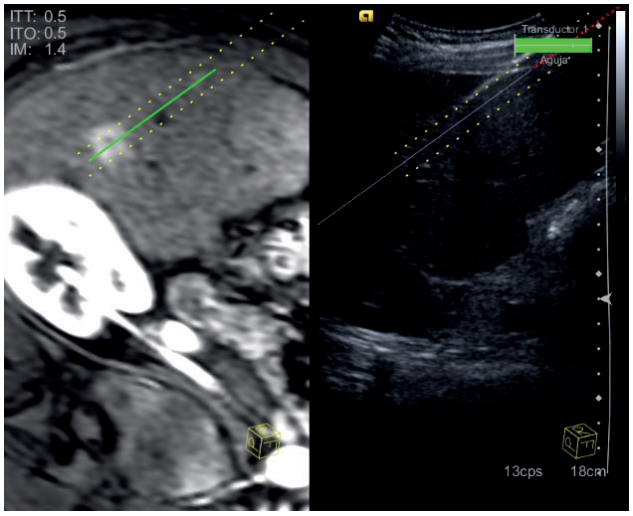

Figure 5. The fuse touchscreen layout

To facilitate accurate alignment, the fusion package requires knowledge of the patient orientation. The Fuse tab, shown in Figure 6, offers two preset options of supine or prone. Or, to accomodate other positions such as LPO, the preprocedural image can be rotated to match the patient orientation. The fusion package also allows for selection of the axial, coronal or sagittal views with which to inititialize. The goal of the initial patient orientation step is to provide an approximate alignment between the positioning of the patient on the table, the ultrasound image plane that would be typically observed during the procedure and the pre-procedural CT/MRI dataset. Typically for abdominal procedures, an **axial** plane seems to best facilitate initial alignment in most cases. The **sagittal and coronal** MPR planes on the CT/MRI dataset provide very useful alternative options for complex anatomies of MSK. Buttons for commonly used positions such as supine and prone as well as Left/Right and Up/Down flip are provided to quickly bring the orientations of the live ultrasound image and hence the anatomy being imaged to match the pre-procedural image selected in the left screen. The user can also scroll through the CT/MRI reformatted images to select an image that may be easier to match such as an image that has prominent landmarks visible in both modalities. The user presses the initialization button once they are satisfied with the initial orientation, and the fusion package then switches to fuse mode. Two options using manual interaction and points are supported. Using pre-procedural CT with a curved probe also brings up a third option of automatic fusion. These modes are further described in section 5.0.

Once the user is satisfied with the alignment of pre-procedural images with the live ultrasound, they can switch to the guidance mode by selecting the Scan tab, shown in Figure 7. The scan mode allows displaying of the pre-procedural images alongside the live ultrasound image in various formats. The 1 : 1 view shows them superimposed on each other. The user can add non-gray tints to ultrasound for improving the contrast between reformatted

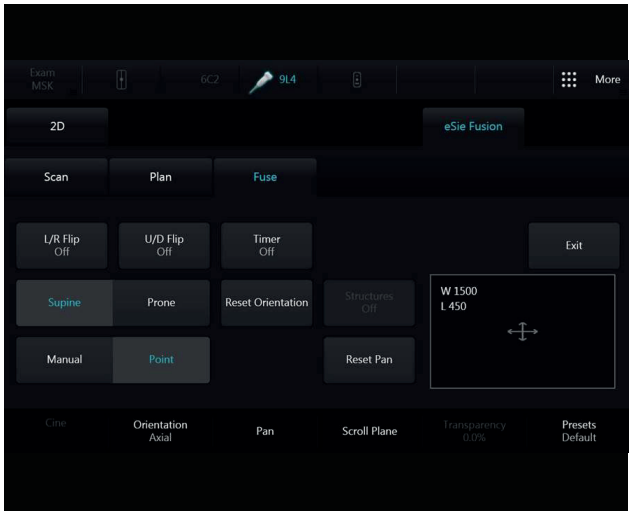

Figure 6. The Scan touchscreen layout

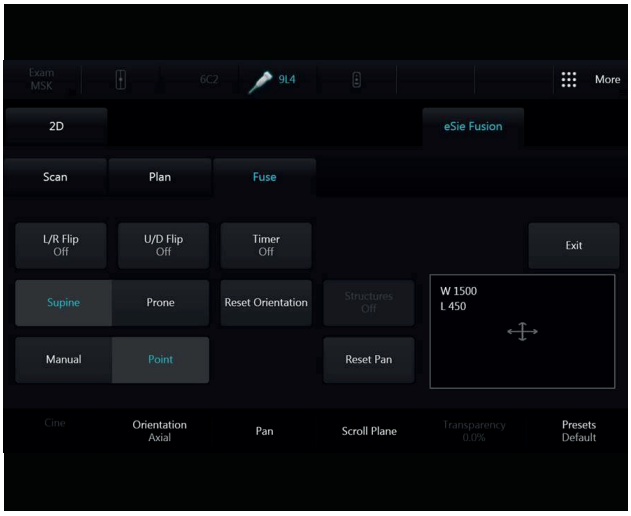

Figure 7. The Scan touchscreen layout

pre-procedural and ultrasound modalities. Further, the relative transparency between ultrasound and reformatted pre-procedural image can be changed to emphasize one modality over another. The 2:1 view shows them side-by-side, whereas the 1:3 view shows the live ultrasound in the left screen and the right strip shows the reformatted pre-procedural image from different viewpoints. The image in the lower right corner shows a 3D depth rendering of the pre-procedural image along with any annotations that were made during the planning. The fusion package uses the alignment determined during the fuse phase to enable this transformation. The structures can be turned on/off using the button on the touch screen.

Areas of use

eSieFusion Imaging supports multiple guiding options for both biopsy or needle procedures. The standard biopsy guides can be used for transducers 9L4, 4C1, 4V1, 6C2 and 6C1HD. Tracked needles (eTRAX™, Civco USA) for 16G and 18G are also supported and when plugged into the system, trigger additional options in the scan tab on the touch screen. These allow the user to toggle on/off the needle overlay and needle tip overlay on the live image. The needle overlay is shown as two parallel yellow lines similar to the standard biopsy guide. Additionally a color-coded centerline is also displayed. This centerline indicates the projection of the current needle path on the ultrasound image. It is shown in blue for the portion of the needle that is *superior* to the ultrasound plane. It is shown in red for the portion of the needle that is *inferior* to the ultrasound plane. If the needle tip graphic is also turned on then a circle indicating the location of the needle intersection point with the ultrasound plane is also shown. Also helpful to pre-plan and avoid major vessels in the liver i.e. arteries/veins.

Figure 8 shows clinical case examples of needle biopsy. Figure 9 shows a clinical case example of radio-frequency ablation (RFA) for liver. The clinical value for the use of multi-modality fusion imaging is that it allows physicians to pre-plan procedures to help avoid major vessels in the needle path. Also to support procedure mapping where the region of interest has a complex shape that may require multiple overlapping ablation zones. Further, the overlaid segmentation functionality can also aid in monitoring the results post-procedure. A tracked needle can also improve confidence for locating the ablation zone before RFA.

Figure 10 shows further examples of fusion applications in renal assessment workflows. In one clinical example, a large renal cystic mass is imaged side-by-side with a pre-procedural CT. In the other example, a renal mass is imaged live on US fused with pre-procedural MRI.

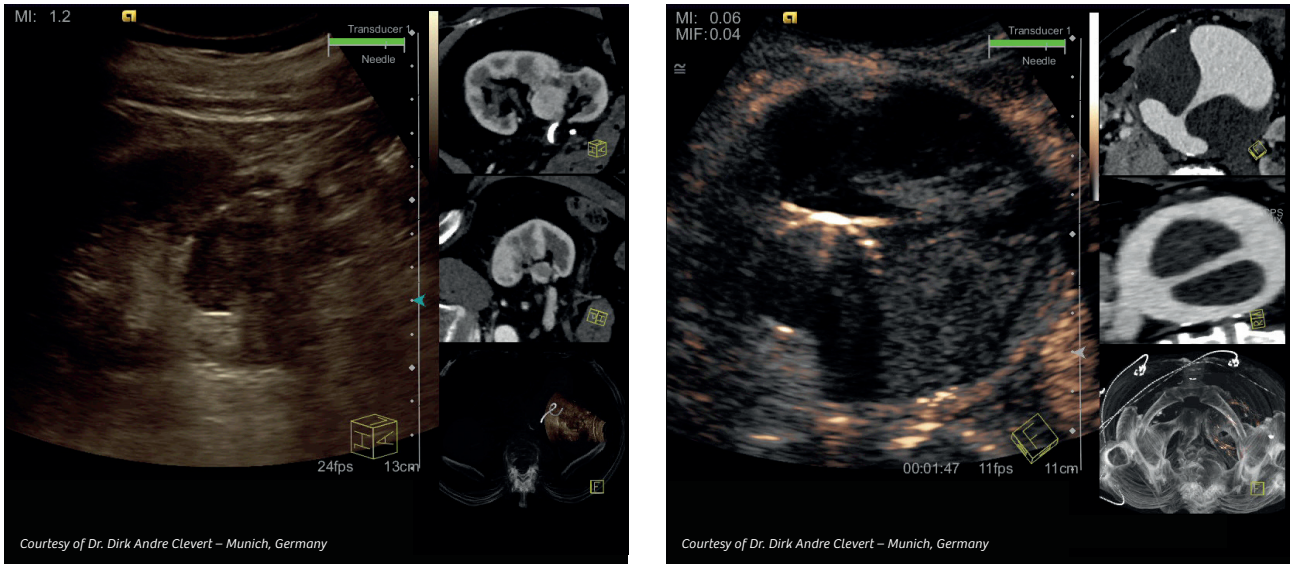

Figure 8. Left: Clinical example of biopsy proven renal cell carcinoma (RCC); Right: Clinical case example of aortic aneurysm post endo vascular aneurysm repair (EVAR)

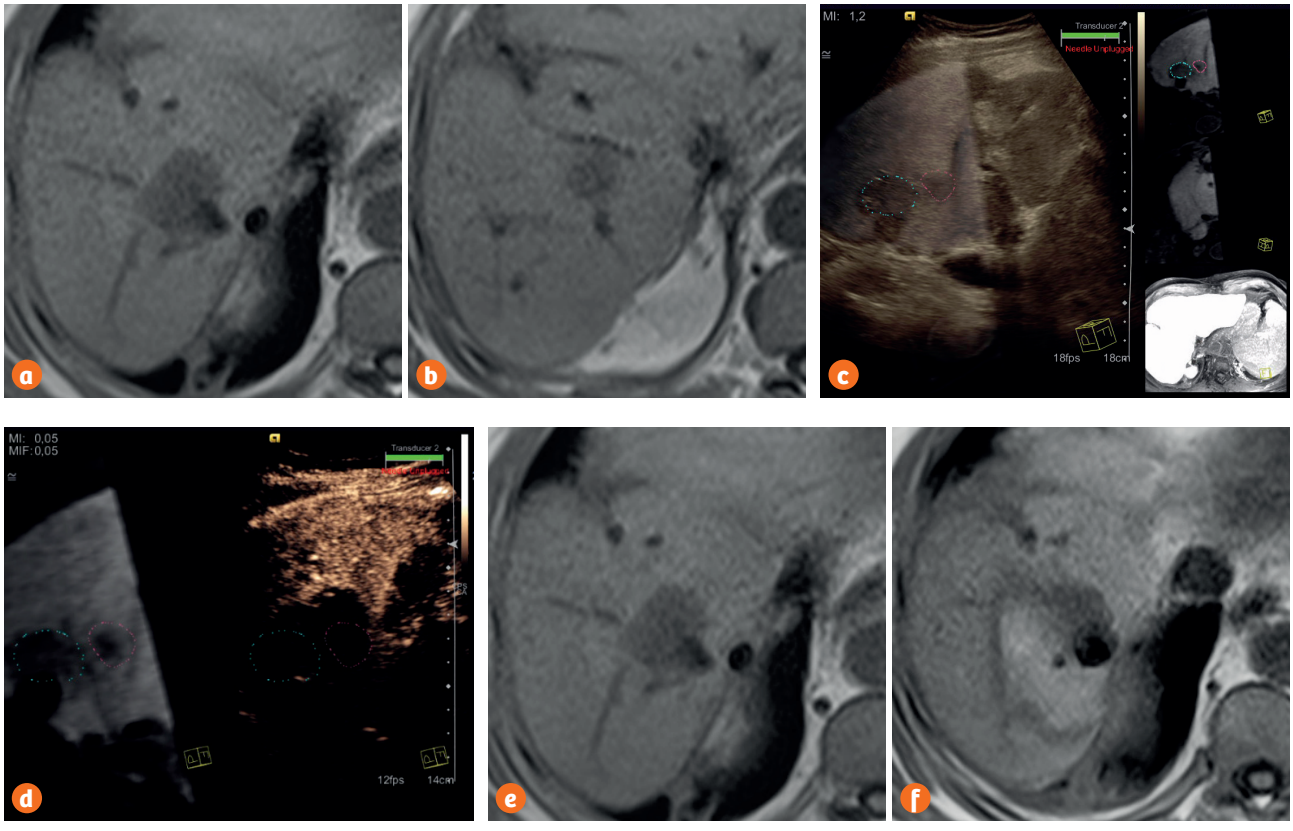

Figure 9. Clinical example of fusion for radio frequency ablation (RFA). (a-b) Pre-procedural CT shows a case example with a difficult shape. (c) CT-US alignment shows segmented boundaries overlaid on ultrasound in 1:3 view. (d) Post-ablation CT-US as side-by-side in 2:1 view. (e-f) Post-procedural follow up CT

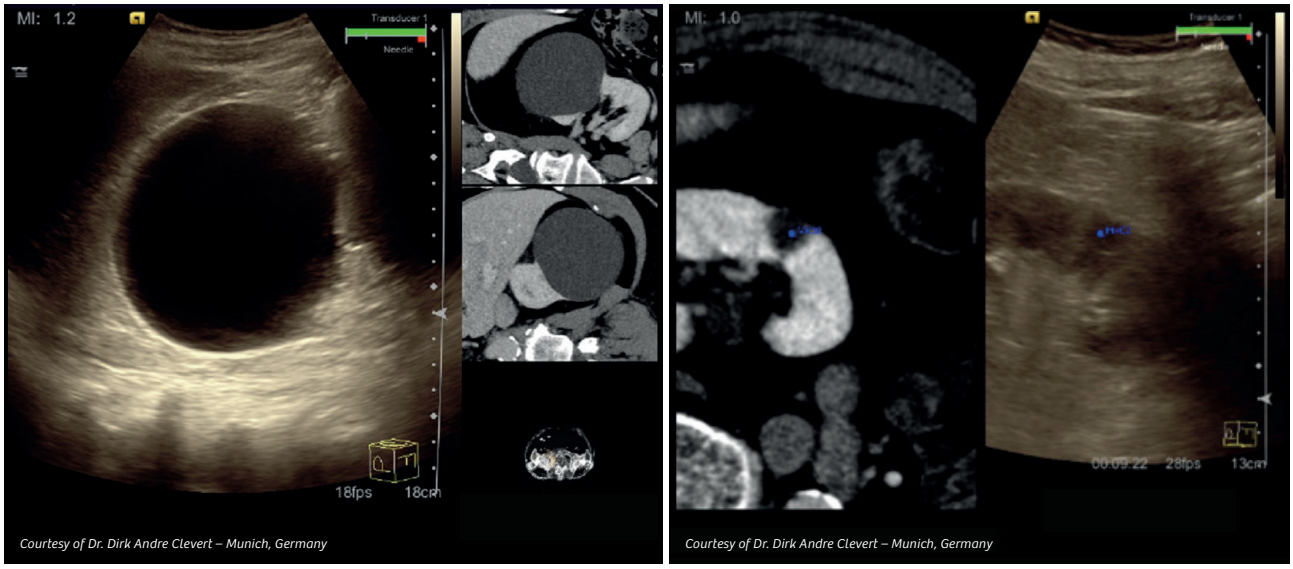

Figure 10. Left: Clinical case example of fusion with large renal cystic mass. Right: Imaging renal mass with live ultrasound and pre-procedural MRI

3. Technical Components

There are several methods to enable image fusion during the procedure. These methods are known as (a) **manual**, (b) **point**-based or (c) **automatic** alignment. Each require two basic components:

1. Capability to import pre-operative data and establish a spatial coordinate system around this data set. To illustrate this, consider a point of interest in this imaging data set $\mathbf{p}_{MRI/CT}$.
2. A stream of ultrasound images that are tagged with spatial location information with respect to a reference in the real-time ultrasound procedure. Let us call the same point of interest in this stream as $\mathbf{p}_{US}$.

In eSieFusion imaging, the DICOM tags in the pre-operative data are used to setup the spatial coordinate system for MRI or CT images. The location of the US image is provided by a magnetic tracker system that comprises a field generator and a sensor that is attached to the transducer. The magnetic tracker system provides the location of the sensor in the magnetic field. Figure 11 summarizes the components of the critical alignment between the spatial coordinate system of the CT or MRI datasets, the ultrasound images and the different components. This alignment can be decomposed into three components as indicated by the following equation.

$$\mathbf{p}_{MRI/CT} = \mathbf{F} \cdot \mathbf{p}_{US} = \mathbf{F}_{registration} \cdot \mathbf{F}_{tracking} \cdot \mathbf{F}_{calibration} \cdot \mathbf{p}_{US}$$

Here, **F** refers to the alignment between the coordinate systems.

In the next section we describe a short summary of the magnetic tracking technique used to obtain the sensor location with respect to the field generator. We describe the methods that are supported by eSieFusion to compute the alignment between the two imaging datasets.

Calibration	*Where is the center of the ultrasound image with respect to the sensor?*
Tracking	*Where is the sensor with respect to the field generator?*
Registration	*Where is the pre-op MRI/CT Volume with respect to the fixed reference frame?*

Figure 11. Critical components that are critical for eSieFusion alignment

Figure 12. eSieFusion imaging kit and its components required to enable multi-modality guidance

4. Magnetic Tracking

Magnetic tracking, sometimes also referred to as "medical GPS" or EM tracking, relies on the generation of a weak magnetic field by several electromagnets in the field generator. These coils are turned on and off to produce a time and spatially varying field around the field generator. This evokes a tiny measureable current in two or more smaller coils that are embedded in the sensor. By measuring these currents between pairs of transmitting and sensing coils the location of the sensor can be triangulated with respect to the field generator. Multiple sensor coils can be tracked and located simultaneously by the system. The field generator produces a usable field of about **60 cm** cubed in front of the field generator. Thus it must be placed such that the target region is within this distance from the center of the field generator. Figure 12 shows the connections of the field generator and the tracking control box in practice. Since the weak magnetic field generated by the generator is only in the front, as indicated by the markings on the cube, it is best to position the patient within a **20-30 cm** radius of this cube. Appropriate proximity is indicated on the ultrasound monitor with a green/red proximity indicator.

The magnetic field generator and both the general purpose and needle tracking sensor plug into a magnetic field tracking control box located on the ultrasound cart. The magnetic field generator cube is placed on a non-magnetic stand and care must be taken such that the stand is out of the flow of traffic so that it will not be accidently bumped or moved. Note: If it is moved after alignment has been performed, a re-alignment will be necessary. The transducer, bracket and sensor are covered in a sterile sheath to prevent cross-contamination in the sterile field.

Sensor port numbers 1-3 on the controller box are for the general purpose sensors attached to the respective transducers. Sensor port 4 is for the needle sensor. The general purpose sensors attach to supported transducers via a plastic bracket. The bracket is available with and without a needle guide. Depending on which port the transducer is plugged into, the sensor is inserted into the controller box's corresponding sensor port. The needle sensor, if used, is a thin long sensor that slips into a cannula, sometimes also referred to as a stylet or introducer. The needle sensor plugs into port number 4 on the controller box.

5. Alignment Methods

As mentioned in Section 3, the alignment between preoperative MR or CT images and live US images can be broken into three components, of which $\mathbf{F}_{registration}$ is computed using the image content. eSieFusion supports three different methods, namely (a) manual (b) point-based and (c) automatic to help compute this alignment. In each of these methods corresponding anatomical structures that can be easily and reliably visualized in both modalities are utilized to match the two datasets.

5.1 Manual alignment

In the manual method, the user either translates (pans) or rotates one image with respect to another until she is satisfied that corresponding anatomical structures are matching. The amount of translation and rotation applied by the user is stored and used for subsequent ultrasound images. The accuracy of alignment that is achieved by this method may be in a range that is consistent with certain clinical applications and can be gauged by navigating to a landmark that is visible in both modalities but was not used to establish the alignment.

5.2 Landmark-based alignment

In the point-based method, the user is asked to specify corresponding anatomical landmarks first in the ultrasound image and then the same point in the CT or MR image. If the user provides fewer than three corresponding landmarks, then the software can only compute the translation (panning) part of the alignment. Three or more corresponding landmarks are required by the software to compute both the translation and the rotation. The accuracy of alignment depends on several factors including the error in localization of the landmarks in the respective modalities and the configuration of the landmarks. Again, similar to manual alignment, the accuracy can be gauged by evaluating the alignment of a landmark that is visible in both modalities but was not used by the software to compute the alignment.

For the point-based method, the terms fiducials and landmarks are often used interchangeably although the former may sometimes refer to a point that is introduced artificially such as a plastic or gold bead or a contrast filled skin marker.

The latter is sometimes exclusively used for naturally occurring points of interest such as vessel bifurcations. For the discussion of the factors that influence the overall accuracy of reaching target points of interest these can be used interchangeably. It is well established in literature [1] and [2] that the accuracy of point-based registration methods can be characterized by

1. **Fiducial Localization Error (FLE)**, which is the error in locating the fiducial or landmark points. In our case, these are the internal point landmarks that are selected by the user. Thus localization error of users in selecting the landmark and the accuracy of the magnetic tracking system are two of the factors contributing to this error;
2. **Fiducial Registration Error (FRE)**, which is the root-mean-square distance between the corresponding fiducial or landmarks after registration and
3. **Target Registration Error (TRE)**, which is the distance between corresponding points other than the fiducial or landmark points after registration. Generally these points depict the region of interest that is being targeted.

Whereas FRE and TRE are the two relevant measures of algorithm performance, FLE is a characterization of the input error (both in terms of user's ability to select a point in space, and the tracking system's ability to localize a point in space). In our typical applications, we are targeting a particular point of interest that may be visible in only one of the modalities. It is safe to assume that it may not be a fiducial or landmark used for registration. Thus TRE becomes the local clinically relevant quality measure. The exact relationship between these three quantities has been established in [2] and can be summarized by the following equation

$$TRE \propto \mathrm{FLE} \cdot \frac{1}{N} \cdot \frac{d^2}{f^2}$$

where N is the number of landmarks provided by the user, d is the distance of the target point of interest from the imaginary coordinate system formed by the centroid provided by the landmarks and f is the mean of the distances of the landmark points from this imaginary coordinate system (see Figure 8).

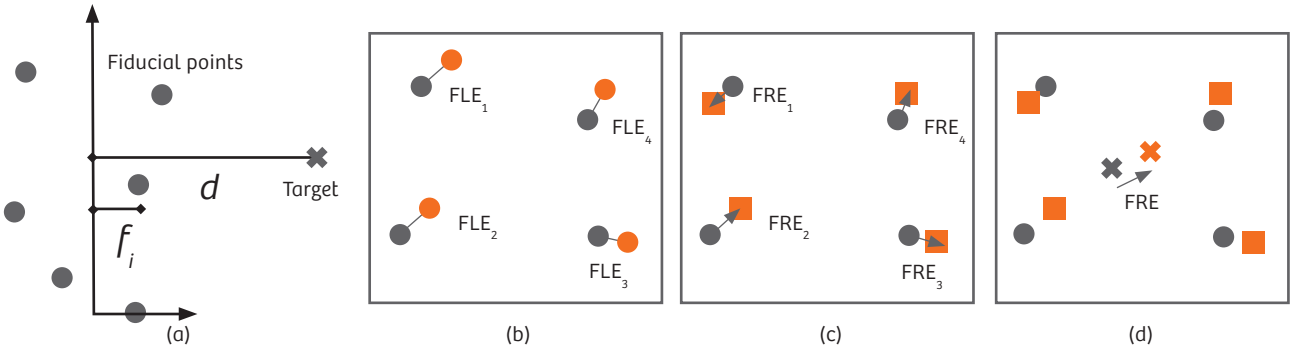

Figure 13. Relationship between typically used error metrics to quantify the quality of registration between modalities. (a) A reference coordinate system formed by the principal axes of the selected landmarks (fiducial points) and the distance to target. (b) Localization error is defined as distance between the user-selected landmark (grey circle) and the true location of the landmark in the same modality (orange circle). (b) Registration error is defined as the distance between the corresponding landmarks after registration. Landmarks in one modality are shown as grey circles. Landmarks in the second modality are shown as orange boxes. (c) Target error is defined as the distance between the point of interest, typically other than the fiducial or landmarks selected for the registration algorithm after registration (shown as grey and orange crosses).

Thus, accuracy can be improved by

(a) Reducing the localization error. This can be achieved by selecting point landmarks that are readily visible in both modalities and can be selected with a high degree of confidence.

(b) Increasing the number of landmarks. A minimum of three landmarks are required to compute both the translational and rotational components of the alignment. However, to reach the desired accuracy a larger number may be required.

(c) Increasing the baseline of the landmarks. The mean of the distance of the landmark point is often referred to as the baseline distance. This can be increased by picking landmarks that are as far apart as possible.

(d) Decreasing the distance to the target. Since TRE is proportional to the distance between the centroid of the landmarks, reducing this distance also reduces the TRE. This implies that ideally the landmarks should be evenly spaced around the target point of interest (see Figure 8).

The relationship presented above relates the statistical expected value of TRE which has a gamma distribution to FLE assuming that FLE is normally distributed. We suggest that the user gauge the alignment accuracy by evaluating the alignment of a landmark that is visible in both modalities but was not used by the software to compute the alignment in the vicinity of the target point of interest.

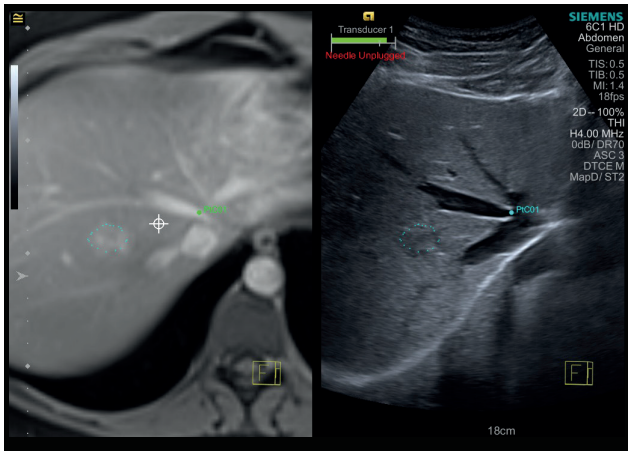

Figure 14. Example of a landmark used for registration for the liver.

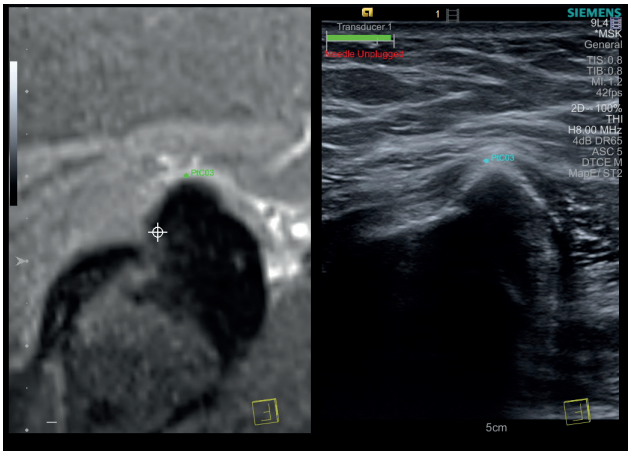

Figure 15. Example of a landmark used for registration for the knee.

5.3 Automatic alignment

Automatic registration has the potential to improve overall workflow by saving time and decreasing the human subjectivity in aligning pre- and intra-operative images. The method used for automatic alignment of US to CT in eSieFusion is described in detail in [3]. Figure 16 illustrates the high level steps of the overall algorithm. The underlying concept is to create a simulation of US from CT that is realistic enough to allow for stable results, yet is computationally efficient. Furthermore, we use a similarity measure that is invariant to missing simulation details, has smooth properties and a maximum at the correct alignment. For automatic alignment the user is asked to acquire a 3D US acquisition by sweeping the transducer over the target anatomy. During this process the system acquires the ultrasound images as well as the corresponding location of the transducer with respect to the field generator. Typically this results in a collection of several hundred frames per sweep. As neighboring frames of the sweep contain similar information, we pre-process the sweep by selecting one out of every *n* frames. This assures that frames which contain unique fine structures, that can be located in CT as well, are picked for subsequent steps. Further, we discard frames at the beginning and end of the sweep if they contain little usable information due to differences in when the "acquire" button was pressed on the machine to the actual motion of the transducer. We define *n* to yield 20-30 frames per sweep.

In automatic image alignment methods, a similarity measure scores the correspondence between two modalities that are being aligned. Since ultrasound and CT are distinct in appearance, direct intensity based similarity measures do not provide a reliable score. Instead we use a proprietary novel scoring that we denote as Linear Correlation of Linear Combination (LC2). It is a statistical measure based on the correlation of US intensities υ_i and a linear combination with unknown weights of signals ρ_i, τ_i extracted from CT. Here ρ_i is a nonlinear mapping of CT Hounsfield units to ultrasound intensities and τ_i is a representation to mimic large scale representations at tissue interfaces. The latter provides a means to simulate large-scale ultrasonic reflection at tissue boundaries, and the related shadowing effects at strong interfaces like bone. As there is no simple relationship between tissue echogeneity and CT Hounsfield units, we use a polynomial function, based on a number of correspondences (liver tissue, liver vasculature, kidney, gall bladder) between CT intensities and tissue echogeneity in ultrasound.

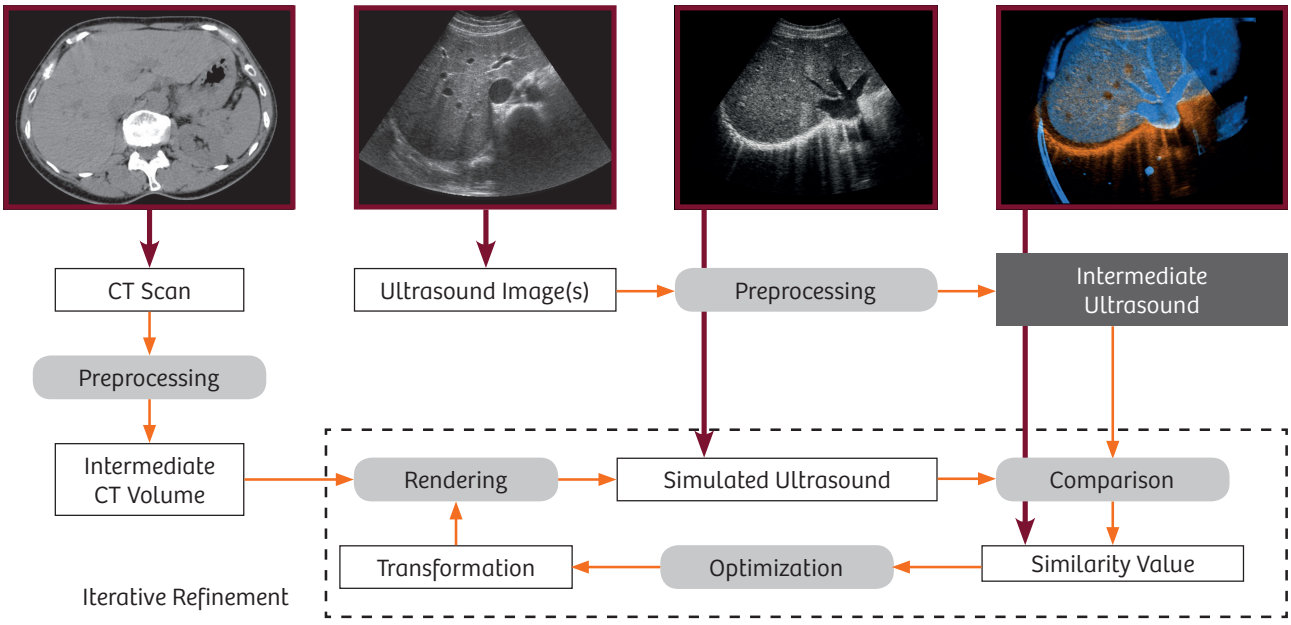

Figure 16. An overview of the automatic registration algorithm for alignment between CT and US

In our method we implicitly compute the weights for linear combinations for ρ_i and τ_i during every post evaluation. This equals a simultaneous optimization of radiometric and alignment parameters with the radiometric parameters providing information for simulating US images from the CT volume. In other words, we do not explicitly generate a simulated US volume from CT data, instead, for each iteration we compute the similarity score based on the current estimate of the weights and the alignment parameters. Then we update both the weights and alignment parameters and repeat these steps until we reach a point at which the similarity score is the maximum.

Like the landmark-based methods, TRE becomes the local clinically relevant quality measure. As image-based technique incorporates information throughout the 3D sweep, trying to find an alignment of all structures visible in both modalities may yield a lower TRE than point-based registration [3]. However there is no known mapping between the freehand sweep and the resultant TRE as there is for the landmark based method. Practical observations suggest that a slowly acquired sweep with more or less uniform applied pressure that avoids excessive shadows yields good results. Additionally, ensuring a high degree of overlap between the anatomies that were acquired for the CT scan and those being acquired during the freehand sweep may also help in improving results.

The choice between the use of point-based and automatic depends on the outcome that is expected. In cases where there is limited difference between pre-operative images and intraoperative images due to patient positioning or respiration, and a certain degree of difficulty in precisely locating corresponding landmarks and an overall quick and accurate alignment is required, the automatic method may be preferred. On the other hand, using the point-based method by selecting matching landmarks distributed around a local target region may yield well-aligned vasculature and targets in the local neighborhood. Such an approach may be desirable if there is large variation between pre-operative and intraoperative images due to factors such as patient positioning or different respiratory configurations.

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