Accuracy and Applicability Analysis of Anatomical Landmarks Point Registration Image Guided Surgery of Neurosurgery

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Abstract: *Image guided neurosurgery system is currently an interesting and active topic for research that covers a wide ranges of knowledge related to medical sciences, image and signal processing and computer programming. Therefore, we are providing an analysis for the accuracy when using different sets of Anatomical Landmarks (ALs) as well as the applicability of the corresponding surgical fields. In addition, one of the significant factors that influence the registration accuracy at the target point is the distribution of the fiducially points. The optimal distribution may be difficult to achieve either due to the limited number of distinct anatomical features on head surface or even due to the poor planning of skin adhesive markers. The simulation experiment of the accuracy analysis showed that, by incorporating a Fiducially Registration Error (FRE) of 3.5 mm measured in the clinical setting, the expected Target Registration Error (TRE) in the whole skull was less than 2.5 mm, and the expected TRE in the whole brain was less than 1.75 mm when using the configuration with all the nine ALs. Results showed an improvement in registration quality in the targeted area in all cases by this kind of correction.*

Keywords: *Accuracy and applicability analysis, Anatomical Landmarks, Point registration, Image guided, Surgery of neurosurgery.*

Introduction

Accurate patient to image registration is the core for successful and safe image-guided neuro-navigation. Point-matching is the most common technique in practice to achieve this registration. While Skin Adhesive Markers (SMs) are widely used in point-matching registration, a proper implementation of Anatomical Landmarks (ALs) may overcome the inconvenience brought by the use of SMs. However, the accuracy and applicability of ALs registration in neuro-navigation have remained a controversial issue due to the great variability of the reported results and conclusions. Therefore, we are providing an analysis for the accuracy when using different sets of ALs as well as the applicability of the corresponding surgical fields. In addition, one of the significant factors that influence the registration accuracy at the target point is the distribution of the fiducially points. The optimal distribution may be difficult to achieve either due to the limited number of distinct anatomical features on head surface or even due to the poor planning of skin adhesive markers. Therefore we have also tried to overcome this problem and correct the quality of the registration in the areas that normally suffer low accuracy when using ALs-based registration. In the accuracy analysis study, we propose a set of three configurations using nine ALs. These configurations are defined according to the required positioning of the patient's head during surgery and the resulting distribution of the expected target registration error.

The use of images to guide the operation depends significantly on the ability of registering patient space to image space accurately. Registration, also known as the absolute orientation problem, can be defined as the use of the corresponding sets of features in the two spaces to establish a spatial relation between their coordinate systems. The methods used for registration in IGS systems generally falls into two categories: surface-matching registration and point-matching registration. Of the point-matching, there are three subtypes: bone mounted markers, skin adhesive markers and anatomical landmarks. Surface-matching methods using laser scanners have proved to be more complex than point-matching registration, exhibiting accuracy lose with the activation of the facial muscles and have many problems regarding their robustness [3, 9]. Nevertheless, due to the automation of these methods they have the potential to dominate the field when the associated problems solved. Point-matching registration methods are currently the most commonly used techniques in practice. In this category of registration, a set of at least three linearly independent positions should be identified in both the image space and the patient space using a tracked pointing device. It is essential that the corresponding points are precisely identified. The IGS system then calculates a spatial transformation that rigidly rotates and translates the points from one space until the alignment is accurately achieved with the corresponding points from the other space. There are several algorithms to calculate the transformation between two spaces from corresponding point pairs [2]. Registration algorithms implemented in IGS are usually rigid, 3D, point-matching based techniques. Analytical methods are more efficient and robust comparing to iterative methods, algorithms represent the transformation components either as matrices [4, 7] or unit quaternions [1, 10, 11] are usually the most appealing in this field. Liu W. P. et al. [6] provided a comprehensive survey on the registration methods used in an Image Guided Neurosurgery Systems (IGNS) and described the advantages and disadvantages of each approach.

Overview

The patient-to-image registration is usually a major source of error in the clinical practice of IGS [6] due to the inevitable error in locating the corresponding fiducially points in point-matching and the variation of facial poses in surface matching registrations as mentioned earlier. Other sources of error include the inaccuracies of the instruments such as the navigation camera and the internal changes such as the brain deformation. To help evaluate the registration quality, Liu J. T. et al. [5] gave definitions of three errors in point-matching rigid registration:

- Fiducially Localization Error (FLE): the average error in locating the position of the fiducially points.
- Fiducially Registration Error (FRE): the Root Mean Square (RMS) distance between corresponding fiducially points after registration.
- Target Registration Error (TRE): the distance between corresponding points other than the fiducially points after registration.

Each one of the point-matching registration methods has it is own weakness and strengths points. Skin adhesive markers are the most commonly used technique of point-matching registration methods and they are generally easy to be located in the patient and image spaces. According to the intended type of imaging (CT, MRI, PET, etc.), it is possible to select markers designed of a suitable materials to ensure their visibility in the image data. However, IGNS using SMs have to consider a preoperative preparation stage, including fiducially planning and image scanning. The fiducially planning must be conducted by trained personnel, who attach the SMs to the patient's head with a proper distribution before the image scanning. It is time-consuming, not applicable in case of emergency and places burden and discomfort on the patient. Once applied, the SMs tend to slip on the scalp or even falling off and may cause skin dislocation, which certainly induces large FLE that affects the registration accuracy. Therefore, the duration from placing the markers and imaging to the surgery should be kept as short as possible. Otherwise, the SMs may need to be retagged again in case they are unintentionally removed and image scans might need to be repeated accordingly. Furthermore, since every patient already has diagnostic images, an image scanning dedicated for image-guided neurosurgery is a redundant procedure. The targeting accuracy reported by many researchers when using this method ranges between 1.5 mm to 4 mm.

Due to their rigid fixation, bone-mounted markers provide a solution to errors caused as a result of skin adhesive markers movement. Bone-mounted markers can provide the highest registration accuracy (TRE), in the range of 0.5 to 1.5 mm [8], when they properly designed. However the disadvantage of this method which has greatly limited its use in the clinical practice is its invasiveness. On the other hand, the preoperative preparation and the accuracy flaw due to the movement of SMs can be avoided by using ALs instead of SMs. The redundant imaging is no longer required since the diagnostic images can be used in IGNS directly. ALs registration is the fastest point matching registration method and offers a simple navigation planning process. Nevertheless, the accuracy of ALs used in point matching registration have reported to be inferior to bone-mounted and SMs and was attributed to the difficulty in matching the corresponding features and to their coplanar distribution. It is reported mean application accuracy (TRE) of 2.49±1.07 mm when using SMs, and 4.97±2.29 mm when using ALs [12]. In [9] it is presented calculated accuracy (FRE) of 3.2±0.2 mm using ALs plus one frontal skin marker comparing to 2.7±0.2 mm when using SMs alone.

Consequently, the applicability and accuracy of ALs used for point-matching registration have remained a controversial issue. Therefore we provide an analysis for the accuracy when using different sets of ALs as well as the applicability of their corresponding surgical fields in neurosurgery. We think it is more useful to use applicable ALs to define certain regions in the brain where the accuracy can be acceptable for surgery. We have as well aimed to address the coplanar distribution problem of ALs by introducing three distant landmarks to form a big range through the axial and coronal direction between the fiducially points. Defining the exact positions of the used ALs in each of the 3 sections of the image in addition to the 3D volume was also considered since it might also improve the selection accuracy of the corresponding points. Analysis for clinical FLEs, FREs and true TREs in addition to the expected values is provided. Certain ALs associated with smaller and larger localization errors were also noted. After that, correction trials for ALs registration errors were conducted. An initial registration using the distinct ALs was used to project several surface points from patient space into image space. The positions of the projected points reflect the errors introduced during the initial registration process. These errors were then identified and used to correct the registration by calculating the nearest points on the head surface to the projected points and adopting them for the subsequent point-matching registration instead of the original surface points.

In the applicability and accuracy analysis trials, the results showed that a small TRE is achieved in the corresponding surgical field by using the suggested configurations of ALs. For the correction trials, the improved in the whole-brain area by approximately 20% and was more prominent in the targeted areas. The ALs configurations proposed in the accuracy analysis provide sufficient registration accuracy and can help to avoid SMs disadvantages if used clinically. The correction technique helps as well overcome the naturally impaired distribution of the ALs, which is the most significant factor that prevents their wide use in registration. The method also allows more precise selection of corresponding fiducially points than normal ALs and without the need for tagging adhesive markers.

Model and algorithm

In conventional surgical methods it is a frequent situation that the actual intended therapy is quiet simple but the process of reaching the targeted site is traumatic or even threatening to the patient life, Fig. 1. A big enough opening is usually necessary to allow direct visual guidance to the surgeon. Information about the functional importance of the tissue, for a safe trajectory to the target, is not available and extremely depends on the surgeon's knowledge and experience.

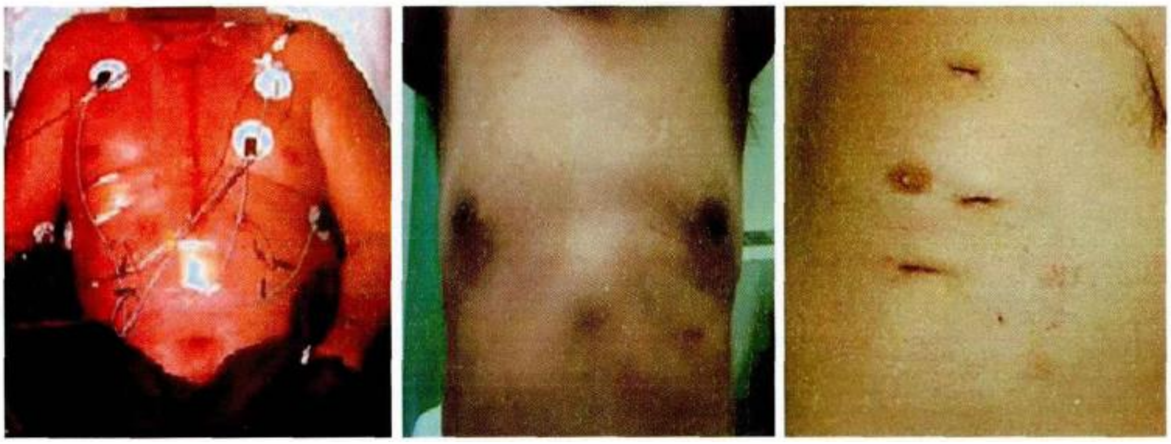

Fig. 1 The subsequent progress in minimal invasive surgery
as suggested by the smaller openings required for the same surgery

These two main shortcomings associated with the conventional methods have motivated the adoption of minimally invasive techniques and hence the development of IGS to augment them. In IGS approaches the surgical instrument can traverse and reach accurately without the need of direct visualization. The functional and anatomical information are both available on surgical site to guide the procedure. Therefore, image guided systems are currently gaining more and more attention and use. The implementation of IGS provides new techniques into the operation rooms, offers more information in both spatial and temporal contexts to the surgeons, facilitates the successful treatment where it was not possible before, and improves the outcome results. Once surgeons are well trained and IGS being used routinely in the procedures, it tends to reduce operative time, lower the overall costs, increase the resection safety, and reduce patient discomfort and recovery time. Most of the developments in IGS originated from the field of neurosurgery, due to the rigid nature of the skull and the importance of the brain tissue. With the attraction of their ability to precisely reach the lesion site with as little as possible harm to the surrounding healthy tissues, other fields began to adopt IGS techniques in their procedures including: orthopedics, spinal, maxillofacial and other fields. Today's IGS systems ensure an intra-operative visual orientation and guidance to the surgeons by tracking surgical instruments in the patient space and transforming their positions into the image space. The development of today's IGS systems has passed through several phases, started with the discovery of the X-ray imaging technique which provided the system with the required information, to the Horsley and Clarke coordinate transformation where the roots of the field have been laid, to the frame stereotactic techniques, and finally the frameless methods.

The algorithm can be expressed with the following equations:

$$\gamma_i(\bar{k}_i, \omega) = \frac{1}{\rho_0 \omega^2} \left(\frac{e_{15}^0}{\eta_{11}^0} \right)^2 \frac{\beta_\perp^2}{\bar{k}^2 - \beta_\perp^2} m_i , \tag{1}$$

$$g_{ik}(\bar{k}, \omega) = -\frac{1}{\eta_{11}^0} \frac{1}{\bar{k}^2} + \frac{1}{\rho_0 \omega^2} \left(\frac{e_{15}^0}{\eta_{11}^0} \right)^2 \frac{\beta_\perp^2}{\bar{k}^2 - \beta_\perp^2} , \tag{2}$$

in which,

$$\alpha^2 = \frac{\rho_0 \omega^2}{C_{11}^0} , \tag{3}$$

$$\alpha^2 = \frac{\rho_0 \omega^2}{C_{66}^0} , \beta_\perp^2 = \frac{\rho_0 \omega^2}{C'_{44}} , \tag{4}$$

$$C'_{44} = C_{44}^0 + \frac{(e_{15}^0)^2}{\eta_{11}^0} . \tag{5}$$

Rewrite again Eq. (1) as

$$\hat{f}_H^\alpha(x) = \frac{1}{\Gamma(1+\alpha)} \int_{-\infty}^{\infty} \frac{f(t)}{(t-x)^\alpha} (dt)^\alpha = \frac{1}{\Gamma(1+\alpha)} \int_{-\infty}^{\infty} f(t) g(x-t)(dt)^\alpha = f(x) * g(x), \tag{6}$$

$$\partial_j (C_{ijkl} \partial_k u_l + e_{kij} \partial_k \varphi) - \rho \ddot{u}_i = 0 , \tag{7}$$

$$\partial_j (e_{ijkl} \partial_k u_l - \eta_{kij} \partial_k \varphi) = 0 . \tag{8}$$

The linear equation can be expressed into the following simplified forms:

$$L(\nabla, \omega) f(x, \omega) = 0 , \tag{9}$$

$$L(\nabla, \omega) = T(\nabla) + \omega^2 \rho J . \tag{10}$$

So we get the *PR* value as the following:

$$PR(u) = \sum \frac{PR(V)}{L(V)}, \tag{11}$$

$$L_k = \frac{d_e}{\sum_{e=1}^{n} d_e}. \tag{12}$$

Materials and methods

In this study, we used nine ALs on the surface of head, as presented in Table 1. Fig. 2 shows their positions from different viewing directions on a three-dimensional visualization image of the CT images of a patient's head. Fig. 2 illustrates the position of inion and parietal eminence on three MRI section images. The parietal eminence appears as the point immediately before the steep fall of the contour of the head surface in the coronas section in Fig. 3 (A) and the prominent and highest point in both the horizontal and the sagittal sections in Fig. 3 (B, C). The inion is defined as the center of the first appearing structure in the coronal section in Fig. 3 (D), which are also the lowest middle point in the horizontal section in Fig. 3 (E) and the point adjacent to the center of the internal occipital protuberance (confluence of sinuses) in the sagittal plane in Fig. 3 (F).

Table 1. The anatomical landmarks positions

No.	Position on the surface of the head
1	Nasion: the intersection of the frontal and two nasal bones of the human skull
2-3	Bilateral Lateral Canthus: is either corner of the eye where the upper and lower eyelids meet
4	Tip of the nose
5-6	Bilateral Tragus: is a small pointed eminence of the external ear, situated in front of the conchs, and projecting backward over the meatus
7-8	Bilateral Parietal Eminence: external surface of the parietal bone is convex, smooth, and marked near the center by an eminence, the parietal eminence, which indicates the point where ossification commenced.
9	Inion: is the highest point of the external occipital protuberance, the most prominent projection of the occipital bone at the poster inferior part of the skull. The ligamentous nuchal and trapezius muscle attach to it.

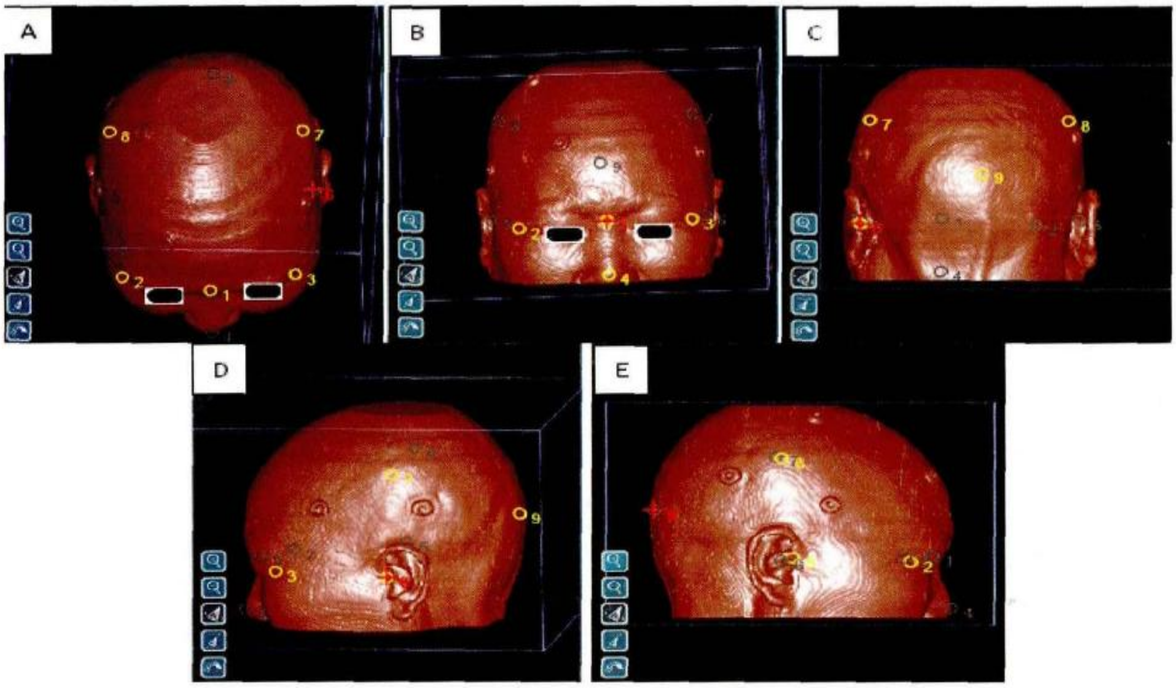

Fig. 2 The position of the anatomical landmarks (A-E) illustrations from five different viewing directions. Each small circle corresponds to a indicial point. A yellow circle indicates that the fiducially point is visible from the corresponding direction, while a gray circle indicates that the fiducially point is invisible. The number of each fiducially point is marked near the corresponding circle.

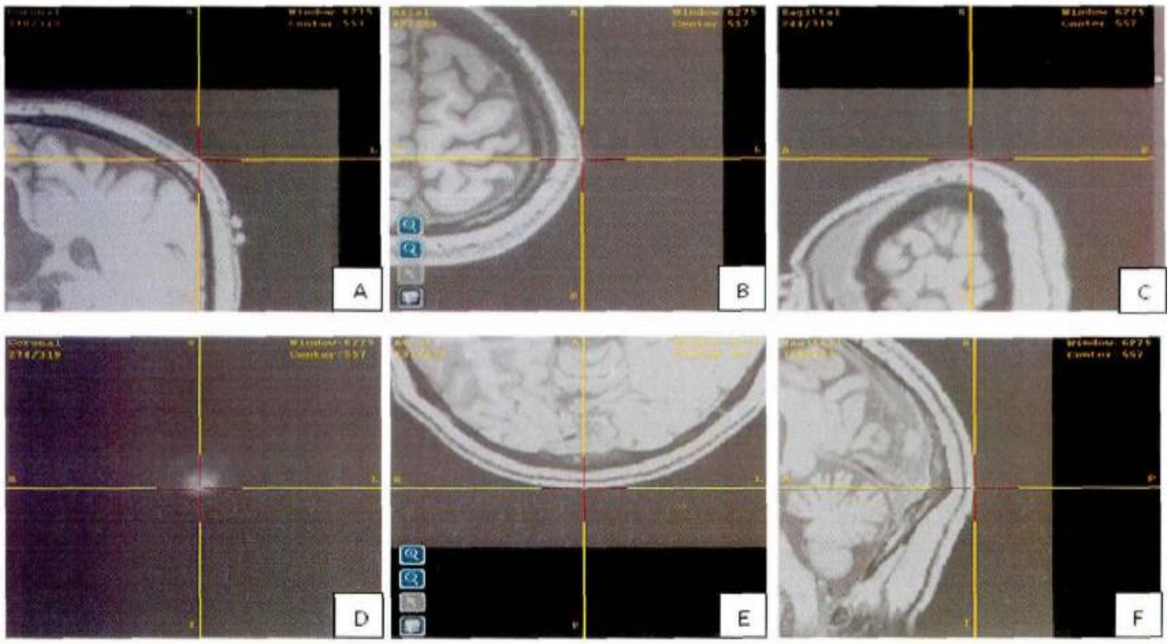

Fig. 3 The locations of inion and parietal eminence on MRl sectional images. Parietal eminence in coronal (A), axial (B), and sagittal (C), Inion in coronal (D), axial (E), and sagittal (F).

Due to different head positioning required for different surgical approaches, it may be hard to reach all the nine ALs listed in Table 1 for intro-operative registration. Therefore, we defined three configurations considering both the head positioning and the resulted theoretical expectation of TRE:

- Configuration 1: Using all nine ALs except the inion, which is used for supine positioning, where the patient lies facing upward.
- Configuration 2: Using all nine ALs except tragus, canthus and parietal eminence on the side facing the floor, which is used for lateral positioning, where the patient lies on one of his sides.
- Configuration 3: Using all nine ALs except facial ones like Nasion, tip of nose and the bilateral lateral canthus, which is used for prone positioning, where the patient lies facing downward.

Configurations 1, 2 and 3 are named as supine, lateral and prone configuration, respectively.

Comparing to the supine configuration, fewer ALs are used in the prone and lateral configurations. This is due to the limited number of anatomical features that can be reached in the patient space, and it makes the enhancement of TRE distribution a difficult task. In an effort to improve the accuracy of them, we have investigated the possibility and influence of adding more ALs to these configurations. It may be hard to directly reach and add the bilateral lateral canthus in prone position, but with some appropriate optimization, the surgery may be performed with the ipsilateral (left or right) shoulder and hip slightly elevated. Such slight adjustment of positioning will allow easy reaching to either the left or right lateral canthus, which is expected to improve the TRE distribution. The addition of the bilateral medial canthus to the lateral configuration is also examined.

Results and discussion

By comparing Fig. 2 (D, E) with Fig. 3 (D, E, F) we can see that the addition of one lateral canthus to the prone configuration whenever it is possible will significantly improve the accuracy and expand the area with small expected TRE. This improvement is due to both the increase of the number of fiducially points and the enhancement of their distribution, because the added AL is distant from the other ALs in this configuration.

Fig. 4 indicates that the statistical distributions of the TRE (r) for different cases among each configuration are very similar and there was no significant difference between the cases from different hospitals as well, which proved the stability of these configurations across different patients. When using SMs, it is impossible to place a marker exactly at the planned position, and it is also difficult to precisely localize the exact center of the marker during registration in the real clinical setting. These variations are analogous to that of localizing the exact ALs. The FLE data shows that the FLE in the patient space usually are larger than that in the image space. It is also noticeable that the different ALs is exhibiting different FLEs. The difference in the FLEs of ALs reflects the different repeatability in selecting them in the two spaces, which may also be influenced by the accuracy of the IGNS navigation probe, the experience of the surgeon, the positioning of the patient, and so on. We have also noticed a learning curve in the surgeon's performance which characterized with a FRE value of 3.6±0.36 mm in the first four patients approaching 3.4±0.29 mm in the last four patients. A true measured TRE value of 3.84±0.69 mm is also noticed in the first four patients approaching 2.67±0.94 mm in the last three patients. Several sources of error influence the accuracy of the IGNS, such as those related to the computed registration transformation, the fiducially and targets localization in image and patient space, the tracking system and those related to internal changes like brain deformation. Usually, each registration technique (SMs, ALs or Surface matching) will be considered appropriate according to the degree of error that is acceptable for the particular case. For example, for larger lesions involving conventional exposures, surface matching registration might be sufficient. Whenever a very high overall accuracy is required, such as needle biopsy involving small lesions or deep brain stimulation, bone-mounted markers might need to be considered. The expected and the measured TRE in this study can give the surgeon a general idea about when these AL configurations are applicable in practice. We are now working on trials to facilitate the selection of the ALs with larger FLE. We think that with the help of an initial registration performed using the facial ALs, we can transfer some surface points from the patient space to the image space and use them to correct the position of some AL in the image space and further improve the registration accuracy.

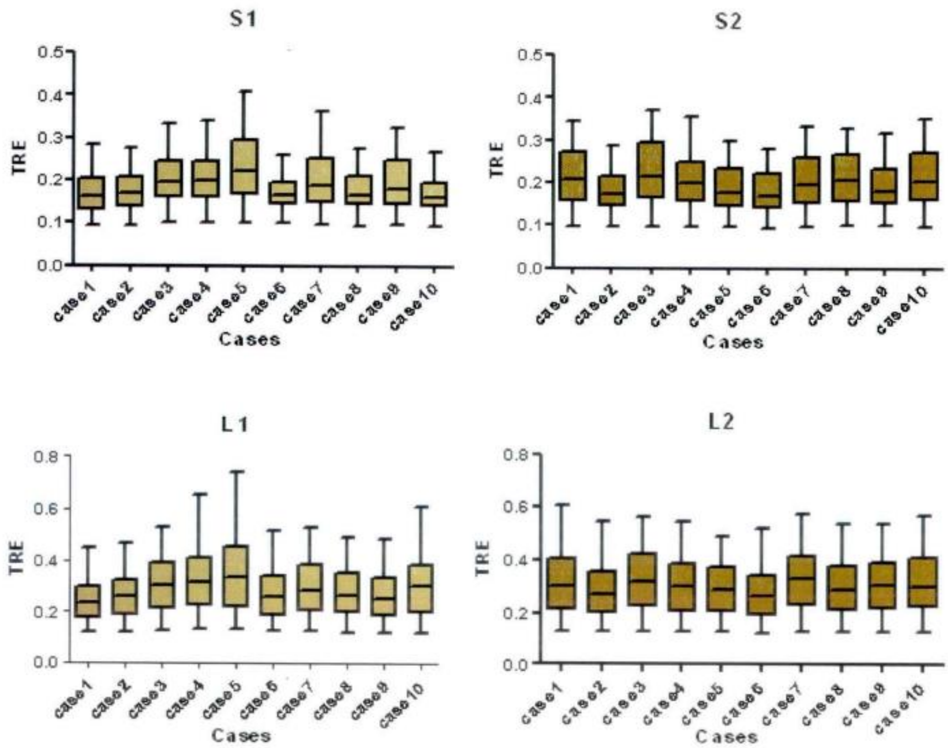

Fig. 4 The statistical distribution of the TRE (r) for the cases of two hospitals:
S1, S2 are the supine configuration at hospital 1 and 2,
L1, L2 – lateral configuration at hospital 1 and 2.

Conclusion

Image guided neurosurgery system is currently an interesting and active topic for research that covers a wide ranges of knowledge related to medical sciences, image and signal processing and computer programming. IGNS systems have become key devices in the neurosurgical operation room. Accurate patient to image registration is the basis of the navigation procedure, with SMs being the most commonly used technique in the registration process. However, registration using SMs suffers from a preoperative preparation stage. Bone mounted markers are presented to solve the problem introduced by the movement of the SMs but they are rarely used, only when a very high accuracy is required due to their invasiveness. ALs provides the fastest and easiest registration technique. Some investigations have reported that registration by this technique gives accuracy level comparable to that of methods using SMs, whereas others contended that ALs are inferior to SMs. Some of these investigations did not provide a 3D description of the ALs locations used and they tend to compare the accuracy between the registration methods independently of the target locations, while TRE is anisotropic, and it may be quite different in different regions in the brain even under the same registration.

Benefiting from the strength and weakness characteristics shown by ALs in the results of the applicability and accuracy study, we persisted to conduct correction trials to further improve the quality of the ALs-based registration. The correction trial method makes use of the large featureless region of the head surface by allowing surgeons to select surface points on them to participate in the registration process. The proposed method allows us to calculate a closer value to the real TRE by calculating the distance between the projected surface point and the relative nearest point in the head surface. The enhancement of TRE was successfully achieved in all positions within the brain. Image-based navigation systems using ALs as described in the correction study is an easy and fast method comparing to SMs based method and more accurate than the traditional use of ALs.

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