Title page

Increase of accuracy in intraoperative navigation through high resolution flat-panel Volume-CT: Experimental comparison to multi-slice-CT based navigation

Basic Science Report

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Short title page

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Abstract

Hypothesis: High-resolution imaging as provided by flat-panel based volume computed tomography (fpVCT) could increase navigation accuracy and could therefore improve image-guided procedures or make novel navigated surgery concepts possible.

Background: Intraoperative navigation is an accepted tool in head & neck surgery. However its use is limited in the lateral skull base due to its low surgical accuracy. Surgical accuracy is substantially influenced by the resolution of the underlying dataset. FpVCT offers a nearly two times higher resolution than multislice computed tomography (MSCT). Target registration error (TRE) - as a measurement for surgical navigation accuracy - should decrease when navigation is based on fpVCT datasets.

Methods: An acrylic glass phantom with 37 fiducial points was scanned in a current MSCT (GE Lightspeed 16 Pro) and in an experimental fpVCT (GE). Both datasets were imported in an optical navigation system (BrainLab VectorVision^2). Five fiducial points were used for registration and seven for measuring TRE. The distance between indicated pointer tip and corresponding fiducial point in dataset was measured as TRE. Registration and TRE measurement was repeated five times for each CT dataset. Average TREs were calculated and results compared using t-test.

Results: The average TRE using MSCT (0.82 (standard deviation: 0.35) mm) was significantly higher than using fpVCT (0.46 (standard deviation: 0.22) mm) ($p<0,01$).

Conclusion: Submillimetric surgical navigation accuracy is possible using high resolution fpVCT. This could be highly beneficial in skull base surgery navigation.

Introduction

Image-guided surgery (IGS) systems have found widespread use in ENT surgery. IGS systems allow real-time, intraoperative tracking of current location within volume datasets (CT or MRI)(1). They are commonly used for sinus surgery (2-6) and lateral skull base surgery (7-11).

The demand on surgical accuracy (12) of the intraoperative navigation in different regions varies strongly. Intraoperative navigation during sinus surgery is highly supportive with the currently reached surgical accuracy (2, 13-15). However, in the lateral skull base intraoperative navigation could be much more useful if the surgical accuracy could be improved beyond the currently achieved (14). This is primarily because the structures of the lateral skull base are much smaller than the structures of the maxillo facial and sinus region (8). The currently reached surgical accuracy does not allow the full utilization of the benefits of intraoperative navigation for surgery of the lateral skull base (e.g. microsurgery of the middle ear or cochleostomy for cochlear implantation) (16-19). Therefore it is necessary to improve surgical accuracy.

The surgical accuracy of intraoperative navigation is a complex function that is affected by various factors. The resolution of the underlying imaging is one of the most important (12, 20).

A new kind of CT scanner, a flat-panel based Volume-CT (fpVCT) offers an increased resolution when compared to state-of-the-art MSCT scanner (21-25). FpVCT scanning of the human skull base has been recently shown (26). The surgical accuracy of intraoperative navigation might therefore improve if navigation is based on fpVCT datasets.

Material and Methods

A surgical accuracy comparison of intraoperative navigation based on MSCT and on fpVCT by average target registration error analysis (TRE) using a phantom (12, 15) was performed.

TRE is the difference between corresponding positions in the real world (e.g. phantom or patient) and the underlying dataset (e.g. CT-scan) following registration. A comprehensive overview of errors associated with intraoperative navigation and their clinical relevance is given in (15). TRE is the error of interest for the surgeon (15).

Phantom

The acrylic glass phantom used for TRE measurement is shown in Figure 1. The testing area consisted of two quadratic plates that were attached using two oblique quadratic plates. It measured 10 cm in width, height and length. It was affixed with 37 nearly equally distributed fiducial points in form of precisely defined inverted cones that were drilled into the acrylic glass. The reference device was fitted on the phantom (Figure 1).

Flat-panel based Volume-CT scanning

The phantom was scanned in an experimental flat-panel Volume-CT (Figure 2). The scanner consisted of a X-ray tube and 2 flat-panel detectors mounted on a standard CT gantry (22, 23, 27). The scanner can be used in a two-panel- or one-panel-mode.

In two-panel mode it provides a scan field of view big enough for a complete human head (27 cm), while the scan field of view in one-panel-mode was sufficient for the scanning of the phantom as used in this study (13.5 cm). Both detectors consisted of 1024 by 1024 detector elements on an area of 20.48 cm by 20.48 cm, resulting in a detector element size of 200 µm by 200 µm. A 360° rotation took 8 seconds and 1000 projections were acquired. Z-coverage was 4.21 cm per rotation. Three scans in a step and shoot scanning mode were performed to scan the testing area of the phantom. The scan field of view in the X/Y plane was 13.5 cm. A tube voltage of 140kV together with a current of 20mA was used. The used scanning parameters were empirically derived in earlier experiments to optimize image quality for high resolution.

For reconstruction a 512 by 512 matrix was selected to assure compatibility with standard post-processing software. The resulting voxel size was selected to be $(190\ \mu m)^3$ resulting in a reconstruction field of view of 10 cm in diameter. The reconstruction was based on the Feldkamp-Davis-Kress cone beam algorithm (28). The reconstructed volume dataset was exported in standard DICOM3 format. The measured, isotropic spatial resolution using a 25 µm Tungsten wire object (10% MTF, high resolution scanning and reconstruction) is approximately 25 line-pairs(lp)/cm (≈ 200 µm feature size) for this scanner in a similar scanning mode (23).

Multislice-CT scanning

The phantom was scanned in a 16-slice-CT (GE Lightspeed 16Pro, GE Healthcare, Milwaukee, WI) using a high resolution scanning protocol: 120 kV, 80 mA, 0.625 mm slice thickness and a pitch of 0.5.

The reconstruction was performed with a reconstruction field of view of 9.6 cm, a z-voxel dimension of 0.3 mm, a ”bonepuls” kernel in “standard” modus (180° weighted interpolation), resulting in 187 μm by 187 μm by 300 μm voxels. The measured spatial in plane and Z-direction resolution using a 25 μm Tungsten wire object (10% MTF, high resolution scanning and reconstruction) is approximately 14-15 lp/cm (≈ 350 μm feature size) for this scanner (23, 29).

Navigation system

An optical navigation system VectorVision[2] (BrainLAB, Heimstetten, Germany) was used. The system is based on paired infrared cameras that detect reflecting markers. Reflecting markers are placed on the pointing and reference device. By means of triangulation navigation pointer and reference device can be located in space.

Registration, accuracy measurement and data analysis

Registration is the correlation of the coordinates of the phantom in real world and CT dataset using fiducial points.

The deepest points of the inverted cones were defined as fiducial points (Figure 4). For registration five evenly distributed fiducial points were selected after importing the DICOM3 datasets into the navigation system. During the registration process all five points were touched with the pointer one after another (Figure 1b). The pointer was slightly swayed around without leaving its position within the inverted cone until the navigation system signalled for successful detection of the pointer’s tip position.

After registration, TRE analysis was performed using seven fiducial points which were different from the registration points. Fiducial points were marked within the CT dataset and the pointer was placed in the fiducial point while the shaft of the pointer was perpendicular to the surface of the phantom. The distance between the indicated pointer position and the marked fiducial point in the CT dataset was measured by the system and noted. Screenshots were taken for documentation. The phantom was not moved during the measurements. The registration and TRE measurement procedure were repeated five times (passes) for each CT modality, resulting in 35 data points for each CT modality. The average target registration error (TRE) and standard deviation (SD) were calculated. Average TREs of both CT modalities were compared. The significance of the difference between both CT modalities was calculated by performing two sided t-test on dependent samples.

Results

Scans of the phantom, the subsequent import of the datasets into the navigation system and registrations were successful in all cases. All registration fiducial points could be identified and all distances (TRE) could be measured.

The average TRE using the MSCT dataset was 0.82 (standard deviation: 0.35) mm with an error range from 0.3 mm to 1.7 mm. The average TRE using the fpVCT dataset was 0.46 (standard deviation: 0.22) mm with an error range from 0.1 mm to 1 mm.

As a result, the average TRE using fpVCT was significantly lower than the average TRE using MSCT ($p<0.01$). Further, the standard deviation, error range as well as maximal error were lower in fpVCT based navigation. A box plot diagram of the TRE results is given in Figure 3.

Representative screenshots are given for MSCT (Figure 4 A) of the measurement of data point 7 of pass 1 and for fpVCT (Figure 4 B) of the measurement of data point 6 of pass 3.

Discussion

Surgical accuracy and target registration error

The terms “accuracy”, “precision” and related expressions are well defined (12, 15). Often less appropriate error measurements ranging from calculated registration error (CRE) to fiducial registration error (FRE) have been taken as a measurement for surgical accuracy (12).

The term “surgical accuracy” has been defined to provide a clinically useful measurement of intraoperative navigation quality. It is defined as the maximal deviation of a navigation system from the true position together with the precision (in terms of reproducibility)(12). Under experimental conditions comparable to this study, measuring the TRE provides a good approximation of “surgical accuracy” (12, 15).

CT resolution and its influence to surgical accuracy

The resolution of the fpVCT was higher than the resolution of the MSCT system. The resolution of the fpVCT scanner is with 200 µm isotropic feature size almost half as big as the resolution of the MSCT system with 350 µm.

However, this increase in resolution does not proportionally translate into an increased surgical accuracy or decreased TRE, because surgical accuracy of a navigation system setup depends on a multitude of factors:

First, there are inaccuracies of the navigation system itself, which are complex functions that are influenced by design factors, such as calibration, resolution of the infrared camera and so on. Even the position of an object within the detector field of the infrared camera influences the accuracy and precision of the system (30).

Second, there are additional inaccuracies in the registration process. During registration, corresponding fiducial markers need to be exactly identified to align the preoperative CT scan with the intraoperative anatomy. Fiducial localization errors (FLE) are associated both with the identification of fiducial points in the real world (FLE_w) as well as in the CT-dataset (FLE_{CT}). Lower FLE on both ends usually results in a higher surgical accuracy (15).

The FLE_w is influenced by the navigation system, the shape of the fiducial marker and carefulness of the operator (15). The FLE_{CT} is strongly influenced by the resolution of the CT dataset and might have benefited from the higher resolution of fpVCT.

However, measurement of FLEs and other errors separately is challenging and requires elaborative technology, while their sole relevance for the surgeon is low. Therefore rather the resulting TRE was measured in this study as an endpoint summarizing all potential influences of a higher resolution.

There is another registration method that can further increase the surgical accuracy: So-called frame based registration results usually in lower FLE than “free” fiducial registration as used in this study, because the geometry between fiducial points both in the real world and in the CT dataset is known. Implementation of a frame-based registration method is currently work in progress.

By decreasing error sources that are associated with the resolution of the underlying data set, others that are not directly influenced by imaging gain relative weight. Thus developers and clinicians have to focus on these other error sources to fully utilize the resolution of future imaging modalities.

Fiducial placement

The placement of free registration fiducials with regard to the surgery area of interest is a significant factor that contributes to TRE (31, 32).

In this study, the registration fiducials have been placed in an even distribution around the testing area and relatively close to the target fiducial points. This configuration of fiducial points is considered optimal. However, because of the human anatomy such an evenly distribution close to the surgery field of interest is difficult to realize.

Considering lateral skull base surgery, two alternatives can be realized. First, one could place the registration fiducials somewhat close around one outer ear on the side where the surgery needs to be performed. Alternatively, one could place the fiducials on the calvaria of the whole head, including the other side. The first alternative would only give relatively small TRE values close to the centroid of the registration fiducials that would be within the outer ear or the very lateral part of this side of the skull base (31, 32), but would have the advantage that the navigation datasets do not need to include the whole head. This could be a significant advantage, because very high resolution datasets with a field of view as big as the whole human skull would need tremendous computer memory space and calculation power. Further, flat-panel scanners that become clinically available first could provide only a small scan field of view big enough for just one temporal bone and closely placed fiducials (33).

When the problems of big datasets and small scan fields are solved, the second alternative would certainly be the better registration fiducial point placement.

Nevertheless, in both alternatives, the in vivo placement of registration fiducial would be less optimal as in this experimental study; therefore the TRE values would be worse. Cadaver head studies should follow.

FpVCT for patient scanning?

FpVCT, as it is used in this study, is a new CT modality that is not yet available for patient scanning. Despite the fact that several prototypical scanners that are capable of full head scan - and therefore patient head scanning - exist, this technology is currently in an experimental state. However, it is likely that in the future flat-panel based CT systems could find wider use. The flat-panel CT technology could be promoted further through applications in angiography and maxillo-facial imaging where flat-panel detectors are replacing image intensifier systems. A C-arm angiography system based on flat-panel detectors that offers rotational modes (34, 35) could be used to perform high resolution imaging of the temporal bone and the skull base with a similar image quality to a gantry based CT machine. Their use for intraoperative guidance of sinus surgery has already been described (35).

Despite widespread assumptions, the increased resolution of fpVCT does not necessarily means an increased radiation dose, because a higher noise can be tolerated in imaging of high contrast structures such as the human skull base.

Conclusion

In this study the use of high-resolution fpVCT datasets for intraoperative navigation has been described first.

By contrasting the TRE of navigation that is based on MSCT with higher resolution fpVCT it was shown that the higher resolution CT dataset yields a lower TRE.

Therefore, it can be concluded that fpVCT might improve surgical accuracy in head and neck surgery. Discussed limitations of this phantom study apply.

While the dependences of navigation accuracy on the underlying dataset is already well described, it was not clear that even with standard navigation systems the average TRE could be lowered to half a millimetre when combined with high resolution datasets.

With such a surgical accuracy, intraoperative navigation can be improved and new techniques as well as procedures could become feasible. The results of this study should stimulate research to develop navigation systems or mechatronic assistance systems that take full advantage of the higher resolution CT datasets that might become clinically available soon.

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Figure legends

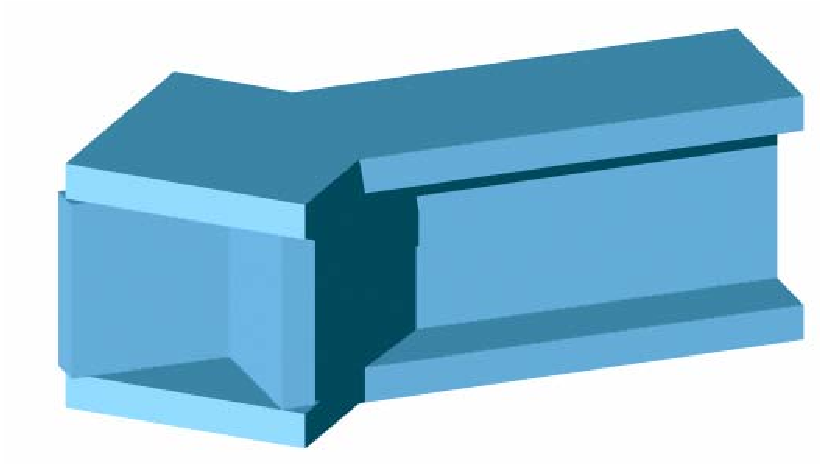
Figure 1 Accuracy measurement acrylic glass phantom consisting of a testing cuboid and a rack to attach the reference device. The navigated pointer is located in one of the inverted cone tips.

Figure 2 Flat-panel based Volume-CT prototype as used in this study. Despite the fact that from a technical viewpoint scans of entire human skull are possible, the machine is not approved for human scanning yet.

Figure 3 Comparison of box plots of TREs (in mm) of navigation that is based on high resolution fpVCT and of state-of-the-art MSCT. TRE was significantly lower when navigation was based on high-resolution fpVCT datasets.

Figure 4 Representative screenshots during TRE measuring. While the pointer tip in the real world is located in the inverted cone tip the indicated distance between the tip of the green line (as indicated pointer tip) and the red cross (that marks the inverted cone tip as fiducial point) gives the target registration error. It varies significantly between MSCT (A) and fpVCT (B).

Images



A

B

Figure 5 Accuracy measurement phantom consisting of a testing cuboid and a rack to attach the Laterostar. The navigated pointer is located in one of the inverted cone tips.

Figure 6 Flat-panel based Volume-CT prototype as used in this study. Despite the fact that from a technical view point scans of whole human skull base are possible, the machine is not approved for human scanning yet.

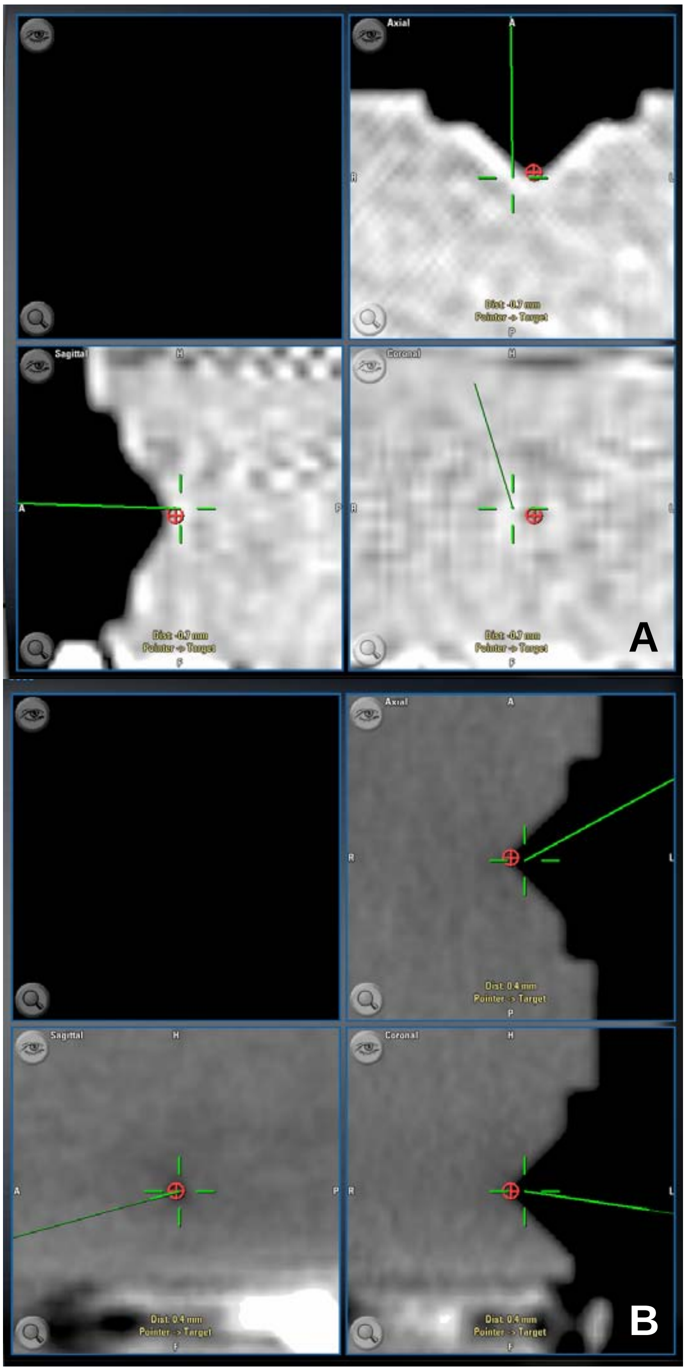


Figure 7 Representative screenshots during TRE measuring. While the pointer tip in the real world is located in the inverted cone tip the indicated distance between the tip of the green line (as indicated pointer tip) and the red cross (that marks the inverted cone tip as fiducial point) gives the target registration error. It varies significantly between MSCT (A) and fpVCT (B).

Table

Pass	Data point	TRE fpVCT	TRE MSCT
1	1	0,50	0,70
	2	0,50	0,90
	3	0,40	0,70
	4	0,70	0,90
	5	0,60	0,60
	6	0,40	0,60
	7	0,30	0,70
2	1	0,30	1,00
	2	0,40	1,10
	3	0,40	0,80
	4	0,80	1,60
	5	1,00	1,50
	6	0,90	1,70
	7	0,90	1,60
3	1	0,70	1,00
	2	0,20	0,40
	3	0,70	0,50
	4	0,20	0,70
	5	0,30	0,70
	6	0,40	1,00
	7	0,50	0,60
4	1	0,60	0,70
	2	0,30	1,20
	3	0,50	0,80
	4	0,30	0,80
	5	0,10	0,70
	6	0,40	0,40
	7	0,30	0,70
5	1	0,40	1,00
	2	0,20	0,60
	3	0,30	0,50
	4	0,70	0,30
	5	0,40	0,80
	6	0,50	0,80
	7	0,10	0,30

Table 1 Comparison of TRE of fpVCT and MSCT based navigation. The TRE has been measured using seven different fiducial points in five passes resulting in 35 measurements.