Accuracy of navigated percutaneous needle insertions

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Abstract:

A navigation system for radiological interventions (CAS-One IR, CAScination, Bern) has been used to evaluate three different needle insertion methods on a non-rigid liver phantom. The insertion methods under investigation include: navigated free-hand needle insertion, aiming device-based insertion with active depth control and aiming device-based needle insertion with passive depth control. For each method a series of 25 punctures was performed and assessed by computing residual error (RE) given by the system and target positioning error (TPE) given from control CT scans.

Keywords: navigation system, interventional radiology, aiming device

1 Problem

In minimally-invasive percutaneous radiological interventions,such as radiofrequency or microwave ablation, the success of treatment is highly dependent on accurate placement of the ablation needles. In order to aid with this process, before each intervention a patient-specific treatment plan is created. This plan defines a set of ideal needle trajectories avoiding critical anatomical structures. However, it is still up to the radiologist´s experience and skills to mentally transfer this information to the surgical site. Hence, in terms of accuracy and patient safety, the usage of stereotactic CT-image-guided navigation systems may be beneficial, especially for difficult out-of-plane trajectories [1]. As presented in previous studies, navigated percutaneous radiofrequency ablation of primary and secondary liver malignancies improve therapeutic outputs and may achieve equivalent results to the open liver surgery [2].

The main challenge in stereotactic navigation is soft tissue deformation and patient motion, which cause undesired changes in the treatment site [3]. Therefore, minimization of this deformation through respiratory control (such as temporary disconnection of the endotracheal tube in anaesthetized patients during intervention and image acquisition), appropriate body fixation or patient tracking technology seems necessary [4]. Alternatively, one can estimate the position of the moving target using implanted needle-shaped optically tracked navigation aids and a real-time deformation model [5]. Nonetheless, even with feedback from navigation systems it is still difficult to stabilize the needle in a desired orientation as well as to prevent additional bending during needle insertion.

Several needle insertion methods have been developed in response to these problems. Robotic assisted needle interventions have been developed to tackle tissue deformation and needle bending,which could change the needle track and cause displacement at the target [6]. Although operator errors may be reduced, the clinical acceptance of robotic needle guidance is currently low due to high complexity and costs of such systems. The use of a passive, mechanical aiming device, such as this presented in work, may provide accurate targeting while keeping the procedural complexity and costs low [2].

The aim of this study is to compare the feasibility and accuracy of three different needle insertion methods in a non-rigid liver phantom: navigated free-hand needle insertion, needle insertion with the mentioned aiming device and active depth control as well as needle insertion with the aiming device and passive depth control. All experiments were performed using a navigation system (CAS-One IR, CAScination, Bern) equipped with a non-rigid, automatic registration method.

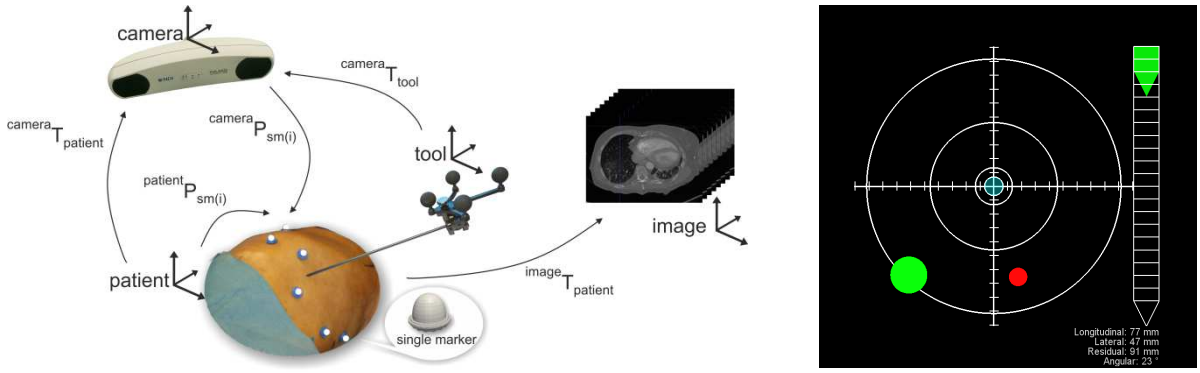
2 Methods

Navigation system
The CAS-One Liver navigation system [7] has been adapted to carry out CT-guided percutaneous needle interventions [8]. The navigation system consists of a workstation that is attached to a movable cart, user interface, an optical position

measurement system (NDI Vicra, Northern Digital, Canada) and a set of custom-made marker shields with retro-reflective passive markers that can be adapted to a variety of tools, enabling their accurate tracking within the operating room.

Real-time patient tracking is done using a set of single retro-reflective marker spheres (SM) that are attached to the patient skin around the area of the expected needle incisions (Fig.1a). A sterilizable plastic shell around the marker and biocompatible tape allow integration of SM into clinical scenarios.

Navigation proceeds as follows: when the needle tip is placed at the entry of the planned trajectory, a targeting viewer is enabled (Fig.1b). By projecting the needle tip (red dot) and shaft (green dot) on a 2-dimensional plane placed at the target, the operator is visually aligning the needle with the planned trajectory. A depth bar on the right indicates, the distance from the needle tip to the planned target as well as the following supplementary errors: residual error separated into longitudinal and later components, angular error. A cross-sectional view at the needle axis visualizes anatomical obstacles along the trajectory.



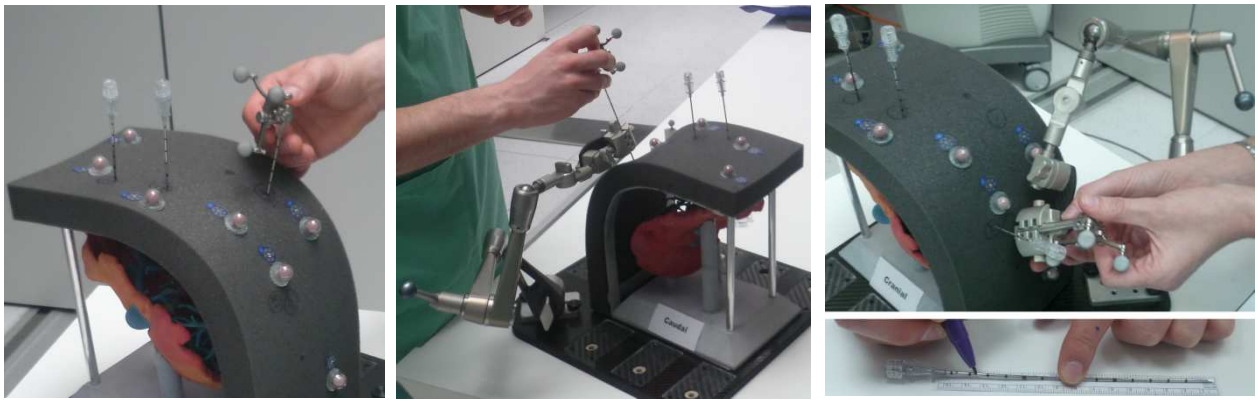
a) b)

Fig.1: Coordinate systems and transformations for automatic registration method using single retro-reflective marker spheres (SM) in CAS-One IR navigation system (a); targeting viewer for active depth control (b).

Experiment

Three series of 25 punctures were performed on a non-rigid liver phantom. The phantom was produced by rapid prototyping using a segmented 3D model of the liver (MeVis Distant Services, Bremen, Germany) that included several anatomical obstacles (portal vein, hepatic vein) and tumors, which require careful planning and needle placements. 1 mm metal screws were fixed on the liver phantom and used as targets. The liver phantom was placed under deformable plastic foam (Fig. 2) in order to simulate the patient skin. Six single markers were attached to the surface of the foam in a non-symmetrical configuration for the automatic registration. The following needle insertion methods were then evaluated on the presented phantom:

1) **Navigated free-hand needle insertion:** The procedure does not utilize any stabilization device during the puncture. After definition of the trajectory, the marker shield is placed on the needle shaft. The position and axis orientation of the needle are obtained from calibration. The operator moves the needle above the entry and guides the needle towards the target based on the information shown on the targeting viewer and depth bar (Fig. 2a).
2) **Navigated needle insertion with the aiming device and active depth control:** The procedure uses an aiming device (ATLAS, Elekta AB, Sweden) to provide stabilization during the adjustment of the needle to the planned trajectory and allow fixation of the final orientation of the needle during the insertion. While screwed to the CT table, an 8mm-thick, rigid, medical-grade titanium cylinder, with an attached marker shield, is used to guide the insertion brackets of the aiming device to the planned entry point. Once the position of the aiming device is correct, the cylindrical tool is removed from the aiming device and replaced with a calibrated needle. During insertion, depth information is shown on the targeting viewer (Fig. 2b).
3) **Navigated needle insertion with the aiming device and passive depth control:** The procedure differs from the method presented above in that the needle insertions are not monitored by the navigation system. Once the position and orientation of the aiming device correspond to the planned trajectory, the distance between the tip of the cylinder and the target is displayed on the navigation system. This distance is then marked on the needle with a biocompatible pen. The cylinder is removed from the aiming device and the needle is inserted up to mark on the needle (Fig. 2c).



a) b) c)

Fig.2: Evaluated methods: navigated free-hand needle insertion (a), navigated needle insertion with the aiming device and active depth control (b) and method with the aiming device and passive depth control (c).

Accuracy assessment

Before each needle insertion, the fiducial registration error (FRE) was measured from the SM tracking system. After needle insertion, the residual error (RE) was stored and the target positioning error (TPE) was evaluated on a control CT dataset. RE measures the distance between the needle tip and the target in the navigation coordinate system. This error expresses how accurately the operator may transfer a trajectory to the patient based on a given visualization scheme. FRE was computed by the system as the root mean square error between registered corresponding points. TPE was measured on the control scans as the distance between the needle tip and the planned target [10]. TPE was separated into longitudinal (along the planned trajectory) and lateral components (along the orthogonal direction). The angular error of each needle insertion was also computed.

3 Results

The average FRE measured among all methods just before needle insertion was 0.7 ± 0.1 mm, with a maximum value of 0.9 mm.

Targeting accuracy is described in Table 1. The Euclidean TPE is similar for each method (ranging from 4.6 ± 1.2 to 4.9 ± 1.7 mm), however lateral error components are significantly lower for the method using the aiming device (unpaired t-test, p = 0.01). The longitudinal error component is markedly lower for the free-hand method without utilization of the aiming device. The highest average angular error was measured for the free-hand insertion. Methods using the aiming device have a lower angular error but the difference was not significant. RE represents the error given by the navigation system at the final needle position and is similar for both methods with needle guidance (free-hand needle insertion and aiming device-based with active depth control). RE values are not available for the method with passive depth control as needle insertion was not monitored by the navigation system.

Table 1 - Comparison of mean and standard deviation of TPE and RE along different directions as well as final angular error for three presented navigation methods.* represents statistically significant difference from free-hand insertion.

Method		Navigated free-hand needle insertion	Needle insertion with aiming device and active depth control	Needle insertion with aiming device and passive depth control
TPE	Longitudinal [mm]	2.1 ± 1.2	3.3 ± 1.6	3.7 ± 1.3
	Lateral [mm]	4.2 ± 2.0	*2.8 ± 1.6	*2.3 ± 1.3
	Euclidean [mm]	4.9 ± 1.7	4.6 ± 1.3	4.6 ± 1.2
	Angular[°]	1.8 ± 0.9	1.1 ± 0.6	1.2 ± 0.8
RE	Longitudinal [mm]	1.1 ± 1.0	1.2 ±1.0	-
	Lateral [mm]	1.8 ± 1.2	1.8 ± 1.0	-
	Euclidean [mm]	2.3 ± 1.2	2.2 ± 1.2	-

4 Discussion

An *in vitro* accuracy evaluation of three needle insertion methods was performed with a navigation system dedicated for percutaneous needle interventions utilizing a non-rigid single sphere-based method for patient tracking.

TPE represents the final positioning error of the needle; it includes registration, tracking, user, and process errors such as needle bending, however in this case it does not include errors introduced by patient motion. Average measured Euclidean TPE (4.6 ± 1.2 mm, maximum 8.1 mm) was similar for all methods and comparable to previously reported accuracy. For example, Maier-Heinet al. [9] performed 32 free-hand punctures in an *in vivo* experiment with ventilated swine and reported an overall error of 3.7 ± 2.3 mm and maximum error of 11.1 mm. Neither lateral, longitudinal nor angular error components were computed.

Separating TPE into longitudinal and lateral components is of clinical relevance because the correction of lateral placement errors, unlike longitudinal errors, requires replacement of the needle, which is time-consuming and increases the risk for complications. The lowest lateral errors were achieved using the aiming device (2.3 ± 1.3 mm and 2.8 ± 1.6 mm respectively). These results are statistically significantly better than in the free-hand case. The reason behind this may be that during free-hand insertions it is difficult to maintain the correct needle trajectory angles while advancing the needle into the phantom. The accuracy of the navigated free-hand needle placement depends largely on the surgeon's hand-eye coordination and ability to guide the needle based on the feedback provided by the navigation system. It is essentially impossible to effectively correct the needle path once insertion has commenced; any attempts to correct needle position will cause bending and displacement at the target.

Additionally, these results show that active depth control does not provide accuracy improvements when compared to passive depth control. However, tracking of the needle during insertion may allow detection of potential damage to critical anatomical structures while inserting a needle.

This study has presented an *in vitro* comparison of three needle insertion methods. The results obtained demonstrate that usage of an aiming device leads to increased lateral accuracy during needle insertion.

5 References

[1] Najmaei N, Mostafavi K, Shahbazi S, Azizian M. «Image-guided techniques in renal and hepatic interventions.» *The International Journal of Medical Robotics and Computer Assisted Surgery*, 2012.

[2] Schullian P, Widmann G, Lang TB, Knoflach M, Bale R. «Accuracy and diagnostic yield of CT-guided stereotactic liver biopsy of primary and secondary liver tumors.» *Computer Aided Surgery*, 2011.

[3] Clifford M,Banovac F, Levy E, Cleary K.«Assessment of hepatic motion secondary to respiration for computer assisted interventions.» *Computer aided surgery*, 2002.

[4] WidmannG, Schullian P, Haidu M, WiedermannF.J, Bale R. «Respiratory motion control for stereotactic and robotic liver interventions.» *The International Journal of Medical Robotics and Computer Assisted Surgery*, 2010.

[5] Maier-Hein L, Müller SA, Pianka F, Wörz S, Müller-Stich BP, Seitel A, Rohr K, Meinzer HP, Schmied BM, Wolf I. «Respiratory motion compensation for CT-guided interventions in the liver.» *Computer Aided Surgery*, 2008.

[6] AbolhassaniN, Patel R. V. «Minimization of needle deflection in robot-assisted percutaneous therapy.» *Int J Med Robotics Comput Assist Surg*, 2007.

[7] PeterhansM, Weber S. «A navigation system for open liver surgery : design, workflow and first clinical applications.» *International Journal of Medical Robotics and Computer Assisted Surgery*, 2010.

[8] Kettenbach J, Toporek G, Wallach D, Peterhans M, O. Dos Santos, Weber S. «Feasibility evaluation for an optical, single-marker based navigation system for image-guided percutaneous ablation treatments.» *Radiological Society of North America 2012 Scientific Assembly and Annual Meeting. Chicago IL*, 2012.

[9] Maier-Hein L, Tekbas A, Seitel A, Pianka F, Müller SA, Satzl S, Schawo S. «In vivo accuracy assessment of a needle-based navigation system for CT-guided radiofrequency ablation of the liver.» *Medical physics*, 2008

[10] Widmann G, Stoffner R, Sieb M, Bale R. «Target registration and target positioning errors in computer-assisted neurosurgery: proposal for a standardized reporting of error assessment.» *Int J Med Robot*, 2009.