Bio-Medical Materials and Engineering 24 (2014) 3361–3371
DOI 10.3233/BME-141159
IOS Press

Fiducial markers configuration optimization in image-guided surgery

Nan Bao[a,b], Yu Chen[a], Yong Yue[c], Hong Li[a,b], Zhiming Cui[a], Jinfeng Zhuang[a], Shi Tian[a] and Yan Kang[a,b,*]
[a] *Sino-Dutch Biomedical and Information Engineering School, Northeastern University, Shenyang, China*
[b] *Key Laboratory of Medical Imaging Computing (Ministry of Education), Northeastern University, Shenyang, China*
[c] *Department of Radiology, Shengjing Hospital of China Medical University, Shenyang, China*

Abstract. The rigid registration is a key step of Image Guided Surgery (IGS), and the point-pair method is the main way used for registration. However the configuration of fiducial points has a great influence on the registration accuracy at the target point. Now almost all the optimization method of fiducial points configuration relies on the empirical simulation-based Fitzpatrick's target registration error (TRE). In this paper, a phantom and some markers were designed and some experiments were conducted to measure and compare the affecting factors on the registration. By the markers repeated selections, the fiducial location error (FLE) has a small deviation of maximum 0.4 mm, and the average of the Fitzpatrick's TRE (F-TRE) has almost 86% proportion to the average of the actual TRE (A-TRE), but the standard deviation (STD) just has 7% proportion. Also, the experiment result showed that six fiducial markers already had the 86% accuracy, and spreading the fiducial markers led to 30% reduction in mean of A-TRE and 40% reduction in STD of A-TRE comparing with the centralized. Overall, to find a strategy of optimization, reducing the TRE has the great meaning to support safer and more accurate minimally IGS procedures.

Keywords: Image guided surgery, target registration error, registration, fiducial markers, number and distribution

1. Introduction

Now, the image-guided surgery (IGS) is increasingly used in connection with the minimally invasive procedures in endoscopic sinus surgery, maxillofacial surgery and neurosurgery [1–3]. The IGS has mainly three steps: diagnostic and preoperative imaging, preoperative planning and intraoperative execution [4]. The rigid registration in the preoperative planning is the key factor for the IGS system's accuracy. It maps the MRI/CT image coordinate system into the patient coordinate system by matching corresponding landmarks in both spaces. The method can be generally classified into two categories: point-pair registration and surface-based registration [5]. Many researchers have reported the surface-based registration problems in accuracy and robustness [6–8], and the point-pair registration has higher application accuracy [9]. In the point-pair registration, each of the two spaces must have at least

*Corresponding author: Yan Kang, Sino-Dutch Biomedical and Information Engineering School, Northeastern University, Shenyang, China. Tel.: +86-24-83676663; Fax: +86-24-83681955; E-mail: kangyan@bmie.neu.edu.cn.

four fiducial markers that cannot be collinear. There are several analytical algorithms to calculate the transformation from the corresponding point sets [10].

Quantifying the registration error is of great clinical importance, which has the direct implications on the treatment decisions and assessment of the risk [4]. So, the target registration error (TRE) has been proposed to express the accuracy of registration in point-matching. TRE is the distance between target points that were defined on the preoperative image and the corresponding target points on the physical space after registration. In 2001, Fitzpatrick et al. [11] gave an equation to calculate the expectation of TRE. The equation shows that TRE is not only determined by the accuracy in the location of the fiducial markers but also by the number and distribution. Several studies have been performed to determine the effect of fiducial markers configuration on different surgical application. Liu et al. [12] proposed a method to reduce TRE through optimizing the position of fiducial markers on the skin in photogrammetry based patient positioning system. Riboldi et al. [13] combined genetic and taboo search to minimize the estimated TRE. Their test on 10 datasets of prostate patient shows that optimizing a set of randomly placed fiducial markers with their method reduces the TRE by 26% versus 19%. Wang and Song [14–16] performed three studies on improving the accuracy of TRE, proposing guidelines, and distributing templates for fiducial placement in image-guided neurosurgery. Zhang W. et al. [17] also investigated the effect of landmark configuration on TRE in cranio-maxillofacial surgery. Note that all these except Zhang W.'s work use the TRE estimation method described in Fitzpatrick et al. [4,18]. As an empirical simulation-based model, TRE has been widely used to assess the accuracy. All methods use the analytic TRE estimation equation described by Fitzpatrick et al. [19]. However, R.R. Shamir et al. [20,21] had showed that it is not always a good estimation of the actual TRE. But their experiment just adhesives the whole fiducial and target markers on the surface of the head to calculate the TRE rather than in the head. Also, there is no previous study to quantify the actual improvement in accuracy that can be achieved by optimizing fiducial markers placement [4].

Broadly speaking, a phantom and some markers were designed in this paper, and these instruments were used to make some experiments to validate and optimize the distribution of fiducial markers from the perspective of the real inner space rather than the empirical simulation-based model. Because the TRE is directly related to the fiducial localization error (FLE) [18], In order to ensure an optimum minimization of the FLE, the FLE was estimated in the IGS platform by repetitive selections. Then, a series of experiments were conducted with the different number and distribution of fiducial markers. After analyzing the experiment result quantitatively and comparing the Fitzpatrick's TRE and actual TRE, it was concluded that the Fitzpatrick's TRE cannot accurately reflect the actual TRE. However, for the different fiducial markers configuration, the results showed that when the number of fiducial markers is 4-6, the number influence on the TRE is higher than the distribution, and when the fiducial markers number is more than 6, the influence of distribution is more important than the number. It is observed that six to seven fiducial markers are suitable for the point pair registration.

2. Materials and methods

2.1. Mathematical definition

2.1.1. Fiducial localization error

Since the fiducial markers cannot be determined precisely, it must have an error between the actual and the selected fiducial markers locations, which is commonly known as the FLE in the literature.

However, the actual markers location is unknown, in general, the FLE is estimated by the average value when measured the distances between repeated selections in the same marker [19].

2.1.2. Fiducial registration error

One measurement of registration accuracy is the distance between the location of fiducial markers on images and physical location after registration. It is called fiducial registration error (FRE) [18].

2.1.3. Target registration error

The TRE is defined as the distance between actual target points and the corresponding estimated points after registration. In this paper, it is defined as A-TRE and the equation is showed below:

$$A-TRE=\left\|C_{target}^{P}\times T^{P-I}-C_{target}^{I}\right\| \tag{1}$$

The P and I represent the physical space coordinate and the image space coordinate. The C_{target}^{P} and C_{target}^{I} are corresponding to the physical space coordinate and the image space coordinate of the target points.The T^{P-I} is the transformation matrix from physical space coordinate to image space coordinate, which will be introduced in 2.5.

Because the TRE cannot be directly measured for targets inside the body, several methods have been developed to estimate it. The most famous is the Fitzpatrick et al. [18] method. In this paper, it is defined as F-TRE, and the equation is showed as following:

$$F-TRE=\frac{\left\langle FLE^{2}\right\rangle}{N}\left(1+\frac{1}{3}\sum_{k=1}^{3}\frac{d_{k}^{2}}{f_{k}^{2}}\right) \tag{2}$$

Where, the d_k is the distance between the target and the fiducial markers configurations principal axis k (in x, y, z coordinates), and f_k is the Root-Mean-Square (RMS) distance between the fiducial markers and the principal axis k.

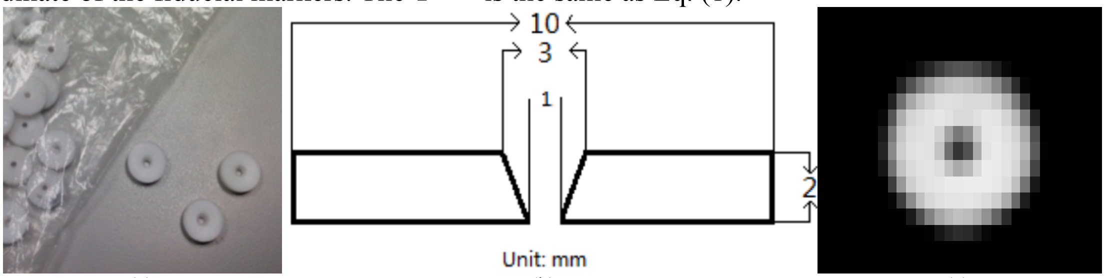
Because the $\left\langle FLE^{2}\right\rangle$ is usually unknown, Fitzpatrick et al. [18], in his paper, used the following FRE-based estimate equation as Eq. (3):

$$\left\langle FLE^{2}\right\rangle=\frac{\sum_{i=1}^{N}FRE_{i}^{2}}{N-2} \tag{3}$$

Where

$$FRE_i = \left\| C^{P}_{fiducial-i} \times T^{P-I} - C^{I}_{fiducial-i} \right\| \tag{4}$$

The $C^{P}_{fiducial}$ and $C^{I}_{fiducial}$ are corresponding to the physical space coordinate and the image space coordinate of the fiducial markers. The T^{P-I} is the same as Eq. (1).



(a) (b) (c)

Fig. 1. Markers. (a) Photograph of the markers. (b) Structure chart of the marker. (c) Marker image in pixels.

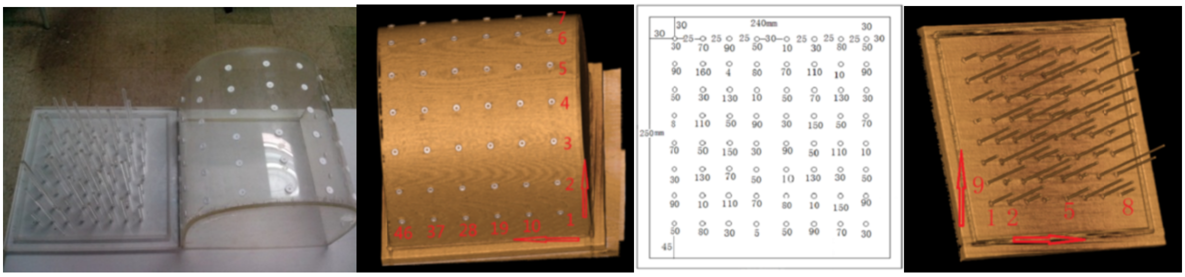
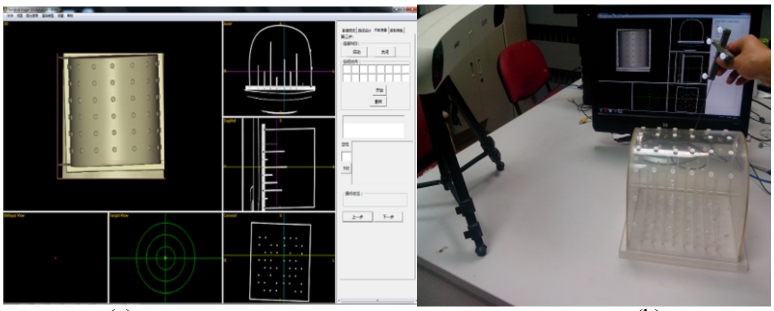

(a) (b) (c) (d)

Fig. 2. The designed phantom. (a) The photograph of the phantom. (b) The volume rendering of the phantom. (c) The distribution and height of the pillars on the base. (d) The volume rendering of the base and the pillars.

2.2. Markers and phantom

In this research work, a particular marker was designed (see Figure 1(a)). This marker has an outer diameter 10 mm, and a small hole in the center of the marker. The small hole of 2 mm thickness is a cone shape and has two sides, while the upper side diameter is 3 mm and the lower side diameter is 1mm (see Figure 1(b)). On the other hand, the CT compatibility of the material used in the markers is essential. Polytetrafluoroethylene (PTFE) material was used to make this marker. It is very bright in the image scanned by the CT (see Figure 1(c)).

A phantom showed in Figure 2(a) was also designed, which is constructed from a lid and a base, and used to simulate the head or chest. The lid could be well fixed on the base. On the surface of the lid, 54 markers are pasted. In order to specify the markers better, the whole markers were numbered as the Figure 2(b). Sixty-four pillars with different height are also evenly distributed on the base. The Figure 2(c) shows the distribution and the height of all the pillars, which are used to estimate the whole inner space approximately. The Figure 2(d) is the volume rendering of the base and the pillars.



(a) (b)

Fig. 3. The IGS platform. (a) The software interface. (b) The devices and the experimental environment.

2.3. Image acquisition and experiment devices

The phantom was scanned by CT and the axial slices were acquired with voxel size of 0.625*0.625*1.0 mm^3, and the image size of 512*512*319.

The position tracking system is Polaris spectra optical positioning system made by Northern Digital Incorporation (NDI) in Canada. This equipment can locate a tip of a probe with an accuracy of 0.15 mm. Base on the tracker, the IGS platform has been developed (see Figure 3(a)). By providing the serial number, the corresponding fiducial markers were selected to be used to registration. All the markers have been segmented out manually on software of Mimics 10.0. The Figure 3(b) shows the experimental environment combining the three devices.

2.4. Fiducial points location

The fiducial points' location cannot be absolutely accurate. The float direction of the FLE was random on the sphere in a uniform distribution, and the FLE is normally distributed with a bias $N(\mu_{ai}\sigma_{ai})$ [4]. The standard deviation (STD) σ_{ai} is estimated by computing the STD of distance between repetitive selections of the same fiducial marker. So in order to obtain a reliable model for FLE, the anisotropy and inhomogeneity of FLE distribution was taken into consideration [4]. So, the average of the distance between repetitive selections of the same fiducial marker in 20 trials was chosen to model FLE bias μ_{ai}.

2.5. Point registration

Because the FLE has a direct influence on fiducial registration error and the target registration error, in the experiment, it can be performed by associating anisotropic weights to each fiducial points used in the registration [21].

The fundamental of rigid fiducial registration is to find the best rotation (R) and translation (T) matrix that make Eq. (5) minimum.

$$E(R,T) = \min\left(\sum_{i=1}^{N} \left\| Y_i^{'} - (RX_i^{'} + T) \right\|^2\right) \tag{5}$$

Where

$$X_i^{'} = X_i + \nabla X_i \tag{6}$$

$$Y_i^{'} = Y_i + \nabla Y_i \tag{7}$$

The $X_i^{'}$ and $Y_i^{'}$ are the points of 3x1 matrix in the two spaces. The ∇X_i and ∇Y_i are the uncertain deviation.

In this paper, a kind of non-iterative algorithm with rigid mathematics was used to calculate the R and T to minimize the objective function E. It is a closed-form analytical least-squares method proposed by Horn [22], which is the most popular registration method in commercial navigation systems.

2.6. Experiment design

The extensive experiments were performed to calculate out the average FLE according to the repetitive selections result and considering different markers configuration on the lid.

From the Eq. (2), it is obvious that the TRE is not only determined by the accuracy of FLE, but also influenced by the number and distribution of fiducial markers. Hence, the study was divided into two aspects. First one was the number of fiducial points varied from 3 to 8, and the six kinds of different configurations were proposed. Second one was the distribution of five-group fiducial markers keeping their number same. It should be noted that, the fiducial markers must have the minimum and the maximum coordinate values in x, y, z, and Eq. (8) is proposed to analyze the distribution quantitatively:

$$V = (x_{\max} - x_{\min}) \times (y_{\max} - y_{\min}) \times (z_{\max} - z_{\min}) \tag{8}$$

It is obvious that the V represents the volume that the whole fiducial markers surrounded.

3. Results and discussion

In this study, the markers placed on the surface of the lid are used to registration, and the pillars are used to estimate the registration accuracy as the targets in the phantom. The top of the pillars position in the CT scanned images have been segmented manually on the Mimics 10.0.

A series of experiments was conducted to evaluate the different numbers and the distribution affecting the TRE for the specified targets. Each experiment has three steps: (1) Fiducial markers location in physical space by repeated selections. (2) Rigid registration calculation to get the mapping relation between the two spaces. (3) Different fiducial markers configurations were tested and proposed the optimum configuration.

3.1. FLE estimation

In this experiment, the FLE was calculated while each attached markers were picked in the physical space for 20 trials. Because the each point has three principle axis in x, y, z, the average of the meas-

Table 1

The mean and the STD for five markers' three principle axis in 20 trials

FLE Difference		Marker number					Average of 5 markers
		1	2	3	4	5	
		1	5	9	39	43	
X	Mean	0.33	0.08	0.37	0.25	0.26	0.26
	STD	0.31	0.06	0.30	0.18	0.20	0.21
Y	Mean	0.06	0.31	0.05	0.29	0.30	0.20
	STD	0.05	0.23	0.05	0.25	0.25	0.16
Z	Mean	0.34	0.33	0.31	0.40	0.37	0.35
	STD	0.31	0.30	0.30	0.35	0.35	0.32

Table 2

The mean and the STD of the F-TRE and A-TRE in five-group markers

TRE Difference	Marker number				
	1	2	3	4	5
	1, 5, 9, 50	1, 5, 9, 23, 50	1,5,9,23,46,50	1,5,9,23, 46, 50, 54	1,5,9,21,25, 46, 50,54
F-TRE Mean	1.80	1.24	0.93	0.80	0.76
F-TRE STD	0.16	0.09	0.05	0.03	0.02
A-TRE Mean	1.65	1.38	1.02	0.91	0.88
A-TRE STD	0.54	0.41	0.35	0.31	0.29

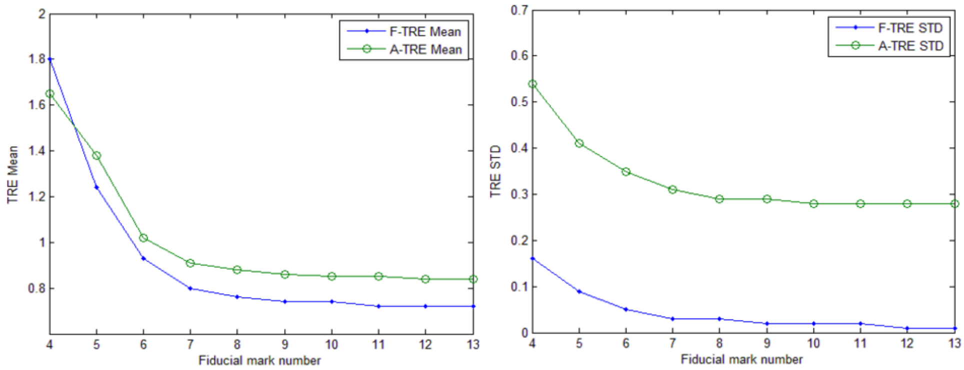
ured distance between repeated selections of the same marker was calculated along the principle axis, and the STD was also calculated accordingly. The inhomogeneous and anisotropic noise was modeled in these markers acquired by the navigation equipment. The selected five different markers test in 20 times and the results show in Table 1.

From Table 1, it shows that the markers specific designed has caused a small deviation of maximum 0.4 mm for the needle tip movement during different measurements. It is different in the three principle axes, the five markers range in X is 0.26 ±0.21 mm, Y is 0.20±0.16 mm, Z is 0.35±0.32 mm. The marker number 1 and 9 has a very small Y value, the number 2 has a very small X value, and all the markers have almost same Z value. With the reference to the markers serial number in Figure 2(b), the angles between the normal vector of the marker surface and the three principle axes can be calculated. It is known that the angle is smaller, and the value of corresponding axis is smaller.

3.2. Different markers number on configuration

In order to measure the influence of the markers number for the A-TRE, the experiments were conducted with the arrangement of the fiducial markers as Table 2. Considering the influence of the random error, every test was repeated for 10 times and obtained the average value.

Because the equation of the Horn [22] has showed that the minimum of the number is four for the registration, the test was started from 4 fiducial markers. The markers were numbered as the Figure 2(b) and it is known that the five groups of markers in Table 2 have the same V in Eq. (8). Because the



(a) (b)

Fig. 4. (a) The fiducial marker number effect on F-TRE mean and A-TRE mean. (b) The fiducial marker number effect on F-TRE STD and A-TRE STD.

Table 3

The mean and the STD of the F-TRE and A-TRE in five-group markers

TRE Difference	Marker number				
	1	2	3	4	5
	1, 5, 9, 10, 14, 18	*1, 5, 9, 19, 23, 27*	*1, 5, 9, 28, 32, 36*	*1, 5, 9, 37, 41, 45*	*1, 5, 9, 46, 50, 54*
F-TRE Mean	1.02	1.03	1.08	1.12	1.14
F-TRE STD	0.13	0.10	0.07	0.05	0.03
A-TRE Mean	1.08	1.01	0.97	0.90	0.76
A-TRE STD	0.52	0.47	0.42	0.38	0.31

fiducial marker has three principle axes, as well as the inhomogeneous and anisotropic noise being modeled, the three principle axes' Euclid distance represented the TRE.

From Table 2, the A-TRE has a limited value, and decreased slowly as the increase of the markers number. We had increased the marker number to thirteen. Figures 4(a) and 4(b) showed that the A-TRE will approach to a certain value, but the F-TRE decreased continuously. In theory, when the number of fiducial markers is enough, the registration error will be zero, and the F-TRE and A-TRE will be zero, but they will be influenced by the image resolution or navigation equipment accuracy and will not tend to zero.

The Figure 4(a) illustrates that the F-TRE is closely to the A-TRE. The limitation number of the F-TRE has an almost 86% proportion to the limitation number of A-TRE. In theory, with the increasing of the number, the whole inner space will tend to same deviation, which conforms from the Figure 4(b). However, according to the Figure 4(b), the F-TRE has a great difference with the A-TRE. The F-TRE is obviously much less than the A-TRE. It just have an almost 7% proportion, which shows that the F-TRE cannot very exactly estimate the distribution of the internal space.

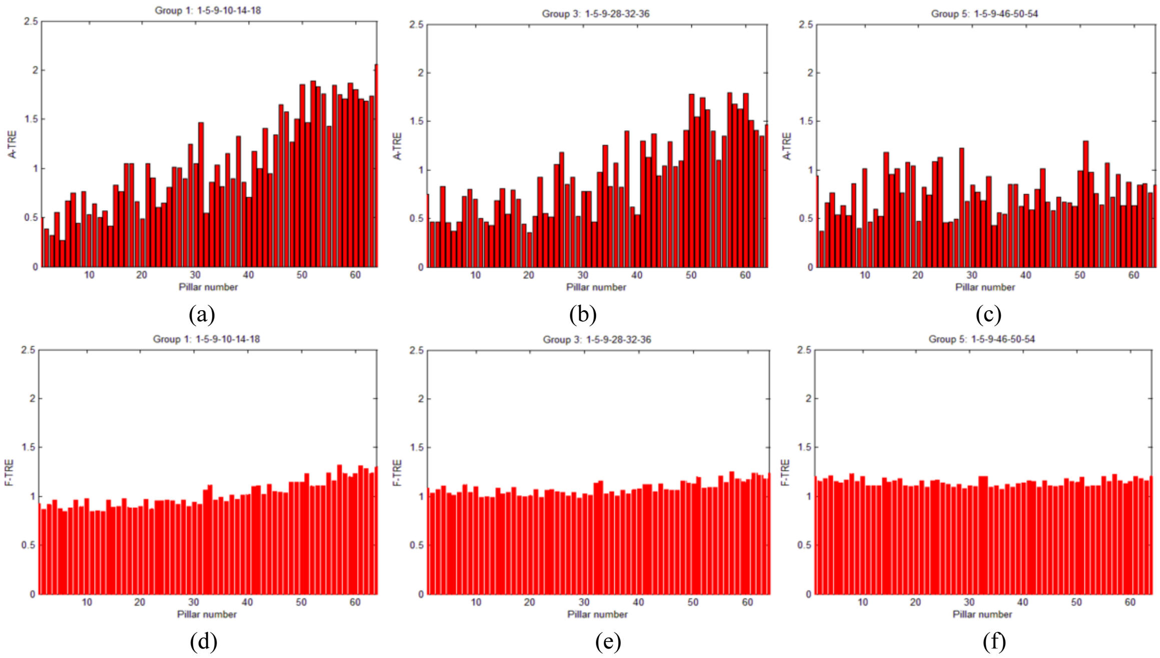


Fig. 5. The pillars' TRE of group 1, 3, 5 in Table 3. (a) A-TRE of group 1. (b) A-TRE of group 3. (c) A-TRE of group 5. (d) F-TRE of group 1. (e) F-TRE of group 3. (f) F-TRE of group 5.

3.3. Different markers distribution on configuration

In this step, the influence of the number was minimized. Referring to the experiment in 3.2, six markers were taken as the fiducial markers, and the number is showed in Table 3. Also, in order to decrease the random error, every test was repeated for 10 times and the average value was obtained.

From Table 3, it is obvious that the F-TRE changed a little, but the A-TRE changed a lot. The distributions of the markers almost have no influence on the F-TRE in this experiment situation.

In the Figure 5, the histograms of 64 pillars of group 1, 3, 5 are illustrated. The upper figures represent the A-TRE, and the below figures represent the F-TRE. Comparing these six figures, the A-TRE and the F-TRE increased with the distance between pillars and the scale of the fiducial markers surrounded. In these figures, with the fiducial markers' volume calculated by Eq. (8) increasing, the F-TRE and the A-TRE become smooth. It shows that the mean of F-TRE almost has no change, the mean of A-TRE decreased 30%, the STD of F-TRE decreased 77%, and the STD of A-TRE decreased 40%. It is also found that the front part of the pillars do not have any significance change, because this part of pillars are in the scale of the fiducial markers surrounded volume.

Therefore, in this paper, according to the experimental result, four observations may be recorded: (1) The Fitzpatrick's TRE cannot accurately reflect the actual TRE. (2) 6 to 7 fiducial markers are already suitable for the point pair registration. (3) When the number of fiducial markers is 4-6, the number influence on the TRE is higher than the distribution. (4) When the number of fiducial markers is more than 6, the distribution influence on the TRE is more important than the number. Moreover, some validated advices will give a better accuracy: (1) Arranging the fiducial markers as nonlinear as possible; (2) Spreading the fiducial markers' distribution; (3) Arranging the fiducial markers around the target; (4) Keeping the center of fiducial markers gravity much close to the target point.

4. Conclusion

In the IGS, the target registration accuracy is crucial for the surgeons, and especially the number and the distribution of the fiducial markers have a significant influence on the TRE. Although the surgeons may be able to accept the error in a certain scale by according some guidelines or the experience ability of the surgeons, to improve the accuracy still has important significance. Also, the experiments on the actual data showed that there was still much room for improvement.

In this paper, some experimental studies were performed on designed phantom. According to the Horn's registration method and the Fitzpatrick's TRE equation, the number and the distribution of the fiducial markers was taken as the factors to analyze the influence on the accuracy of the actual TRE quantitatively. In addition, an FLE model was considered into the incorporate the localization uncertainty of the physical points.

In fact, when the fiducial markers are enough and the target points are absolutely in the center of the fiducial markers volume, the A-TRE and F-TRE will be zero in theory. But in the experiments results showed that the limitation value of the A-TRE and F-TRE's mean and the STD is not zero. There must be other factors influence on the accuracy, which can be a meaningful field to do research further.

The future work is to improve accuracy of the FLE, and take more target points and fiducial points in the registration and the TRE calculation. Also, more registration method will be considered into the experiments as the impact factors. By doing so, some distribution templates will be built according to the position and the shape of the target points, and be promoted into the clinical operation.

Acknowledgement

The authors are grateful for grants from the National Science Fund of China (NSFC; Grant No. 61372014 and 61201053).

References

[1] M. Caversaccio and W. Freysinger, Computer assistance for intraoperative navigation in ENT surgery, Minim Invasive Ther. Allied. Technol. **12** (2003), 36–51.

[2] F. Postec, D. Bossard and P. Froehlich, Computer-assisted navigation system in pediatric intranasal surgery, Head Neck Surg. **128** (2002), 797–800.

[3] S. Kherani, A.R. Javer, J.D. Woodhamand and H.E. Stevens, Choosinga computer-assisted surgical system for sinus surgery, J. Otolaryngol. **32** (2003), 190–197.

[4] R.R. hamir, L. Joskowicz and Y. Shoshan, Fiducial optimization for minimal target registration error in image-guided neurosurgery, IEEE Transaction on Medical Imaging **31** (2012), 725–737.

[5] M.N. Wang and Z.J. Song, Guidelines for the placement of fiducialpoints in image-guided neurosurgery, Int. J. Med. Robot **6** (2010), 142–149.

[6] R. Marmulla, J. Muhling, T. Luth et al., Physiological shift of facial skin and its influence on the change in precision of computer assisted surgery, Br. J. Oral. Maxillofac. **44** (2006), 273–278.

[7] A. Raabe, R. Krishnan, R. Wolff et al., Laser surface scanningfor patient registration in intracranial image-guided surgery, Neurosurgery **50** (2002), 797–801.

[8] J. Schlaier, J. Warnat and A. Brawanski, Registration accuracy and practicability of laser-directed surface matching, Comput. Aided Surg. **7** (2002), 284–290.

[9] P.A. Woerdeman, P.W.A. Willems and H.J. Noordmansetal, Application accuracy in frameless image-guided neurosurgery: A comparison study of three patient-to-image registration methods, J. Neurosurg. **106** (2007), 1012–1016.

[10] D.W. Eggert, A. Lorusso and R.B. Fisher, Estimation 3D rigid bodytransformation: A comparison of four major algorithms, Machine Vision Applic. **9** (1997), 272–290.

[11] J.M. Fitzpatrick and J.B. West, The distribution of target registration error in rigid-body point-based registration, IEEE Transactions on Medical Imaging **20** (2001), 917–927.
[12] H.S. Liu, Y.Yu, M.C. Schell et al., Optimal marker placement inphotogrammetry patient positioning system, Med. Phys. **30** (2003), 103–110.
[13] M. Riboldi, G. Baroni, M.F. Spadea, B. Tagaste, C. Garibaldi, R. Cambria, R. Orecchia and A. Pedotti, Genetic evolutionary taboo search for optimal marker placement in infrared patient setup, Phys. Med. Biol. **52** (2007), 5815–5830.
[14] M.N. Wang and Z.J. Song, Guidelines for the placement of fiducial points in image-guided neurosurgery, Int. J. Med. Robot. **6** (2010), 142–149,
[15] M.N. Wang and Z.J. Song, Improving target registration accuracy inimage-guided neurosurgery by optimizing the distribution offiducial points, Int. J. Med. Robot. Comp. **5** (2009), 26–31.
[16] M.N. Wang and Z.J. Song, Distribution templates of the fiducial points in image-guided neurosurgery, Neurosurgery **66** (2010), 143–150.
[17] W. Zhang et al., Effect of fiducial configuration on target registration error in image-guided cranio-maxillofacial surgery, J. Cranio-Maxillofac. Surg. **39** (2011), 407–411.
[18] J.M. Fitzpatrick, J.B.West, C.R. Maurerand Jr., Predicting error in rigid-body point-based registration, IEEE Trans. Med. Imag. **17** (1998), 694–702.
[19] R.R. Shamir, L. Joskowicz, S. Spektor and Y. Shoshan, Localizationand registration accuracy in image guided neurosurgery: A clinical study, Int. J. Comput. Assist. Radiol. Surg. **4** (2009), 45–52.
[20] R.R. Shamir, L. Joskowicz and Y. Shoshan, What is the actual fiducial localization error in image-guided neuronavigation? Int. J. Comput. Assist. Radiol. Surg. **5** (2010), 107–108.
[21] M. Ershad, A. Ahmadian, N.D. Serej et al., Minimization of target registration error for vertebra in image-guided spine surgery, Int. J. Comput. Assist. Radiol. Surg. **9** (2014), 29–38.
[22] B.K.P. Horn, Closed-form solution of absolute orientation using unit quaternions, Journal of the Optical Society of America **4** (1987), 629–642.