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A region-based anatomical landmark configuration for sinus surgery using image guided navigation system: A phantom-study

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ABSTRACT

Purpose: To evaluate the current beliefs about the ways to reduce target registration error (TRE) values in image guided Sinus surgery by rearranging the fiducial configuration, and investigating the best configurations for various surgical fields in a phantom study.
Methods: A new CT-compatible skull phantom consisting of implanted targets was designed to enable direct measurement of TRE in four fields of sinus surgery, Frontal, Ethmoid, Sphenoid and Maxillary. The effects of different landmark configurations on TRE values, measured by the Parsiss-IV navigation system were investigated to find the best landmark arrangement for each region, and compared to the TRE prediction formula to assess the clinically accepted landmark selection approaches based on this formula.
Results: It was shown that smaller values of TRE could be attained by arranging the center of the fiducials to be more focused on the surgery target. The addition of more fiducials and keeping non-linear arrangement of landmark would not necessarily decrease the TRE value.
Conclusion: Optimizing the landmark configuration is important for increasing the localization accuracy in image guided sinus surgery. The common beliefs accepted in the clinical community about the ways to reduce the TRE are very general and should be adapted to specific field of image guided surgery.

1. Introduction

Image guided surgery (IGS) systems have become indispensable tools in sinus surgery (Hemmerdinger et al., 2005; Fei et al., 2007). These systems require precise localization of targets in order to ensure the accurate tracking of the surgical tools. In order to do so, corresponding fiducial markers, which may be invasive implanted markers on the skull, non-invasive adhesive markers, dental splints, or anatomical landmarks, in the pre-operative image space and the physical space should be aligned through rigid-body point-based registration (Maurer and Fitzpatrick, 1993; Fitzpatrick et al., 1998; Hardy et al., 2006). In recent years, different registration strategies employing invasive or non-invasive fiducial markers have been under investigation in several head and neck surgical scenarios, including brain, sinus and cranio-maxillofacial surgery. Among various registration approaches, the anatomical landmark registration has been most commonly used in practical situations, as it utilizes the anatomical features, which are natural markers, and is non-invasive and simple (Maurer et al., 1995; Maurer et al., 1998; Claes et al., 2000; Hong et al., 2009; Lübbers et al., 2011).

The error associated with point-based registration of fiducial markers, as the result of localization errors, can be provided for the surgeon by directly measuring the error of fiducial alignments using the navigation system. This error could have negative impacts on the registration of the targets of surgery, which cannot be directly measured by the navigation system. Thus, it is important to obtain good knowledge of the sources of errors for surgical guidance by evaluating the main measures of error: the fiducial localization error (FLE), fiducial registration error (FRE), and target registration error (TRE) (Maurer et al., 1998; Fitzpatrick and West, 2001; West et al., 2001; Labadie et al., 2005).

Through extensive studies in various surgical scenarios, it has been shown that the accuracy of TRE calculation is not only determined by accurate localization of the fiducials, but also

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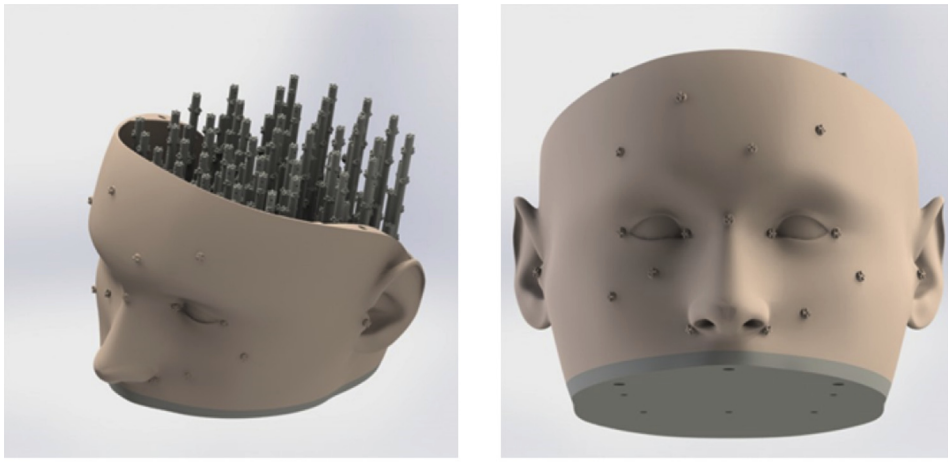

Fig. 1. (a) View of the Parsiss Skull Phantom (PSP); (b) Anatomical points as landmarks, placed on the face.

influenced by their number and distribution (Fitzpatrick et al., 1998; Claes et al., 2000; Sun et al., 2012). Fitzpatrick et al. by assuming identical independent distribution for FLE, introduced an equation to predict an approximation of TRE (Fitzpatrick et al., 1998). In 2001, West et al., using cranial MR/CT images tested TRE values, calculated by Fitzpatrick's formula over various arrangements of fiducial markers. They concluded that the arrangement and the number of fiducials can significantly affect the TRE. Their recommendations for lower TRE values include spreading the fiducial placement around the target of surgery, while keeping the center of gravity closer to the target, employing more fiducials and arranging fiducials non-linearly (West et al., 2001).

The above recommendations are very general to follow and do not provide the surgeons or operating room (OR) technicians with specific rules for the best selection of fiducials (Shamir et al., 2009a; Shamir et al., 2009c). Optimization of the fiducial configuration plays a more important role than the abovementioned guidelines for fiducial placements (Atuegwu and Galloway, 2008; Shamir et al., 2009b).

In image guided sinus surgery, the problem of optimal landmark configuration has not been well studied. This problem was the main motivation for the authors of this paper to address the effect of landmark distribution in a more direct and focused way. In this work, we aim to provide ENT surgeons with some specific guideline about the best landmark selection strategy in different operation fields during sinus surgical navigation. We tackled this issue by relying on previously mentioned observations about the fiducial selection and distribution, and followed them in a more practical way, by considering the available and most rigid anatomical points surrounding the field of surgery, namely Frontal, Ethmoid, Sphenoid, and Maxillary.

For evaluating the accuracy of navigation more precisely, we designed a unique skull phantom, called Parsiss Skull Phantom (PSP©) similar to the human skull. To have a better understanding about the TRE values in the targets located inside the skull, artificial targets were inserted inside the phantom and spread out over anatomically important sites, providing suitable accessibility of the markers to the operator. Several fiducials were also embedded in the locations of most important anatomical landmarks, on the phantom face.

The importance of the distribution and number of fiducials for image guided sinus surgery were then evaluated employing Parsiss© ImageVision, IV Guided Navigation system on PSP. This paper concludes by incorporating the information gathered by TRE values computed using Fitzpatrick's prediction formula with the measured TRE values, to recommend which fiducial point configuration is better to be utilized for each surgical field in sinus surgery.

2. Materials and methods

2.1. Data acquisition

A unique skull phantom was designed and fabricated as a reference for navigation system, as shown in Fig. 1. To achieve the best possible design, an extensive study was performed to gather the necessary information. The most important features of this design are the similarity of the skull phantom to the human skull, presence of enough markers located at the anatomically important places with good accessibility of the markers to the navigation operator.

On the phantom face, 17 fixed fiducial points are embedded in the locations, which are most commonly used as anatomical landmarks for registration during image guided surgery of head and neck.

These fixed fiducial markers provide easier access in different directions for navigation purposes (Fig. 1). The phantom is equipped with 732 intra-cranial numbered columns, for TRE evaluation in the inaccessible target locations in various surgical fields, i.e. Frontal, Ethmoid, Maxillary and Sphenoid.

The CT scanning was performed using a multi-slice CT scanner, with no gantry tilt, a slice thickness of 0.6 mm, without 3D reconstruction, with tube current of 400 mA and the Field of View (FOV) including the entire head and mid-face.

2.2. Configurations of anatomical landmarks

In this work, we tested 11 configurations of 4–8 anatomical landmarks, which were performed and tested clinically during extensive experiences of our team during image guided ENT surgery using Parsiss©[1] system and approved to provide the best registration errors. Hereafter, we describe each configuration as a fiducial distribution "pattern". The underlying concepts behind the proposed selection of the anatomical landmarks (fiducial points on the phantom) in the configurations are as follows: (1) the nose bridge landmark is selected, as it is easy to find and due to its central position on the face, it provides a suitable place to adjust the