Robotic versus Freehand Needle Positioning in CT-guided Ablation of Liver Tumors: A Randomized Controlled Trial

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Conflicts of interest are listed at the end of this article.

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Purpose: To compare the accuracy of freehand versus robotic antenna placement in CT-guided microwave ablation (MWA) of liver tumors.

Materials and Methods: This study was conducted as a prospective single-center nonblinded randomized controlled trial (Netherlands Trial Registry, NTR6023). Eligible study participants had undergone clinically indicated CT-guided MWA of liver tumors and were able to receive a CT contrast agent. Randomization was performed per tumor after identification on contrast material–enhanced CT images. The primary outcome was the number of antenna repositionings, which was compared by using the Mann-Whitney U test. Secondary outcomes were lateral targeting error stratified by in-plane and out-of-plane targets and targeting time.

Results: Between February 14 and November 12, 2017, 31 participants with a mean age of 63 years (range, 25–88 years) were included: 17 women (mean age: 57 years; range, 25–77 years) and 14 men (mean age, 70 years; range, 52–88 years). The freehand study arm consisted of 19 participants, while the robotic study arm consisted of 18 participants; six participants with multiple tumors were included in both arms. Forty-seven tumors were assessed; five tumors were excluded from the analysis because of technical limitations. In the robotic arm, no antenna repositioning was required. In the freehand arm, a median of one repositioning was required (range, zero to seven repositionings; $P = .001$). For out-of-plane targets, lateral targeting error was 10.1 mm $\pm$ 4.0 and 5.9 mm $\pm$ 2.9 ($P = .007$) for freehand and robotic procedures, respectively, and for in-plane targets, lateral targeting error was 6.2 mm $\pm$ 2.7 and 7.7 mm $\pm$ 5.9, respectively ($P = .51$). Mean targeting time was 19 minutes (range, 8–55 minutes) and 36 minutes (range, 3–70 minutes; $P = .001$) for freehand and robotic procedures, respectively.

Conclusion: Robotic antenna guidance reduces the need for antenna repositioning in microwave ablation to accurately target liver tumors and increases accuracy for out-of-plane targets. However, targeting time was greater with robotic guidance than with freehand targeting.

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Over the past 20 years, thermal ablation has emerged as a successful treatment method for hepatic malignancies (1–3). Radiofrequency ablation and microwave ablation (MWA) are currently recommended for the treatment of hepatocellular carcinoma (HCC) and colorectal liver metastases in patients who are unfit for surgery or in combination with surgery (4–6). The main drawback of percutaneous liver tumor ablation is local recurrence of disease, with reported ablation site recurrence rates ranging from 5.0% to 32.1% (2,7–9). Risk factors for recurrences include larger tumor size, peritumoral vascularity, and insufficient ablation margin surrounding the tumor (10–12). The latter can be caused by inaccurate placement of the ablation antenna. Currently, antenna placement is mostly performed manually (freehand), with CT as a frequently used imaging modality for guidance.

To improve antenna placement accuracy, various robotic needle guiding systems have been developed. They generally offer higher positioning accuracy and/or improved procedure times compared with freehand needle placement (13–16). However, to our knowledge, none of these devices have been compared with freehand CT-guided needle placement in randomized controlled trials. We developed a robotic needle positioning system that proved highly accurate in a phantom study (17).

The purpose of this study was to compare the accuracy of robotic-guided antenna placement versus freehand antenna placement in study participants with liver tumors treated with percutaneous CT-guided MWA in a randomized controlled trial. We hypothesized that robotic MWA antenna placement increases accuracy. Results were stratified according to difficulty (in-plane vs out-of-plane antenna placement). The primary end point was the number of repositionings required to obtain an adequate antenna position.
Robotic versus Freehand Needle Positioning in CT-guided Liver Tumor Ablation

Abbreviations
DLP = dose-length product, HCC = hepatocellular carcinoma, MWA = microwave ablation

Summary
For CT-guided microwave ablation of liver tumors, robotic antenna guidance offers significant advantages over freehand antenna placement in terms of the number of antenna repositionings and placement accuracy.

Implications for Patient Care
- For CT-guided microwave ablation of the liver, out-of-plane targeting errors were 40% lower with robotic guidance than with freehand localization.
- For CT-guided microwave ablation, robotic antenna guidance reduced the need for antenna repositioning, which has the potential to improve ablation efficacy.
- Longer targeting times for robotic guidance than for freehand placement suggests the need for further optimization of robotic guidance.

Materials and Methods

Study Design
This prospective single-center nonblinded randomized study was performed in the Netherlands and was approved by the institutional review board of the University Medical Center Groningen. The study protocol can be found in the Netherlands Trial Registry (NTR6023). The study was financially aided by Samenwerkingsverband Noord-Nederland (grant T2017). DEMCON Advanced Mechatronics (Enschede, the Netherlands) provided equipment (the robotic device) for the study. Neither agency had a role in study design or data analysis. Only the authors who are not employed by DEMCON had control of inclusion of any data and information that might present a conflict of interest. Written informed consent was obtained from all participants prior to the procedure.

Study Participants
Participants who were candidates for CT-guided MWA of the liver were eligible to participate if (a) their tumor size was less than 50 mm, (b) the number of tumors was three or fewer, and (c) they were 18 years of age or older. Participants were excluded if (a) their tumor was adjacent to biliary structures, (b) they were unable to undergo general anesthesia, or (c) they were unable to tolerate the CT contrast agent. All participants were discussed in a multidisciplinary tumor board meeting for CT-guided percutaneous liver ablation.

Randomization and Masking
Procedures were randomized per tumor by using block randomization, as described previously by Arifin (18). Results were revealed from sealed opaque envelopes after tumors were given unique identifying number by a researcher (W.J.H., with 4 years of experience) who was not involved with participant selection or clinical decision making.

Procedures
All procedures were performed with the participant in general anesthesia and in a stable position on a vacuum mattress to eliminate patient movement. Procedures were performed with a 64-multidetector row CT system (Somatom Sensation 64; Siemens Medical Systems, Erlangen, Germany). Image acquisition and antenna manipulation were performed after controlled apnea. This guarantees maximum relaxation of the elastic recoil in the thorax and thus a reproducible position of the liver. A contrast material–enhanced CT study was performed for planning. Navigational CT images were acquired after each antenna manipulation. Tube voltage was 100 kVp, and quality reference tube current was 110–179 mAs. The planning scan was acquired prior to the admission of intravenous contrast agent (90–110 mL of Iomeron 300; Bracco Imaging, Milan, Italy). Section thickness and section increment were 2 mm. After identification, tumors were given an identifying number, and a target was selected inside the tumor on the contrast-enhanced CT image by using the intervention suite software on the scanner. These targets were stored in key images from which the exact target coordinates were extracted.

Robotic Approach
Robotic-guided procedures were performed with the Needle Positioning System (NPS; DEMCON Advanced Mechatronics), which consists of a robotic arm that slides on a rail parallel to the CT table (Fig 1). Bolting the rail to the CT table takes less than 5 minutes and is done at the start of the day. Patients can get on and off the table easily with the system in place. After patient positioning, the planning CT scan is acquired and the entry point is marked on the skin. The skin is disinfected, and surgical drapes are placed. Subsequently, a disposable sterile cover is put over the robotic arm before it is positioned above the sterile skin. The needle guide itself attaches to the arm through a hole in the sterile cover. The needle guides are reusable and cleaned with autoclave sterilization. The robotic arm is positioned manually on top of the entry point on the skin, using a disposable pointer on the needle guide. After the device is locked into place, a registration CT scan is acquired, on which the four CT fiducials situated inside the robotic arm are visualized. This is a non–contrast-enhanced scan with similar settings as the planning CT scan. The registration scan, together with the selected target, are sent to the system, after which the device automatically orients its needle guide toward the target. Subsequently, the MWA antenna can be clipped into the needle guide and the insertion is performed manually to the depth specified by the system. After a control CT scan, the MWA antenna is unclipped from the needle guide and mechanical ventilation is restarted. A more detailed description of the system and the procedure can be found in Arnolli et al (17).

For the freehand procedures, use of the vacuum mattress and controlled apnea was similar. The microwave antenna was positioned manually, and CT images were used to verify the position and, if necessary, the antenna was repositioned and checked again by using CT until the position was...
adequate for ablation. “Adequate” was defined as a position within the tumor, with the potential exception of a position with close proximity to the liver capsule. If ablation cycles in multiple areas in the tumor were necessary, the repositioning of the ablation antenna was performed by hand. Hence, only the placement of the antenna toward the initial position differed between the two study groups. Subsequently, MWA was performed according to the protocol provided by the manufacturer.

For the first 29 procedures (in 26 participants), the Emprint MWA system (Medtronic, Minneapolis, Minn) was used. Because of a global recall during the study by Medtronic, a different ablation system (Amica, HS Medical, Rome, Italy) was used for the remainder of the study (13 procedures in eight participants). A contrast-enhanced CT examination was performed directly after the procedure. If the ablation zone was determined to be inadequate, additional ablation was performed. A follow-up contrast-enhanced CT examination was performed 1 week after the ablation procedure to evaluate if the ablation zones completely covered the tumor and included a safety margin.

Data Analysis
The freehand and robotic groups were compared with regard to participant age, tumor type, tumor diameter, tumor depth, applied ablation energy, angulation (in-plane and out-of-plane procedures), and treatment type (first ablation and ablation of recurrence). The tumor diameter was measured as the long-axis diameter in the transverse plane. Tumor depth was determined as the Euclidian distance between the entry point on the skin and the selected target (Fig 2). Measurements were performed by a radiologist with 10 years of experience (J.P.P.). The procedures were categorized as in plane or out of plane on the basis of the angle of approach. If the microwave antenna was angled 5 or more degrees from the axial plane, the approach was considered to be out of plane.

Outcomes
Primary outcome was the number of antenna repositioning attempts required to reach a position inside the tumor. This was verified during the procedure by a radiologist who did not perform the antenna placement (J.P.P.). Advancement of the antenna along the same path to reach the correct depth was not considered repositioning. The secondary outcomes were antenna placement accuracy, targeting time, number of CT scans acquired during the MWA procedure, dose-length product (DLP), number of incomplete ablations at the 1-week control contrast-enhanced CT study, and complications.

The accuracy of antenna positioning was defined in multiple ways. The Euclidian error was determined as the distance between the antenna tip and the target, and the lateral error was determined as the shortest distance between the needle path and the target. The angles between target, skin entry point, and needle tip were also determined (Fig 3). These measurements were determined automatically after selection of the skin entry point and the tip of the MWA antenna by radiologist J.P.P. both after initial antenna insertion as well as when the antenna’s position was deemed adequate.

The targeting time was defined as time from target selection until adequate antenna position. For the robotic approach, this included application of the sterile cover, the placement of the needle guide, acquisition of the fiducial CT scan, and data transfer. The robot installation at the start of the day, which took approximately 5 minutes, was not included because it was not repeated for each procedure. For solitary tumor ablations, total procedure time was determined as the time from the patient’s arrival in the CT room to the time of the patient’s departure from the CT room. The number of CT scans acquired to reach this position and the corresponding DLP were determined as well, excluding the contrast-enhanced CT scans. For the robotic procedures, this included the fiducial scan.

Complications were monitored and classified as minor or major according to the International Working Group on Image-Guided Tumor Ablation standards of terminology and reporting criteria (19). Minimal perihedral fluid or blood collection was considered an expected side effect and was therefore not classified as a complication.

To investigate the differences between in-plane and out-of-plane approaches, the outcomes of the freehand and robotic
shows the inclusion flowchart. Five of the robotic approaches (in five participants, two of whom had more than one tumor) were excluded from analysis. In one instance, only three of the device fiducials were inside the scanner’s field of view. Another approach proved to be technically impossible because of steep cranial angulation. A third robotic approach suffered from technical malfunctioning of the system, which was resolved before the operators proceeded to the next target. The other two procedures were excluded because of antenna deflection that was so substantial that it prevented liver penetration. These procedures were finished by using the freehand approach and were replaced in our analysis by including five additional tumors in three additional participants and in one participant who had previously been included.

For the final analysis, 21 robotic approaches in 16 participants and 21 freehand approaches in 18 participants were included. Table 1 shows the participant characteristics. Twenty-one participants had a single tumor, nine had two tumors, and one had three tumors; six participants were included in both arms. Twenty-six colorectal liver metastases were treated (in 17 participants), 12 HCCs were treated (in seven participants), and four tumors were benign liver nodules. Overall, mean participant age was 61 years (range, 25–88 years), mean tumor diameter was 23.1 mm $\pm$ 11.1, and mean depth from skin was 88.4 mm $\pm$ 29.1. For the robotic and freehand groups, respectively, tumor diameter was 21.2 mm $\pm$ 10.2 and 24.9 mm $\pm$ 11.9 ($P = .31$) and tumor depth was 92.2 mm $\pm$ 31.8 and 84.0 mm $\pm$ 26.1 ($P = .33$). For men, the mean age was 70 years (range, 52–88 years); for women, mean age was 57 years (range, 25–77 years). For the robotic and freehand arms, respectively, the mean participant ages were 60.1 years $\pm$ 15.2 and 62.8 years $\pm$ 15.2 ($P = .52$). Tumor characteristics for freehand and robotic procedures are presented in Table 2.

**Statistical Analysis**

Sample size calculation.—An analysis of 50 consecutive CT-guided freehand liver ablations performed at our department showed that the mean number of antenna manipulations required to reach an adequate ablation position was 2.1 $\pm$ 1.3 (standard deviation). To enable us to demonstrate that the robotic approach will improve to a mean of 1.2 $\pm$ 0.2 needle manipulations with a power of 0.8 and an $\alpha$ of .5, the number in both arms was calculated to be 21. Power calculations were performed by using G-power 3.1.9.2 (Dusseldorf, Germany) (20).

All variables were checked for normality by using the Shapiro-Wilk test. The means and standard deviations were determined for continuous parametric variables (age, tumor diameter, tumor depth, all accuracy measures) and were compared by using the independent samples $t$ test. For categoric parameters (tumor type, angulation, treatment type, liver side, incomplete ablations), the $\chi^2$ test was used. For nonparametric variables (number of repositionings, number of CT scans), the median and range were determined and were compared by using the Mann-Whitney $U$ test. Statistical significance was set at $P < .05$. Statistical analyses were performed in SPSS 23 (IBM, Armonk, NY).

**Results**

Between February 7, 2017, and November 13, 2017, 47 tumors in 31 participants were included in our study. Figure 3 shows the inclusion flowchart. Five of the robotic approaches (in five participants, two of whom had more than one tumor) were excluded from analysis. In one instance, only three of the device fiducials were inside the scanner’s field of view. Another approach proved to be technically impossible because of steep cranial angulation. A third robotic approach suffered from technical malfunctioning of the system, which was resolved before the operators proceeded to the next target. The other two procedures were excluded because of antenna deflection that was so substantial that it prevented liver penetration. These procedures were finished by using the freehand approach and were replaced in our analysis by including five additional tumors in three additional participants and in one participant who had previously been included.

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**Table 1: Participant Characteristics**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Datum</th>
</tr>
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<tr>
<td>No. of participants</td>
<td>31</td>
</tr>
<tr>
<td>Mean age (y)</td>
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</tr>
<tr>
<td>Age range (y)</td>
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<tr>
<td>No. of men</td>
<td>14</td>
</tr>
<tr>
<td>Mean age (y)</td>
<td>70</td>
</tr>
<tr>
<td>Age range (y)</td>
<td>52–88</td>
</tr>
<tr>
<td>No. of women</td>
<td>17</td>
</tr>
<tr>
<td>Mean age (y)</td>
<td>57</td>
</tr>
<tr>
<td>Age range (y)</td>
<td>25–77</td>
</tr>
<tr>
<td>No. of tumors per participant</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>21</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Robotic procedure</td>
<td>12</td>
</tr>
<tr>
<td>Freehand procedure</td>
<td>13</td>
</tr>
<tr>
<td>Both*</td>
<td>6</td>
</tr>
</tbody>
</table>

* Participants with multiple tumors could be randomized in both groups.
The number of repositionings was zero (range, zero to zero) and one (range, zero to seven) for robotic and freehand procedures, respectively. For initial placement, the Euclidean error was smaller for robotic procedures—namely, 10.2 versus 22.2 mm ($P < .001$). All other error measures were also smaller for the robotic approach, with values of less than half of those for the freehand approach ($P < .005$). For adequate antenna position, the Euclidean error of the robotic procedures was still smaller than that of the freehand procedures—namely, 9.3 versus 13.8 mm ($P = .02$). All technical outcomes can be found in Table 3.

Mean targeting time for freehand procedures was 19 minutes, as compared with 36 minutes for robotic procedures ($P = .001$). Total procedure times for solitary tumor ablations were 2 hours 40 minutes and 2 hours 36 minutes for robotic ($n = 10$) and freehand ($n = 11$) procedures, respectively ($P = .76$). Total ablation time and amount of energy applied until the post-MWA contrast-enhanced CT scan were acquired were approximately similar between groups. The numbers of incomplete ablations in the robotic and freehand groups at the follow-up CT were three and one ($P = .34$), respectively. There were two complications in this study. The first, which occurred in the freehand group, consisted of an abscess that required laparotomy with resection of the left liver lobe. The second, which occurred in the robotic group, consisted of a self-resolving pneumothorax.

Table 4 shows the technical outcomes, stratified for in-plane and out-of-plane procedures. Eleven of the 21 freehand procedures were out of plane, compared with 13 of the robotic procedures. In the in-plane procedures, targeting times were 18 and 32 minutes ($P = .004$) for freehand and robotic procedures, respectively. In the out-of-plane procedures, targeting times were 19 and 37 minutes, respectively. For in-plane procedures, only the depth error was significantly better (10.1 vs 3.2 mm, $P = .03$) for the robotic group, but other error measures were similar. For the out-of-plane procedures, the robotic system outperformed freehand positioning on all error measures ($P < .05$ for all).

### Discussion

The goal of our study was to compare antenna placement accuracy in robotic and freehand CT-guided liver tumor ablation. With robotic guidance, antenna repositioning was not needed in any of the study participants. However, in the freehand group, between zero and seven repositionings were needed. For out-of-plane procedures, the lateral accuracy improved from 16.1 to 5.6 mm. This shows that robotic guidance is of value for CT-guided liver ablation with complex angulations.

The number of CT scans was equal in both groups, but the DLP for the robotic group was significantly higher because of a greater scan length required to visualize all the fiducials. The robotic targeting times were, on average, 20 minutes longer than the freehand targeting times (18 minutes, $P = .001$). This can be attributed to the application of the sterile cover and to some technical issues with data transfer. It did not significantly affect the total procedure times for solitary tumors, which were 2 hours 36 minutes and 2 hours 40 minutes ($P = .76$) for freehand and robotic procedures, respectively. For shorter procedures without general anesthesia, this may be more substantial.

In the robotic group, three ablations were incomplete even though the lateral error was measured as less than 5 mm. In one participant, no contrast-enhanced scan could be acquired at the end of the procedure because of a malfunctioning CT scanner. The other two ablations were in the same participant, where tumor borders were difficult to visualize at contrast-enhanced CT. Hence, in these instances, a lack of ablation zone feedback likely played a role. This feedback is important, because complete ablation is also dependent on the creation of predictable ablation zones. The latter is affected by heat-sink and tumor type (10,21). The incomplete ablation in the freehand group occurred in a difficult out-of-plane procedure where the antenna was repositioned seven times, resulting in a final lateral error of 15 mm.

Devices comparable to the Needle Placement System include MAXIO and ROBIO (Perfint Healthcare, Chennai, India), two large floor-mounted robotic devices with a reported accuracy of 6.5 mm (13); the CAS-One (CAScination, Bern, Switzerland), a table-mounted navigation system that uses visual fiducials requiring a line of sight, with a reported accuracy of 4.9 mm (15); and the iSYS1 (iSYS Medizintechnik, Kitzbühel, Austria), which...
is most similar to the Needle Placement System in using CT fiducials, with a reported accuracy of 2.3 mm (22). Despite the relatively large number of (experimental) robotic systems, there are few randomized patient studies that assessed their functionality in real clinical environments. We have identified only two randomized controlled trials that compared robotic with freehand needle placement, with only one trial performed in patients with liver tumors. In 2005, Patriciu et al (14) tested a robotic device (AcuBot) in a randomized study with only 14 patients. The AcuBot reduced the number of needle repositionings and targeting time, but needle placement accuracy was not reported. To this date, the AcuBot is not on the market. In another nonrandomized clinical study, Engstrand et al (23) analyzed the accuracy and procedural safety of the CAS-One for CT-guided percutaneous MWA of liver tumors. In 28 tumors, they reported a lateral accuracy of 4.0 mm, although no comparison with freehand positioning was made. None of the aforementioned studies differentiated between in-plane and out-of-plane procedures.

There were some limitations to our study. Randomization was performed per tumor and tumors were considered independent, even though correlation between tumors in one patient can occur. For example, accuracy can be affected by patient size or level of cirrhosis. Additionally, five procedures could not be finished with the robotic device because of extreme antenna deflection, limited fiducial detection, or insufficient locking pressure. The problem with antenna deflection was most likely exacerbated by the flexible, blunt MWA antennae that were used initially. We did not encounter the same issue with the antennae that were used for the last 15 procedures. Finally, great lengths were taken in this study to eliminate motion, including the use of general anesthesia with suspended respiration and the use of vacuum mattress. Because in many centers CT-guided liver ablation is not performed with the patient in general anesthesia, this limits the generalizability of this study.

In a future study, we intend to use a coaxial needle with a rigid stylet that can be exchanged for the MWA antenna and prevent deflection from the intended path. The next version of the robotic system will work with three instead of four fiducials, increasing the range of potential suitable positions. Additionally, we are planning to use robotic guidance with conscious sedation to determine whether providing patients with breathing instruction is sufficient to result in accurate antenna placement or if respiratory tracking systems would need to be used.
To our knowledge, our study was the first substantial randomized controlled trial to analyze robotic needle placement for ablation of liver tumors. We showed that robotic antenna guidance offers advantages over freehand antenna placement in terms of the number of antenna repositionings needed and placement accuracy. The advantage is most prominent for out-of-plane procedures.

**Author contributions:** Guaranor of integrity of entire study, K.P.d.J.; study concepts/study design or data acquisition or data analysis/interpretation, all authors; manuscript drafting or manuscript revision for important intellectual content, all authors; manuscript final version approval, all authors; agrees to ensure any questions related to the work are appropriately resolved, all authors; literature research, W.J.H., R.V.; clinical studies, W.J.H., S.J.S.R., J.P.P., M.O., K.P.d.J.; experimental studies, W.J.H., B.L., M.O.; statistical analysis, W.J.H., M.O., K.P.d.J.; and manuscript editing, all authors.

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**References**


**Table 4: Technical Outcomes Stratified according to Angulation**

<table>
<thead>
<tr>
<th>Outcome</th>
<th>In-Plane Angulation</th>
<th>Out-Of-Plane Angulation</th>
<th>P Value</th>
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<tr>
<td>No. of tumors</td>
<td>Freehand</td>
<td>Robotic</td>
<td>Freehand</td>
</tr>
<tr>
<td>Depth from skin (mm)</td>
<td>80.6 ± 27.5</td>
<td>80.9 ± 33.8</td>
<td>82.6 ± 25.9</td>
</tr>
<tr>
<td>No. of needle repositionings*</td>
<td>1 (0–5)</td>
<td>0 (0–0)</td>
<td>1 (0–7)</td>
</tr>
<tr>
<td>Targeting time (min)*</td>
<td>18 (4–25)</td>
<td>32 (3–43)</td>
<td>19 (7–55)</td>
</tr>
</tbody>
</table>

First placement accuracy

| Euclidian error (mm)     | 20.1 ± 3.6 | 10.4 ± 4.8 | .03 | 24.1 ± 11.5 | 10.1 ± 5.6 | .002 |
| Lateral error (mm)       | 13.9 ± 9.7 | 17.7 ± 5.9 | .13 | 16.1 ± 10.7 | 5.6 ± 2.7 | .009 |
| Depth error (mm)         | 10.1 ± 8.1 | 3.2 ± 2.7 | .03 | 11.4 ± 10.2 | 3.9 ± 6.5 | .04 |
| Angle error (degrees)    | 8.9 ± 5.3 | 5.5 ± 4.4 | .16 | 11.3 ± 6.3 | 3.6 ± 2.0 | .002 |

Adequate placement accuracy

| Euclidian error (mm)     | 13.0 ± 6.7 | 10.4 ± 4.8 | .36 | 14.5 ± 6.4 | 9.2 ± 4.0 | .02 |
| Lateral error (mm)       | 6.2 ± 2.7 | 7.7 ± 5.9 | .51 | 10.1 ± 4.0 | 5.9 ± 2.9 | .007 |
| Depth error (mm)         | 10.1 ± 8.2 | 3.2 ± 2.7 | .03 | 8.7 ± 6.8 | 3.5 ± 2.5 | .03 |
| Angle error (degrees)    | 4.4 ± 1.9 | 5.5 ± 4.4 | .47 | 7.7 ± 4.3 | 3.7 ± 2.0 | .006 |

Note.—Unless otherwise specified, data are means ± standard deviations.

* Data are medians, with ranges in parentheses.