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# Effect of fiducial configuration on target registration error in image-guided cranio-maxillofacial surgery☆

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ABSTRACT

*Objective:* To investigate the effect of the configuration of fiducials on target registration error (TRE) and test the accuracy of theoretical model of TRE prediction in image-guided cranio-maxillofacial surgery.
*Methods:* A skull specimen was prepared with 20 titanium microscrews placed at defined locations and scanned with a 64-slice spiral computed tomography unit. These markers were separated into a registration fiducial group and a target fiducial group. An optical tracking system was used to perform skull-to-image registration procedures. Subsequent to each registration, the TRE was calculated by the navigation system. Each configuration registration was performed 50 times and the average was regarded as TRE of the configuration. The TRE prediction was also calculated for each configuration.
*Results:* The TRE ranged from 0.58 mm to 3.88 mm. Relatively smaller values of TRE may be achieved by placing a majority of fiducials on the maxillary alveolus in proximity to the target and placing a small number on the cranium contralaterally. The TRE values are always larger than the corresponding TRE prediction but there is a high correlation between them.
*Conclusion:* The configuration of fiducials is an important factor in minimizing TRE and the TRE prediction is a good guide for fiducial marker placement.


## 1. Introduction

Image-guided surgery is being increasingly used in cranio-maxillofacial surgery, for procedures such as bone modelling and reconstruction (Pham et al., 2007), implant placement (Wittwer et al., 2007), foreign body removal (Eggers et al., 2005) and radiofrequency ablation (Bale et al., 2006) and radiosurgery (Jacob et al., 2000). Compared with conventional surgery, image-guided navigation systems allow linking the preoperative 3-dimensional dataset of the patient to the patient in the operating room and tracking surgical tools by projection onto the preoperative image data in real time (Eggers et al., 2006). That makes it possible to transfer complex visual planning information to the actual operation as previously planned (Nijmeh et al., 2005). Advances in image-guided surgery have led to minimally-invasive, high-precision procedures that increase the efficacy of treatment, minimize surgical complications, and reduce patient recovery time.

In most image-guided cranio-maxillofacial surgery systems, point-based rigid transformation is used to perform the registration. First, corresponding fiducial points are defined in image and surgical space, then, a coordinate transformation is subsequently calculated to minimize the average residual distance between these corresponding fiducial points. The accuracy of the performed registration is an important factor which has direct impact on the operation quality. A good measure for registration accuracy is the target registration error (TRE) which is the distance between a pair of corresponding points not used in the registration process.

The properties of TRE have been under investigation for the last few years. Fitzpatrick derived an approximation of the root mean squared value of TRE and gave an equation for calculation of the expected TRE (Fitzpatrick et al., 1998). Moghari analytically approximated the TRE distribution up to at least the second-order accuracy based on the Unscented Kalman Filter algorithm (Moghari and Abolmaesumi, 2006). West demonstrated that improvement in

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fiducial heuristics decreased the TRE rate in neurosurgery (West et al., 2001). However, some studies reported that TRE estimator was an unreliable predictor of application accuracy in a clinical setting (Shamir et al., 2009; Woerdeman et al., 2007). In this paper, the TRE predication values are compared with the real TRE results in an experimental setting. The optimal fiducial configurations are investigated for clinically relevant cranio-maxillofacial landmark (i.e infraorbital foramen, inner canthus, orbit floor, supraorbital foramen and zygomatic process point).

## 2. Materials and methods

### *2.1. Placement of fiducial markers (Fig. 1)*

20 Titanium microscrews(diameter 1.0 mm, length 4.0) were inserted at the following locations on a cadaver skull at points that would represent a common situation in cranio-maxillofacial surgery: (1), 7 microscrews on the cranium, (2), 6 microscrews at the both infraorbital foramens, inner canthus, orbit floor, supraorbital foramen and zygomatic process, (3) 7 microscrews on the maxillary alveolus where they can be easily touched in a real registration situation.

### *2.2. CT scanning and 3D volume-rendering (Fig. 2)*

After being prepared in this manner, the skull was scanned using a 64-slice CT unit (LightSpeed VCT 64-slice Scanner, GE Inc., US) with the following parameters: helix, 0.625 mm slice thickness, tile of gantry: 0.0°, and high resolution filter. The projections were transferred as raw image data to the Stryker Navigation System expert workstation (Stryker Corporation, Kalamazoo, MI, US). The primary reconstruction was performed using filtered back projection techniques to build the 3D data volume. Secondary reconstruction was equivalent to multiplanar reformatting, allowing the operator to obtain image slices through the 3D volume in any directions. The positions of the markers were planned using three multiplanar reconstruction views and a 3D volume-rendering view.

**Fig. 1.** The skull attached with titanium microscrews.

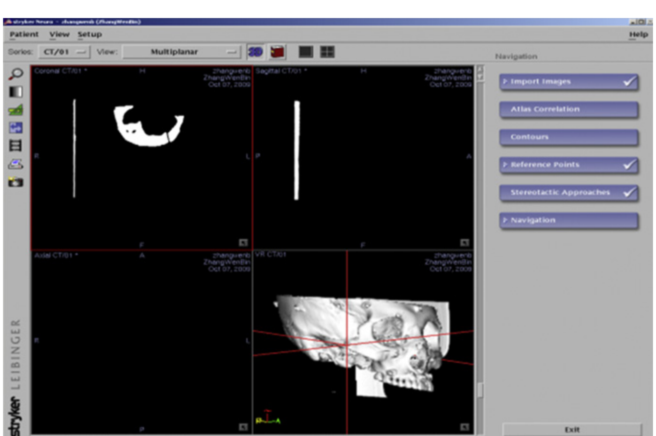


**Fig. 2.** Screenshot of 3D volume-rendering and multiplanar reformatting.

### *2.3. Registration of image and the world coordinates 3D*

These fiducial markers were defined as “registration fiducials” for image-to-world registration and “target fiducials” for TRE measurement respectively. Each registration fiducials group and target fiducials group composed a fiducial markers configuration. Frameless stereotactic localizations were performed with the Stryker Navigation System using a standard calibrated probe. Fiducial marker-based registration of the noncoplanar reference attached to the skull was used for the alignment. The registration was performed by a senior surgeon according to rigid-body point-based alignment of coordinate systems as described by Bale (Bale et al., 2006).

### *2.4. Measurement of target registration error*

After each registration procedure, the target marker was digitized and used to determine TRE. During this determination, the investigator was prevented from viewing the computer screen. The TRE, defined as the Euclidean distance between the position of a target in image space (is) and the probe point when the probe reached the target in world space (ws), was reported by the Stryker Navigation System after registration. Although the TREs measured at each fiducial were vector quantities, in general the TRE was reported as scalar values that are the length of the vector, i.e., the root mean square (RMS) of the vector components. The RMS was calculated as follows: $[(X_{is}-X_{ws})^2+(Y_{is}-Y_{ws})^2+(Z_{is}-Z_{ws})^2]^{1/2}$. Each configuration registration was performed 50 times and the average was regarded as TRE of the configuration.

### *2.5. Calculation of TRE prediction*

After each registration procedure, the fiducial registration error (FRE), which is the distance between corresponding fiducial points, was showed by the navigation system. Then the TRE prediction (F-TRE) was calculated using the following formula derived by Fitzpatrick (Fitzpatrick et al., 1998).

$$\mathrm{TRE}^2(r) \approx \frac{\mathrm{FRE}^2}{\left((N-2)\left(1+\frac{1}{3}\sum_{K=1}^{3}\frac{d_k^2}{f_k^2}\right)\right)}$$

where $N$ is the number of registration fiducials, $f_k$ is the RMS distance of the registration fiducials from the principal axis $k$ (in $x$, $y$, $z$ coordinates), $d_k$ is the distance of the target from the registration fiducials configuration principal axis $k$.

We repeated this registration for four trials with a variety of selected registration fiducial configurations and target fiducials locations. From the four different fiducial configurations, 52 different target fiducials pairs were obtained. The data analysis was performed with MATLAB (MathWorks, USA) running on a standard PC. Statistical analysis was performed using Student’s $t$-test.