A study of porcine liver motion during respiration for improving targeting in image-guided needle placements

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Abstract

Purpose Liver motion due to respiration restricts targeting and needle placement accuracy during image-guided interventional procedures. Breath holds, imaging techniques, and navigation systems are used to improve targeting accuracy. Data of in-vivo liver behavior under respiration can enhance these approaches.

Methods An experimental study was performed using the swine model to capture the dynamics of liver motion during respiration using needles tipped with electromagnetic sensors. The swine liver was segmented into four lobes (right lateral, right medial, left medial and left lateral), and two sensor-tipped needles were placed in each location to acquire representative displacement data.

Results Maximum displacement was found to occur in the left medial and left lateral lobes, in the anterior–posterior direction. Significant lobe-dependent variation in motion behavior was recorded, but a variation within a lobe was minimal and independent of needle approach. Magnitude of displacement in all lobes was found to be monotonically correlated to breathing volume. Displacement of liver was found to be out of phase with breathing by approximately 2 Hz. The positioning of the animal was also found to influence direction and magnitude of liver displacement in different lobes.

Conclusions We have presented previously unavailable data and insight into the role of easily controllable parameters such as breathing volume, patient positioning, and lobe-specific heterogeneity in the displacement of liver due to respiration.

Keywords Interventional oncology · Liver · Respiratory motion · Percutaneous needle placement · Computer aided navigation

Introduction

The accuracy of image-guided needle placement in the liver during interventional procedures can be affected by liver motion due to respiration. This significant impediment to accurate needle placement is currently mitigated by techniques such as breath holds, respiratory gating [1, 2], imaging techniques and navigation systems. However, many cancer patients are aged and can be physiologically weak, exhibiting irregular breathing patterns that pose difficulties in performing consistent breath holds. Additionally, patients may also be sedated and cannot cooperate with the physician during the procedure. Therefore, there has been considerable research in developing technological aids to help the physician improve targeting accuracy. Most prominent among these are the use of electromagnetic (EM) sensors for respiratory gating. Wood et al. [3] and Solomon et al. [4] explored and confirmed the early feasibility of embedding EM sensors in needles and catheters for aiding image-guided procedures.
in the liver. Banovac et al. [5] and Borget et al. [6] were among the first research groups to attempt using EM sensor-tipped needles to aid targeting. Krucker et al. [7] conducted a study using a combination of internally placed reference needles, skin fiducials and needles with EM sensors on their tips. Studies with similar approaches and results have also been reported by Zhang et al. [8], Nagel et al. [9] and Bricault et al. [10]. Most recently, Lei et al. [11] performed reconstruction of a flexible needle implanted with multiple EM sensors. Unlike prior studies, the sensors were used to reconstruct needle shape, thereby capturing not just the needle tip location but also the flexion relative to entry point. Khan et al. [12] attempted augmenting the use of EM sensors by providing a graphical overlay on the patient to guide needle placement. Concurrently, research has looked at the use of fiducial markers and optical navigational assists to improve targeting accuracy. This includes use of optical tracking systems and guide needles as demonstrated by Maier-Hein et al. [13] and de Baere et al. [14]. The utility of fiducials placed both internally and externally was investigated by Beddar et al. [15]. Hostettler et al. [16] hypothesized that primary breathing motion occurs due to exertion of the intercostal muscles, and the pelvic diaphragm. They used this hypothesis to place optical markers on the skin close to corresponding locations and then used these markers to register with CT data and track the tumor. Simulation and modeling has been another approach used to evolve a better understanding of liver dynamics during breathing; to aid targeting. Work in this area includes a dynamic internal margin statistical model by Coolens et al. [17] and a parametric FEM deformation model by Nguyen et al. [18].

Unfortunately, targeting and navigational aids have some inherent shortcomings that have reduced enthusiasm for their wider clinical adoption. Optical navigation techniques have been reported to suffer from errors due to ambient light, set up and calibration problems, and line of sight issues. Use of fiducial markers has been associated with marker migration, inflammation and unnecessary complications due to additional punctures [19]. EM sensors for navigation have yielded positive results in general and form the basis of multiple commercially available navigation systems. However, in cases where the EM sensor was placed on the needle hub (navigation during RF ablation), flexure can introduce a large degree of error during navigation. Also, the practical workspace of an EM sensor is relatively small, and this volume is easily degraded in the presence of ferrous metals.

Direction of needle approach, tidal volume of respiration and patient positioning are breathing-related factors that directly impact liver motion. More importantly, these parameters can be easily controlled in a clinical setting. In addition to this, literature suggests that motion in liver due to respiration is nonlinear [20], and simulation models suggest that magnitude and direction of displacement varies widely between lobes [17,18]. While there have been a few studies [15,18,20] that report typical displacement values of the liver in different directions, lobe-specific motion is poorly studied. Clifford et al. [20] in a review of the literature reported that there was wide disagreement in the reported average displacement and dominant directions of motion. They noted that the majority of reported data came from observations of the organ boundary as observed on imaging during respiration. They suggest that due to this technique of study, there could be substantial uncertainty in the actual estimated motion within a given lobe. Additionally, there is little information on the magnitude of torsion and displacement hysteresis exhibited by the organ, briefly addressed by Coolens et al. [17].

We propose to address this research gap by performing a study of the swine liver using EM sensor-tipped needles. The study maps the effect of nonsubject-specific factors on liver motion and captures their impact on displacement values of different locations in the liver. The study will provide previously unavailable in vivo data, measured using multiple probes that have independently gathered data from multiple locations within the four major lobes of the swine liver. Along with previously identified factors, understanding of lobe-specific motion behavior can help develop clinical strategies to improve targeting accuracy. Availability of such data may also help improve accuracy of some of the existing navigational and targeting aids.

Materials and methods

Equipment

An EM-based measurement system developed by General Electric Research (GE, Buc, France) was used for the animal experiments. The EM sensors in the system were constructed using equipment from the medSAFE product line by Ascension Inc. [21]. The EM measurement system consists of four parts (Fig. 1). The sensor itself is enclosed in a plastic casing that includes an integrated hub and can be assembled into a hollow introducer needle. Other equipment of the measurement system includes a base transmitter, the sensor communication hardware, and a workstation for data collection. Once assembled with the introducer needle, the EM sensor is housed close to the tip of the needle. The EM sensors are 9 mm long and 1 mm in diameter and capable of providing all 6 degrees of freedom (d.o.f) of displacement information. A second EM sensor is mounted on a plastic frame and secured to the sternum of the animal. The second sensor serves as a reference for compensating gross patient movement and respiration. The frame of the second sensor has fiducial markers that can help in registering the needle tip with CT images if necessary and acts as the local reference.