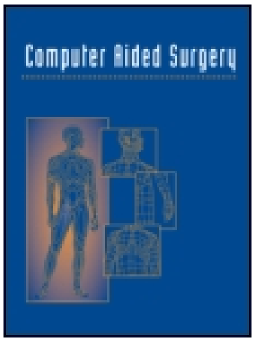

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Automated Fiducial Marker Detection for Patient Registration in Image-Guided Neurosurgery

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ABSTRACT

Objective: The registration of applied fiducial markers within the preoperative data is often left to the surgeon, who has to identify and tag the center of each marker. This is both time-consuming and a potential source of error. For this reason, the development of an automated procedure was desirable. In this study, we have investigated the accuracy of a software algorithm for detecting fiducial markers within the navigation data set. The influence of adjustable values for accuracy and threshold on the sensitivity and specificity of the detection process, as well as the time gain, was investigated.

Patients and Methods: One hundred MP-RAGE MRI data sets of patients with different pathologies who were scheduled for image-guided surgery were used in this study. A total of 591 applied fiducial markers were to be detected using the algorithm of the software VVPlanning 1.3 (BrainLAB, Heimstetten, Germany) on a Pentium II standard PC. The size value of a marker in the y-direction is called "accuracy" and depends on the slice thickness. "Threshold" describes the gray level above which the algorithm starts searching for pixel clusters. The threshold value was changed stepwise on the basis of a constant "accuracy" value. The "accuracy" value was changed on the basis of that threshold value at which all markers were detected correctly.

Results: The time needed for automatic detection varied between 12 s and 25 s. An optimum value for adjustable marker size was found to be 1.1 mm, with 8 undetected markers (1.35%) and 7 additionally detected structures (1.18%) out of 591. The mean gray level (Threshold) for all data sets above which marker detection was correct was 248.9. The automatic detection of markers was good for higher gray levels, with 11 missed markers (1.86%). Starting the algorithm at lower gray levels led to a decreased incidence of missed markers (0.17%), but increased the incidence of additionally detected structures to 27.92%.

Conclusion: The automatic marker-detection algorithm is a robust, fast and objective instrument for reliable fiducial marker registration when used with optimum settings for both threshold and accuracy. Comp Aid Surg 8:17–23 (2003). ©2003 CAS Journal, LLC

Key words: neuronavigation, image guided surgery, fiducial markers

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INTRODUCTION

With the advent and maturation of modern frameless stereotactic devices for precise localization and treatment of subcortical lesions, the practice of neurosurgery was revolutionized.[1] The intraoperative registration of the patient head position is one of the important steps in determining the accuracy of image-guided neurosurgery.[2] Most systems in use today require fiducial markers to be fixed to the patient's head, although laser surface-registration techniques have become commercially available and clinically applicable.[3] Fiducial-based systems require scanning of the patient immediately before surgery to reduce the risk of marker displacement or even loss of markers, and thus achieve a maximum accuracy for the intraoperative marker registration. For different navigation systems, different types of fiducial markers have been developed.[4–7] The registration of the markers in the data set is often left to the surgeon, who has to identify and tag the center of each applied marker. This is both time-consuming and a potential source of error.[8] For this reason, the development of an automated procedure to reliably detect the external fiducial markers was desirable.[9]

In this study, we have investigated the accuracy of a software algorithm for detecting markers in data sets used for image-guided surgery. The influence of the adjustable values for accuracy and threshold on the sensitivity and specificity of the automatic marker-detection process were reviewed.

PATIENTS AND METHODS

Patient Population

This retrospective study reviews the use of a commercially available automatic marker-detection algorithm in 100 consecutive patients with different pathologies that were scheduled for image-guided surgery. Included in this study were MRI data sets of 52 male and 48 female patients (age range: 1 to 82 years; mean: 49 years).

Placement of Fiducial Markers

Fiducial markers were attached to the skull for preoperative 3D imaging. For 3D MP-RAGE MRI scans we attached gel-filled spheres. The markers were clamped into a plastic base, which was fixed to the skull by double-sided adhesive tape discs after preparing the skin. The position of these bases was marked with indelible ink for monitoring of marker displacement. The markers were arranged in such a way that the lesion was situated in the center of gravity of the virtual space enclosed by the markers. As shown by other investigators, the distribution of the fiducial markers on the skull is one of the key functions for optimization of registration accuracy.[8,10]

Data Acquisition

Three-dimensional magnetization-prepared rapid gradient echo (MP-RAGE) MR image volumes (TR: 9.7 ms; TE: 4 ms; flip angle: 12E; slab: 170 mm; 170 slices; slice thickness: 1 mm; FOV: 256 mm; matrix: 256 × 256) were acquired using the head coil in a Siemens Magnetom Vision 1.5-Tesla scanner. Scanning time was about 8 min. Gadolinium was frequently administered.

The data were transferred via local area network or optical disk from the scanner to the planning workstation for further editing.

Marker Detection

Applied fiducial markers were depicted in the data set as pixel clusters with a certain expansion and contrast. The markers usually appear smaller in MRI scans due to noise at the edges and cracks, depending on the resolution and the partial volume effect as a dependent parameter of the image set. An 8-bit MRI image consists of 256 gray levels, and the brightest pixel (white) has a gray-level value of 256.

We used the VVPlanning 1.3 software (BrainLAB, Heimstetten, Germany) for preoperative planning and preparation of the data for intraoperative use with the VectorVision[2] neuronavigation system (BrainLAB, Heimstetten, Germany).

The implemented algorithm for automatic marker detection is based on a two-step procedure with two adjustable parameters, both of which were investigated.

1) The first parameter is the marker segmentation threshold (gray value) at which a marker is recognized and included for further analysis. The control parameter in the program is named "threshold". Its default value is set to a gray value of 250 for MRI scans and can be changed in the program.

2) The second parameter is the marker size. Size describes the median ideal diameter of a marker in three dimensions. The size value in the x- and z-directions is a predefined and fixed variable written to a file in the system software, which is the only place where it can be changed. The default size (accuracy) for CT markers is set to 7.0 mm; for MRI it is set to 6.5 mm. The adjustable marker-size value describes the size of a marker in the y-direction, as the size in this direction depends on the slice thickness and is therefore more inaccurate. The control parameter is named "accuracy" by the software company, but should rather be referred to as marker size or adjustable marker size to avoid confusion, since it has nothing to do with the accuracy of the method or system.

In CT scans, for example, a default size value of 7.0 mm and an accuracy value of 1.2 mm induce the algorithm to search for pixel clusters above 1200 Hounsfield units with a diameter ranging from 5.8 mm to 8.2 mm in the y-direction. As the rigid CT markers cannot be larger than 8 mm in the CT scans, it is not recommended to work with greater values for the y-accuracy, as the software might detect false markers.

For MRI markers the situation is slightly different, as the diameter of these markers may vary due to fabrication by up to 8.3 mm. The gel markers are not sufficiently robust and may deform when exposed to heat (e.g., from sunshine). We therefore store them in a refrigerator to avoid deformation before placement.

Data Analysis

The values for threshold (range: 255–230 with 6 intervals of 5 units) and accuracy (range: 2.1 – 0.1 cm with 0.2 cm intervals) were varied randomly in all MRI data sets. The influence of the gray-level (threshold) value on the sensitivity of marker registration was tested against a constant-size (accuracy) value of 1.3 cm in all data sets. For accuracy, the test was performed at the specific gray level at which all applied markers were registered correctly. In the 100 MRI data sets, a total of 591 markers were applied and had to be recognized. The results were written to a database, and it was noted how many markers had been detected and how many additional structures had been falsely misinterpreted as markers.

RESULTS

The time needed for automatic marker detection varied between 12 and 25 s (mean: 19.4 ± 4.07 s). There was no system failure during the trial.

False-positive detected markers were easily eliminated by browsing through the acquired points with a mouse-click and deleting these additional structures.

If the algorithm misses any fiducial markers, there are two options for proceeding. The first option is manual localization of the fiducial, which is time-consuming and carries the uncertainty of missing the center of the fiducial by tagging it outside the slice that would be the middle of the marker. The second option is to re-start the algorithm with changed parameters, such as lower threshold level and/or higher accuracy levels, both of which result in increased marker detection but also increase the number of false positives (though these false points can easily be eliminated as mentioned above).

Influence of Marker Size

The algorithm searches for pixel clusters above a certain gray level (threshold) whose dimensions are 6.5 mm in the x- and z-directions and 6.5 ± accuracy mm in the y-direction.

As shown in Figure 1, there was an optimum value for an adjustable marker size of 1.1 mm with a total of 8 undetected markers (1.35%) and 7 additional detected structures mimicking markers (1.18%) out of 591 markers. The incidence of markers *not* detected by the algorithm was below 5% for marker-size values between 0.7 mm and 2.1 mm, and increased up to 80.71% for a marker size value of 0.1 mm. At the same time, the rate of falsely detected additional markers, which was 32% for greater marker-size values, decreased to 0% for small values.

Influence of Threshold

The gray level at which the algorithm started the analysis was varied in five steps with a constant marker size of 1.3 mm in all data sets.

With a starting gray level of 255, the marker-detection algorithm found all applied markers in 14% of cases, and in 63% of cases with a starting gray level of 250. Figure 2 summarizes these data. The mean gray level for all 100 data sets above which the marker detection was correct was 248.9. The automatic detection of markers was good for higher gray levels, with just 11 missed markers (1.86%). By starting the algorithm at lower gray

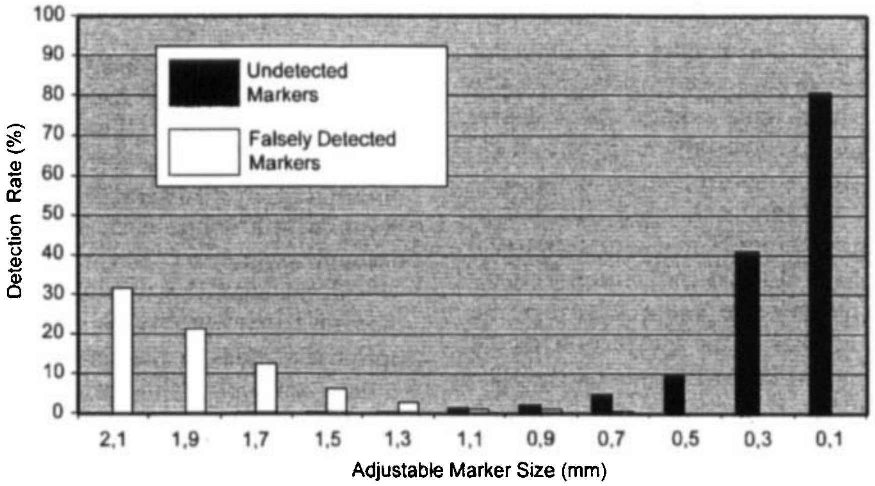

Fig. 1. Bar chart showing the dependence of undetected markers (black bars) and additional falsely detected markers (white bars) on the adjustable marker size (accuracy) in the y-direction. For greater marker-size values, the incidence of undetected markers is low, but there is significant detection of "false" markers. For low values of marker size, the incidence of undetected markers is high, but no additional structures are mistaken for markers. The optimum value for marker size in our data was 1.1 mm, with equally low false-positive and negative marker detection.

Marker size (mm)	2.1	1.9	1.7	1.5	1.3	1.1	0.9	0.7	0.5	0.3	0.1
Falsely detected markers (%) (white bars)	0.17 (1)	0.34 (2)	0.51 (3)	0.51 (3)	0.51 (3)	1.35 (8)	2.37 (14)	4.74 (28)	9.98 (59)	41.12 (243)	80.71 (477)
Undetected markers (%) (black bars)	31.98 (189)	21.66 (128)	12.69 (75)	6.26 (37)	2.71 (16)	1.18 (7)	1.02 (6)	0.51 (3)	0.17 (1)	0.00 (0)	0.00 (0)

Numbers in brackets are absolute numbers of additionally detected and undetected markers.

levels, the incidence of missed markers decreased to 0.17%. At the same time, the incidence of additional structures misinterpreted as markers increased from 5.92% for high gray levels up to 27.92% for lower starting gray levels (see Figure 3).

DISCUSSION

Image-based registration can be divided into extrinsic methods (based on foreign objects introduced into the image space) and intrinsic methods (based on the image information as generated by the patient, i.e., anatomical landmark registration). Extrinsic methods rely on artificial objects attached to the patient, which are designed to be clearly visible and accurately detectable in all pertinent modalities. Commonly used fiducial objects are stereotactic frames and screw-mounted bone-anchored markers, which provide the most reliable and accurate method for surgical registration.[11]

Most neuronavigation systems in use today use external fiducial markers for patient registration.[8,12–14] Before surgery, a series of corresponding points (≥3) must be identified in both the image and physical space. The computer determines a transformation between the image and physical space. With this method, an average application accuracy of 2-7 mm can be achieved.[2,15–17]

Accuracy is important to these systems, as is knowledge of the level of that accuracy. An advantage of marker-based systems is that the registration error depends only on the fiducial registration error (FRE), and is thus to a large extent independent of the particular object being registered.

The successful preoperative registration of the applied markers in the image space is a prerequisite for the intraoperative rigid paired-point registration of the actual head position in the physical space, as the computation of the registration transformation for intraoperative alignment of the images with the patient's anatomy depends upon correct registration of the fiducial markers.

Spatial inaccuracies in image-guided surgery are often caused by image distortion, slice thickness, registration errors, and inexactness of the localizing device or tracking errors.

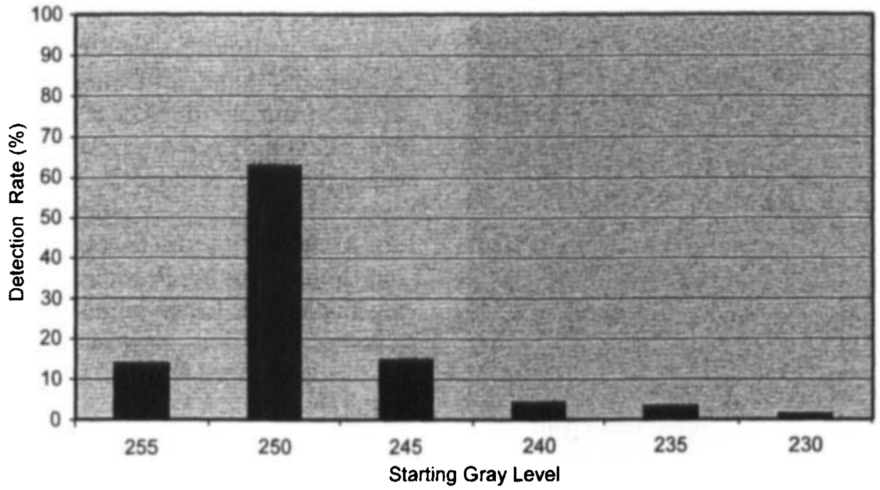

Fig. 2. Bar chart illustrating the successful automatic marker detection in relation to the gray level (threshold) at which the algorithm started on the basis of a constant marker size of 1.3 mm. In 77% of the data sets, a starting gray level above 250 was sufficient to permit successful recognition of all markers in the data set.

Gray level	255	250	245	240	235	230
All markers detected correctly (%)	14	63	15	4	3	1

With the modern scanners and navigation systems, it is mainly the registration procedure that determines the primary accuracy of image guidance before and during surgery. During surgery, i.e., after opening of the dura, following CSF release, and during or after tumor resection, brain shift may further decrease the accuracy and may become the most important source of error.[18,19]

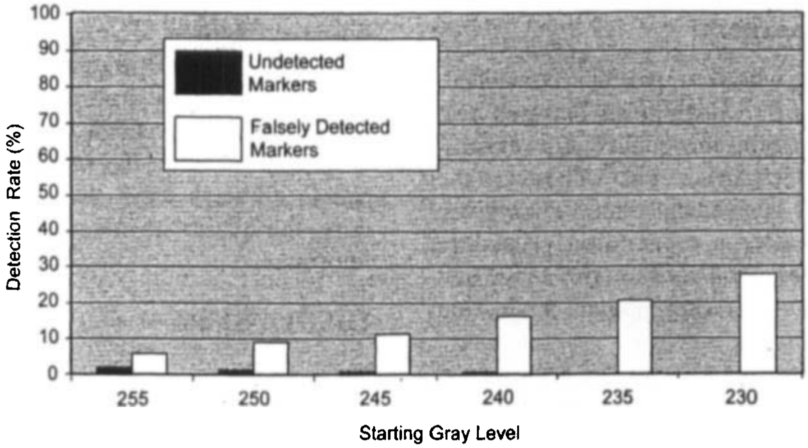

Fig. 3. Bar chart showing the relation of starting gray levels (threshold) and marker detection. For high gray levels, the incidence of missed markers (black bars) is higher and decreases to almost 0% when starting the algorithm at a level of 230. At the same time, the incidence of structures mistaken for markers (white bars) increased from 35 (5.92%) to 165 (27.92%) out of 591 markers.

Gray level	255	250	245	240	235	230
Falsely detected markers (%) (white bars)	7.78 (35)	8.80 (52)	11.17 (66)	15.91 (94)	20.14 (119)	27.92 (165)
Undetected markers (%) (black bars)	1.86 (11)	1.18 (7)	0.68 (4)	0.34 (2)	0.17 (1)	0.17 (1)

Numbers in brackets are absolute numbers of additionally detected and undetected markers.

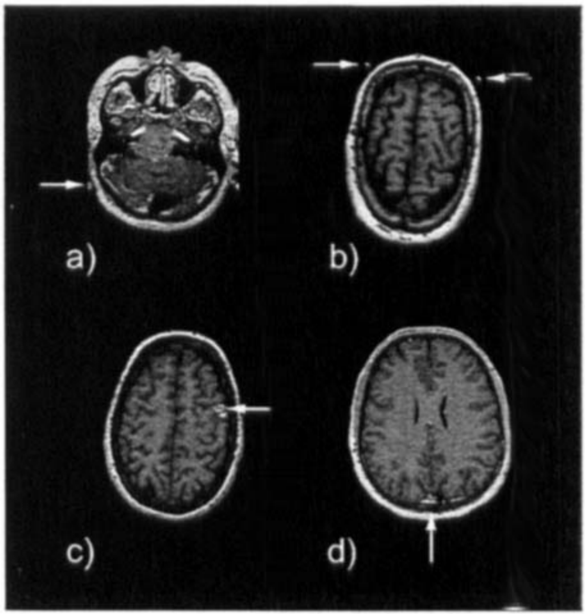

Fig. 4. Sources of error in automatic marker detection (arrows indicate detected marker). a) A marker is split by the field of view, resulting in two hemispherical markers. b) Old markers have lost their elasticity and water content, resulting in small and inhomogeneous signals that are not detected by the algorithm. c) A contrast-enhancing lesion may mimic a marker. d) The sinus can also be mistaken for a marker.

Interpreting Accuracy Values in Image-Guided Surgery

To avoid confusion when comparing accuracy values, it is important to distinguish between two error metrics describing the quality of a registration, as shown by Fitzpatrick et al.[20] These are the goodness of the fit-derived calculated error given by the computer after a registration procedure (FRE); and the real error between the image and the patient's anatomy during surgical navigation (TRE).

The former is a measure of the distance between corresponding fiducials after registration and transformation, i.e., the minimum value of a cost function that has been used to minimize the error between two corresponding sets of points. It is used to provide a measure of the registration quality. Thus, the error may be larger or smaller in the periphery, i.e., the site of approach. The latter (TRE) is the distance between points not used to estimate the registration transformation parameter. This "true" accuracy is also dependant on the geometrical relationship between the region of surgical interest and the objects used for registration (i.e., the fiducial array for point registration or the surface for surface registration). Accuracy will not be uniform throughout the intracranial volume, and when the surgical field is distant from the objects of referencing, a lever-arm effect may produce a significant TRE. Clinically, the TRE within the surgical field is most important, and it is a fundamental requirement not to rely on the FRE calculated by the system but to check the application accuracy before starting any kind of image-guided surgery. Poor registrations caused by poor fiducial configurations may appear to be good due to a small FRE value.[20]

FRE should not be used as a direct accuracy feedback since it does not take the following factors into account: 1) The accuracy of a registration generally increases with the number of registration points used; 2) The accuracy of a registration depends on location and thus cannot be represented as a single number; and 3) The accuracy of a registration depends on a variance and distribution of the points used, so TRE has to be included in decisions concerning the accuracy of intraoperative targeting.

CONCLUSION

Automated marker detection is very time-effective and, due to its independence of the user's interpretation of a marker's center, it is an objective method for marker registration in the navigation data. Optimization of the adjustable parameters of size and accuracy minimizes the number of falsely recognized or undetected markers. By eliminating the observer-dependent fiducial localization error with an automatic procedure, the quality of image-guided surgery can be improved.

DISCLOSURE

None of the authors is employed by BrainLAB, and they have no financial interest in that company or in the VectorVision[2] neuronavigation system.

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