Deliverable 4.5

Guidance System Specifications

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3.0	2016.02.01	*Júlia Oliveira, UKA-IMI*	*Revision*
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1.X = 1st version circulating between the members / 2.X = 2nd version following comments of members / 3.X = 3rd final version

Table of Contents

1 Abstract

This document provides a description of the different guidance system components in the regional anesthesia assistant. The accuracy of the different components is measured and reported.

2 Introduction

2.1 Context

The guidance system of the assistant shows which direction the user should move the ultrasound probe to investigate the region of interest. Its intention is to help the operator to reach the target site for injection of the local anesthetics. The system provides automatic real-time segmentation of the femoral artery, the femoral nerve, and the two layers fascia lata and fascia iliaca. This aids in the interpretation of the 2D ultrasound images. A model of the surrounding anatomy is also registered to the ultrasound images. This allows the user to see the reconstructed artery in 3D together with the surrounding bone from the model. The next section will describe each of these guidance components in more detail. The final section will present and discuss the accuracy of the different guidance components.

2.2 Objectives

2.2.1 Deliverable description

As stated in the Description of Work, the deliverable that constitutes this plan is described as follows:

> ***D4.5 Guidance Systems Specifications***
>
> *The achievable guidance specifications of the regional anaesthesia assistant systems (RAAs), with respect to accuracy, sensitivity, navigation feedback and haptic guidance.*

3 Guidance components

In this section, each component related to the guidance system part of the assistant is described.

3.1 SonixGPS tracking system

SonixGPS is an electromagnetic tracking system developed by Ultrasonix. This tracking system supplies input to the assistant software which is used to reconstruct the femoral artery. The reconstructed femoral artery and tracking information are used to estimate the target location and model registration. Tracking information enables visualizing the probe and needle relative to each other in 3D. The tracking system consists of a transmitter device and embedded sensors in the ultrasound probe and needle. These sensors provide the position and orientation of the probe and needle. The range of the transmitter is limited. The sensors need to be within a specific range of the transmitter to accurately determine the position of the sensors as shown Figure 1. The figure shows that the ultrasound probe has to be close (< 35 cm), and directly in front of the transmitter. The assistant software will notify the user if the transmitter and probe are not properly positioned.

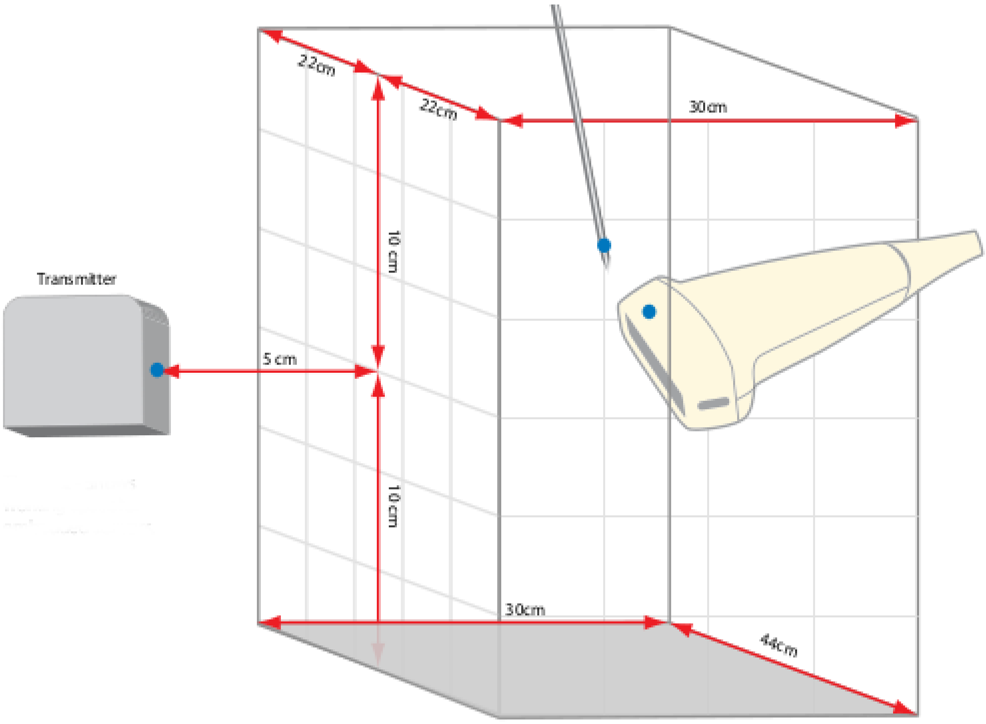

Figure 1: Illustration of the SonixGPS system. Image courtesy of Ultrasonix.

3.2 Target estimation

Two criteria are used for estimating the target injection site:

1) The target should be before the bifurcation of the femoral artery.
2) The target should be where the artery is at minimal depth.

The change in radius of the artery is used to find the bifurcation, as the radius generally decrease after the bifurcation, as shown in Figure 2. The minimal depth requirement will eliminate positions superior of the inguinal ligament which are too deep. The depth is calculated along the imaging direction vector, which is the direction the probe points in. As this may change during the acquisition, the average of all directions during the acquisition is used. The middle of all artery centerpoints that are within 2 mm depth of the minimal depth centerpoint is selected as the target. This was found to be more robust than selecting the centerpoint with the minimal depth, as the depth estimation is not so accurate. Which is mostly due to pressure changes and inaccuracies in the tracking system.

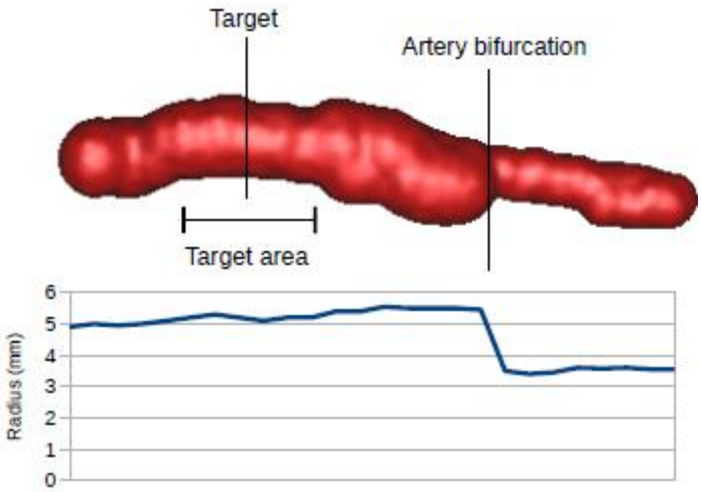

Figure 2: Illustration of the target estimation on a reconstructed femoral artery.

3.3 Model registration and 3D visualization

The model to ultrasound registration is primarily used for providing anatomical context to the user. Visualizing a model of the surrounding structures together with the ultrasound images in the 3D view helps the user to navigate. The anatomical model was created from a single abdominal CT image volume with the patient in supine position. From this CT image volume, the bone was segmented using region growing. Since the model does not incorporate the anatomical variation in this region, the visualization is not expected to be accurate. Registration of the model to the ultrasound images is difficult as there are no easily identifiable landmarks in the ultrasound images. Instead, the estimated target site for injection is used as a landmark, where the estimate is generated using the method in the previous section. The corresponding target point is identified manually in the model and landmark registration is used to register the model to the ultrasound images. Three landmarks are needed for the registration. To obtain two more landmarks, two points at fixed directions and distances are estimated from the ultrasound images. The second landmark is selected in the direction of the artery 1 mm from the target point. The direction of the artery is calculated using the centerpoints from the artery tracking. The third landmark is 1 mm below the target point. The registration is updated continuously when the landmarks change during ultrasound acquisition. More details on this registration procedure can be found in [1].

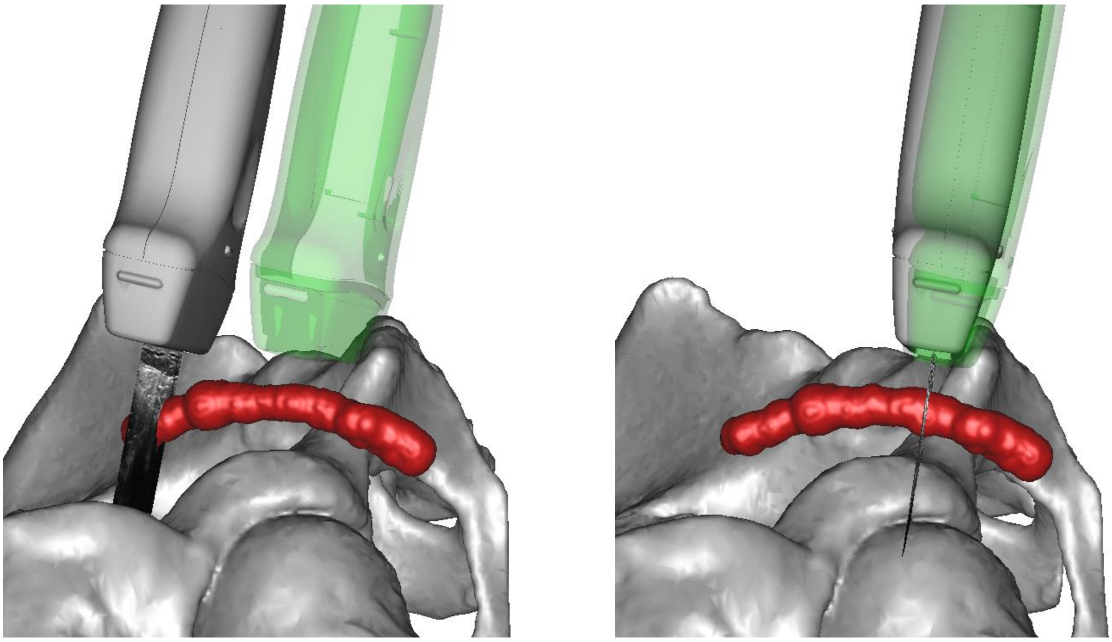

Figure 3: When enough of the artery has been scanned, the target can be estimated. A green transparent probe will then appear at the target position. The user should align the probe in grey with this target probe.

3.4 Probe guidance

When tracking of the femoral artery has started, the user is asked to move the probe upwards towards the head of the patient. This is indicated with a green bar on top of the ultrasound image as shown in Figure 4. While the femoral artery is being reconstructed, the target is continuously estimated. The estimated target is used to give updated probe guidance instructions to the user. Depending on how much of the artery is scanned above and below the target, the user is asked to move up and down, indicated with a green bar at the top or at the bottom of the ultrasound image. When more than 1 cm above and below the target has been reconstructed, a green transparent probe appears at the target position in the 3D view. At this point the user should align the ultrasound probe with this transparent probe as shown in Figure 3. Green bars will appear in the ultrasound image to guide the user to the target. When performing the needle insertion, the ultrasound probe should be placed so that the artery is at the right side of the image for the right leg and the left side for the left leg. This ensures that the femoral nerve will appear in the middle of the image. Green bars on the right and left side of the image are used to tell the user to move the probe to the left or right so that this is achieved. The nerve and fascia segmentation of the ultrasound image does not start until the target probe position is reached and the probe is kept still.

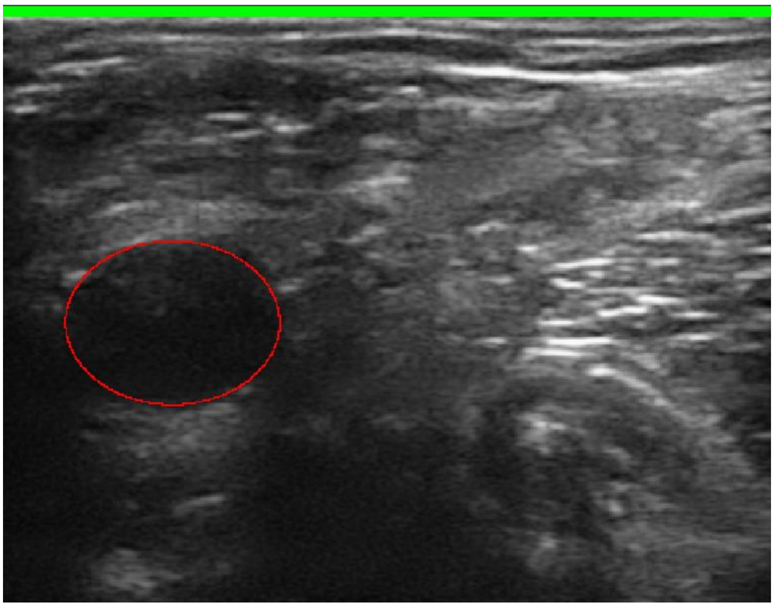

Figure 4: Green bar on top is a visual cue to the user indicating that the probe should be moved upwards on the patient.

3.5 Ultrasound image segmentation

3.5.1 Femoral artery

The femoral artery is modelled as an ellipse in a slice normal to the vessel. The artery is first detected by a novel GPU-based algorithm which initializes the artery tracking. This algorithm is completely automatic and requires no user interaction. The methods do a brute-force search for black ellipses in the ultrasound image. A measure of fit is calculated by comparing the image gradients of the smoothed ultrasound image to the normal vectors of an ellipse. Each pixel in the image is investigated and several different major and minor radii ranging from 3.5 to 6 mm is used. The best scoring ellipse is kept and if the score is above a certain threshold, it is accepted and used to initialize the tracking of the artery. The artery tracking is achieved with an extended Kalman filter and the ellipse model. The Kalman filter predicts the position and shape of the artery for each image frame. The prediction is corrected by edge measurements performed along the normal vectors of the current ellipse. This is used to create an estimate of the position and shape of the artery for the current image frame. If the artery moves out of the image, or the edges disappear, the tracking stops. The artery detection algorithm will then take over to look for a black ellipse to initialize the tracking again. These methods are described in detail in [1].

3.5.2 Fascia lata and fascia iliaca

Fascia lata and fascia iliaca are two layers which have to be penetrated by the needle to reach the femoral nerve. These fascias can vaguely be seen in the ultrasound images as bright horizontal curves (Figure 5). The fascias are extracted from the ultrasound image using the artery location provided by the artery tracking algorithm.

The algorithm first extracts the fascia lata which is above the fascia iliaca, the nerve and the femoral artery. A fascia probability is calculated for each pixel in the ultrasound image. This is based on the distance from the skin surface (the top of the image), the distance to the femoral artery and the presence of bright edges. The presence of bright edges will increase the probability that the current pixel is part of a fascia. Edges are located using the Laplacian of Gaussian algorithm in FAST. A dynamic programming method is used to find the cheapest path from the distal side of the image to the artery. A cheap path is a path which is smooth and goes through high probability pixels. After the fascia lata has been extracted, the fascia iliaca is extracted in the same way. However, the fascia iliaca is also required to be below fascia lata and pass on below the artery.

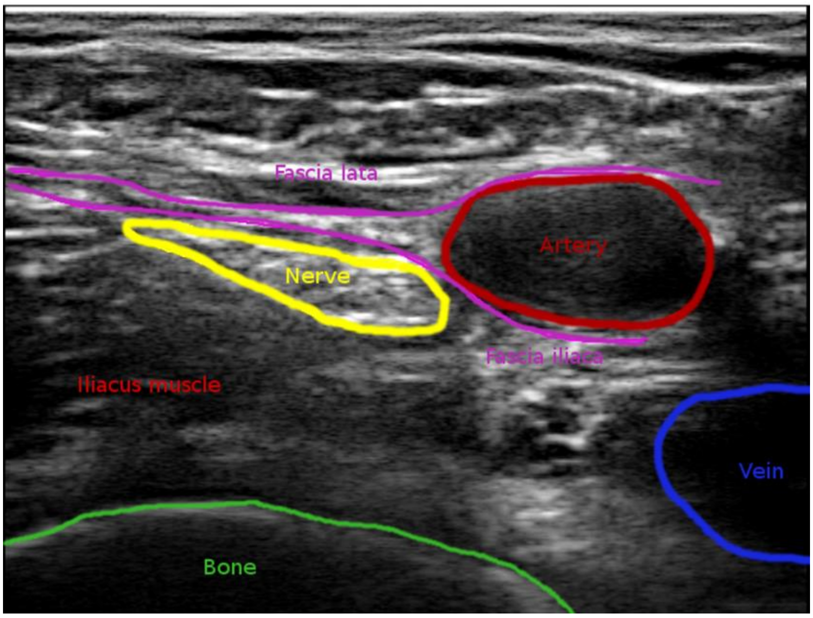

Figure 5: Ultrasound image of the femoral nerve.

3.5.3 Femoral nerve

The femoral nerve should be located below the fascia iliaca, lateral to the femoral artery and resting on the iliacus muscle as shown in Figure 5. The femoral nerve segmentation algorithm therefore uses the already acquired position of the fascia iliaca and femoral artery to find the nerve. The appearance of the nerve in the ultrasound image is bright and sometimes with a honeycomb like texture pattern. The iliacus muscle below the nerve is darker with a different texture. Similar to the fascia segmentation, a probability of femoral nerve is first calculated for each pixel in the ultrasound image. The probability is dependent on the intensity of the pixel and the distance from fascia iliaca. The nerve is not thicker than a couple of mm and thus pixels further away from the fascia iliaca will get a low/zero probability.

After the nerve probability map has been generated it is thresholded to create a segmentation. Holes are then removed from the segmentation using a morphological close operation with a radius of 2 pixels. Any thin parts (< 1 mm) of the segmentation is removed and the largest remaining segmentation object is retrieved using a flood fill method. Finally, the convex hull of this object is created to form a smooth representation of the femoral nerve. All methods except the flood fill and convex hull calculations are done on the GPU to achieve real-time performance.

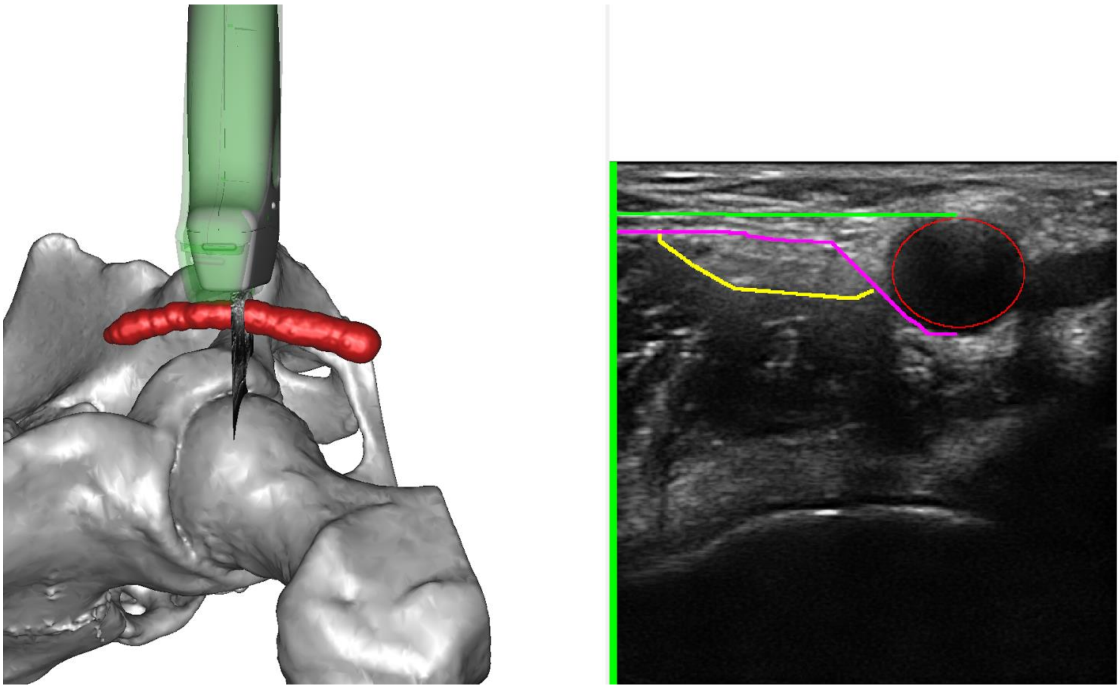

Figure 6: When the probe is placed and kept still at the target area, the ultrasound image will be segmented as shown to the right in this figure.

4 Guidance accuracy

Ultrasound sequences from both the right and the left legs of 6 subjects were acquired in order to measure the accuracy of the target estimation, model registration and segmentations algorithms.

4.1 Target estimation accuracy

The accuracy of the target estimation algorithm was measured by calculating the distance between the estimated target (using the data acquired by the expert) and the final probe position reached by the expert anesthesiologist (acquired with the assistant functionality turned off). Table 1 contains the distances between the estimated target and the target suggested by the expert. On average, the distance was 8.5 mm, with a maximum of 12.8 mm.

Subject	Leg	Target distance(mm)
1	Right	9.5
1	Left	12.8
2	Right	11.0
2	Left	10.1
3	Right	9.5
3	Left	4.7
4	Right	6.6
4	Left	5.0
5	Right	8.6
5	Left	10.7
6	Right	6.9
6	Left	6.4
Average		8.5
Std. Dev.		2.4
Maximum		12.8

Table 1: Distance in millimeters between estimated target and that of an expert anaesthesiologist for each subject and leg (left/right).

4.2 Model registration accuracy

The registration method was evaluated by measuring the distance from each centerpoint obtained with the artery tracking method to the femoral artery centerline of the registered model. The distance was calculated for the entire extracted centerline, thus for the entire scanned area. The mean distance was 2.7 mm, while the average maximum distance was 12.4 mm. Anatomical subject variations of the femoral artery and the artery landmarks are most likely the main causes of the registration error. Currently, a static model of the surrounding anatomy is used, which does not incorporate the anatomical variations seen in a population. However, the model is only used to give the operator an overview of the surrounding bone anatomy. No anatomically invalid orientations were created by the registration, nor were the bone mesh and artery mesh intersecting for any of the acquisitions. It was discovered that the maximum error occurs superior to the inguinal ligament at the artery centerpoints furthest away from the target point. An area which is not of great interest to the procedure. A higher maximum error was observed in those subjects with a very different height compared to the model.

4.3 Image segmentation accuracy

The femoral artery, femoral nerve, fascia lata and fascia iliaca were manually segmented by an expert anesthesiologist in one image frame for each of the image sequences. The mean absolute difference (MAD) between the segmentation contours of the manual segmentations and the result were used to measure the accuracy of the femoral nerve and fascia segmentations. The Hausdorff distance was calculated for the femoral artery and nerve segmentations. For fascia lata and iliaca the maximum distance was calculated instead. For the femoral artery and nerve, the closest contour points of the segmentations were used to calculate the MAD and Hausdorff distance. However, for the fascia segmentations, only vertical distance was used. This was because the lengths of both the manual segmentations and algorithm segmentations were different. These accuracy measurements are all collected in Table 2.

Subject	**Femoral artery**		**Femoral nerve**		**Fascia lata**		**Fascia iliaca**	
	MAD	Hausdorff	MAD	Hausdorff	MAD	Max	MAD	Max
1	0.3	1.0	2.0	8.2	1.4	3.0	1.8	3.9
2	0.3	0.9	1.5	8.5	1.2	2.3	1.4	3.9
3	0.4	1.3	2.6	8.5	0.4	3.6	1.4	3.3
4	0.4	1.1	1.9	7.1	0.7	3.4	1.4	9.5
5	0.4	1.1	2.1	8.1	1.8	4.2	1.7	4.3
6	0.3	0.9	1.6	8.5	1.0	1.8	1.1	4.3
Average	0.3	1.0	1.9	8.2	1.1	3.1	1.4	4.9
Std. Dev.	0.0	0.1	0.3	0.5	0.5	0.8	0.2	2.1
Maximum	0.4	1.3	2.6	8.5	1.8	4.2	1.8	9.5

Table 2: Segmentation accuracy in millimeters.

5 Deviations/Problems

Due to the lack of image and position data from actual clinical cases where the needle is used, we were not able to implement all the guidance features. This includes the enhancement of anesthetics spread. Also, only a few needle guidance features were implemented which have not been evaluated properly. We plan to address this in the remaining time of the project, provided that we receive clinical data from the clinical partners in the project and that sufficient reminding resources are available.

6 Further work

Although, the artery detection and tracking methods work quite well, we experienced that it sometimes fail. To increase the robustness of the system, Doppler measurements may be employed. The artery should give a high Doppler response. This will however require more direct interaction with the Ultrasonix ultrasound system.

Some needle visualization and guidance have been implemented already as described in D5.3. However, more can be done with this feature, for instance suggesting a needle insertion point and trajectory after the nerve has been identified in the image. Implementing needle guidance features will however require clinical position and image data in which the needle is inserted into actual patients.

We also plan to further improve the guidance system based on feedback from the clinical partners over the next months when they receive the prototypes.

7 Publication/Disseminations

7.1 Journal publications

Real-Time Automatic Artery Segmentation, Reconstruction and Registration for Ultrasound-Guided Regional Anaesthesia of the Femoral Nerve. Erik Smistad and Frank Lindseth. IEEE Transactions on Medical Imaging 2015. URL: http://dx.doi.org/10.1109/TMI.2015.2494160

Automatic segmentation and probe guidance for real-time assistance of ultrasound-guided femoral nerve blocks. Erik Smistad, Daniel Høyer Iversen, Linda Leidig, Janne Beate Lervik Bakeng, Kaj Fredrik Johansen and Frank Lindseth. Unpublished, will be submitted to Medical Image Analysis.

7.2 Conference presentations/posters

Automatic real-time annotation of important landmarks in ultrasound-guided femoral nerve blocks. Frank Lindseth, Erik Smistad, Linda Leidig, Daniel H. Iversen1 and Janne Beate L. Bakeng. Eurographics Workshop on Visual Computing for Biology and Medicine (VCBM) 2015 in Chester, UK, 14th-15th September 2015

An assistant for improved ultrasound-guided regional anaesthesia of the femoral nerve. Erik Smistad and Frank Lindseth. MedViz Conference 2015 in Bergen, Norway, 15th -16th of June 2015.

8 Reference Documents

- Deliverable 4.5 – Guidance Systems Specification
- Deliverable 5.4 – RAAs Prototypes (with “user manual” report.
- Deliverable 8.4 and 8.5 – Exploitation plan 1 and 2 for the assistant.
- Milestone 6 - RAAs function available on the portable prototypes.
- RAAs system introduction video: https://www.youtube.com/watch?v=ptRF6dv43HA