Intraoperative 3-Dimensional Computed Tomography and Navigation in Foot and Ankle Surgery

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Abstract: Computer-assisted orthopedic surgery has developed dramatically during the past 2 decades. This article describes the use of intraoperative 3-dimensional computed tomography and navigation in foot and ankle surgery. Traditional imaging based on serial radiography or C-arm–based fluoroscopy does not provide simultaneous real-time 3-dimensional imaging, and thus leads to suboptimal visualization and guidance. Three-dimensional computed tomography allows for accurate intraoperative visualization of the position of bones and/or navigation implants. Such imaging and navigation helps to further reduce intraoperative complications, leads to improved surgical outcomes, and may become the gold standard in foot and ankle surgery. [Orthopedics. 2016; 39(5):e1005-e1010.]

Computer-assisted orthopedic surgery has developed dramatically during the past 2 decades.¹ Improvements in imaging and computer technology have refined intraoperative visualization of anatomy and real-time navigation of instruments and implants, helping to perfect surgical techniques and enhance outcomes.²⁻⁴

Intraoperative imaging traditionally was based on serial radiographs, which were cumbersome and could only provide static images. Development of C-arm–based fluoroscopy revolutionized imaging and navigation. It is portable, can provide serial static images, or can be used continuously for real-time information.²⁻⁴ However, conventional C-arm–based fluoroscopy can only provide images in 1 plane at a time unless repositioned and does not permit simultaneous 3-dimensional (3-D) imaging.² This leads to an intraoperative “black hole” without optimum visualization and guidance.²⁻⁴ An inaccurate position of bones (reduction) or implants (fixation) cannot be identified intraoperatively and must be assessed postoperatively by computed tomography (CT) or magnetic resonance imaging.⁵,⁶

Technology improvements led to the development of second-generation fluoroscopy and CT-based image guidance systems that could provide intraoperative 3-D imaging. This has addressed some of the shortcomings of intraoperative imaging and increased the accuracy of surgical procedures.

Computer-assisted orthopedic surgery was first introduced in spine surgery¹ to improve accuracy of pedicle screw insertion and reduce intraoperative complications. It became useful in other orthopedic procedures involving trauma, tumor, reconstruction (hip/knee), and pelvic surgery. The use of computer-assisted orthopedic surgery in foot and ankle surgery is relatively new and evolving.

Various fluoroscopy and CT-based 3-D imaging and navigation systems are available. The authors use the O-
arm (Medtronic, Minneapolis, Minnesota) to perform intraoperative CT scans, 3-D reconstruction, and 3-D navigation by real-time visualization of implants and instruments.

This article highlights the evolution and value of intraoperative 3-D imaging and navigation in foot and ankle surgery.

**Surgical Technique**

From 2010 to 2014, the authors used the O-arm in 64 foot and ankle procedures. Twenty patients underwent navigation-assisted surgery (Table 1), while intraoperative CT was used for 3-D imaging in 44 patients (Table 2). Representative patients are described below (Figures 1-5).

A 20-year-old runner presented with persistent right foot pain and tenderness at the fifth metatarsal base following a 2-month-old twisting injury. A radiograph (Figure 1A) showed an incompletely healed fracture at this level. The patient underwent navigation-assisted percutaneous osteosynthesis of the fracture (Figure 1B). A postoperative radiograph (Figure 1C) showed excellent position and length of the intramedullary screw.

A 20-year-old football player presented with chronic pain over the medial right ankle without history of trauma. A radiograph (Figure 2A) revealed an osteochondral defect over the posteromedial talar dome. The patient underwent navigation-assisted percutaneous retrograde drilling of the lesion. Figure 2B shows the location of the lesion and the target trajectory (green rectangle). Figure 2C shows the drill in the target lesion (blue rectangle).

A 50-year-old physician fell going downstairs, injuring his right ankle. There was deformity of the ankle with swelling and pain. Radiographs (Figures 3A-B) revealed a Weber C fracture-dislocation of the right ankle with disruption of the syndesmosis. The patient underwent immediate open reduction and internal fixation (ORIF). Intraoperative CT scans (Figures 3C-D) showed accurate reduction of the syndesmosis (contralateral side as control—not shown). Two months postoperatively, radio-

### Table 1

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Procedure</th>
<th>No.</th>
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</thead>
<tbody>
<tr>
<td>Stress fracture of fifth metatarsal</td>
<td>Internal fixation</td>
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<tr>
<td>Osteochondral lesion of talus</td>
<td>Percutaneous retrograde drilling</td>
<td>11</td>
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<tr>
<td>Osteochondral lesion of distal tibia</td>
<td>Percutaneous retrograde drilling</td>
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</tr>
<tr>
<td>Ankle and subtalar arthritis</td>
<td>Ankle and subtalar arthrodesis</td>
<td>2</td>
</tr>
<tr>
<td>Syndesmotic injury of ankle</td>
<td>Percutaneous syndesmosis fixation</td>
<td>2</td>
</tr>
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<td>Stress fracture calcaneus</td>
<td>Percutaneous screw fixation</td>
<td>2</td>
</tr>
<tr>
<td>Fracture navicular</td>
<td>Percutaneous screw fixation</td>
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</table>

### Table 2

<table>
<thead>
<tr>
<th>Diagnosis</th>
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</tr>
</thead>
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<tr>
<td>Talus fracture</td>
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<tr>
<td>Charcot foot</td>
<td>Arthrodesis of medial column</td>
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<td>Triplane fracture of distal tibia</td>
<td>ORIF</td>
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<tr>
<td>Posttraumatic ankle arthritis</td>
<td>Ankle arthrodesis</td>
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<tr>
<td>Subtalar arthritis</td>
<td>Subtalar arthrodesis</td>
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<td>Nonunion of talus neck fracture</td>
<td>Subtalar arthrodesis</td>
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<td>Nonunion of posterior malleolus</td>
<td>Bony debridement</td>
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<td>Osteoarthritic ankle</td>
<td>Excision of talar osteophytes</td>
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<td>Pseudoarthrosis-triple arthrodesis</td>
<td>Revision triple arthrodesis</td>
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<tr>
<td>Osteolytic lesion in talus</td>
<td>Curettage, biopsy, and bone graft</td>
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</table>

Abbreviation: ORIF, open reduction and internal fixation.
graphs showed healing of the fracture with good alignment (Figures 3E-F).

A 44-year-old skier twisted his right ankle, presenting with swelling and ecchymosis anteromedially. Radiographs (Figures 4A-B) revealed a comminuted fracture of the talar neck. He underwent ORIF, and intraoperative CT scans (Figures 4C-E) showed satisfactory reduction. Radiographs at 3 months postoperatively showed fracture union (Figures 4F-G).

A 66-year-old woman was evaluated for chronic right ankle pain. She had a previous talonavicular fusion for arthritis. A radiograph (Figure 5A) revealed a fused talonavicular joint with evidence of subtalar arthritis. She underwent subtalar joint arthrodesis via a lateral approach and navigation-assisted percutaneous screw fixation of the subtalar joint. Figure 5B shows the location and length of the target trajectory (blue rectangle). Figure 5C shows the screw placement across the subtalar joint (blue rectangle). The immediate postoperative radiograph (Figure 5D) showed adequate length and position of screws across the subtalar joint.

DISCUSSION

This article highlights the added value of intraoperative 3-D CT imaging and navigation in foot and ankle surgery for ORIF of fractures (especially calcaneal fractures), syndesmosis reduction, and reconstructive procedures.

A recent retrospective analysis of 165 intra-articular ankle fractures compared intraoperative fluoroscopy with postoperative CT, showing the former had a low sensitivity of 36% for assessing articular congruity. The authors suggested additional axial imaging for better assessment of articular reduction and found it unacceptable to consider intraoperative fluoroscopy a worldwide standard of care.

Eckardt and Lind retrospectively evaluated 62 patients with calcaneal fractures who underwent provisional ORIF under standard fluoroscopy, followed by O-arm 3-D...
CT before definitive fixation to assess if reduction was satisfactory. The 3-D CT evaluation showed an intraoperative revision rate of 40%. In more than half of the cases, fracture re-reduction was necessary. In the remaining cases, adjustment in size or position of implants was required. Without 3-D imaging, these would be missed intraoperatively and diagnosed postoperatively, leading to repeat surgery with the possibility of wound healing problems.

Franke et al\textsuperscript{10} retrospectively reviewed 377 surgically treated calcaneal fractures with the use of intraoperative 3-D imaging and found an intraoperative revision rate of 40.3%, mostly due to inadequate fracture reduction (19.6%) or intra-articular screw placement (17.2%). They suggested intraoperative 3-D would lead to better results.

With intraoperative 3-D CT, Rüberger et al\textsuperscript{11} assessed reduction and navigation guidance for screw placement in 15 intra-articular calcaneal fractures. They found this method achieved high-quality reduction and precise screw placement.

Atesok et al\textsuperscript{12} highlighted similar advantages of intraoperative CT and 3-D imaging over conventional fluoroscopy for accurate reduction and osteosynthesis of a variety of intra-articular fractures of the foot and ankle.

Syndesmosis injury frequently accompanies ankle fractures and a malreduced syndesmosis leads to poor functional outcome.\textsuperscript{13} Even with direct visualization, syndesmosis reduction can remain incongruous in up to 16% of cases.\textsuperscript{14} Intraoperative evaluations by standard fluoroscopy can be difficult. Standard radiographic-based parameters for assessment, such as tibiofibular clear space and overlap, can result in a substantial rate of malreductions easily identified with CT.\textsuperscript{15} Computed tomography can easily identify a diastasis of the syndesmosis by as little as 2 mm, which would otherwise be missed.\textsuperscript{16}
Franke et al\textsuperscript{17} showed that intraoperative 3-D imaging could improve surgical outcomes in up to 32.7% of cases of syndesmotic injuries, most commonly due to improvement in syndesmotic reduction missed with fluoroscopic techniques. Similar findings have been reported by others.\textsuperscript{18,19}

Richter and Zech\textsuperscript{a} and Richter\textsuperscript{b} employed intraoperative 3-D imaging and navigation for various foot and ankle procedures, including corrective arthrodeses. They achieved results with maximum deviation of 2° or 2 mm as compared with planned correction.

Intraoperative 3-D imaging and navigation has been used for percutaneous retrograde drilling of early osteochondral lesions of the talus.\textsuperscript{20} This method does not disturb the intact articular surface and hence has a distinct advantage over arthroscopic or open methods.

Kempainen et al\textsuperscript{11} used intraoperative CT for resection of talocalcaneal coalitions in children, noting improvement in quality of resection with a 4 times greater chance of complete resection. They found that intraoperative CT altered their surgical decision-making while increasing the likelihood of obtaining a complete talocalcaneal resection, favoring such technology if available.

Complications with the use of this technology occur infrequently. Stress fractures through navigation tracker pin sites have been described.\textsuperscript{22,23} Bonutti et al\textsuperscript{22} suggested avoiding bicortical pin placement. Hoke et al\textsuperscript{22} suggested the use of small-diameter pins placed in different planes in metaphysis instead of diaphysis.

There are also radiation concerns for the patient. It was found that a single intraoperative O-arm CT scan emitted 7.9 mGy of radiation, equivalent to 5.6 standard radiographs.\textsuperscript{18} Radiation exposure is unknown and difficult to compare with the use of conventional C-arm imaging for similar surgery. An intraoperative CT scan replaces the need for a CT scan immediately after surgery, sparing the patient inconvenience and radiation. In fact, Eckardt and Lind\textsuperscript{2} have shown that intraoperative radiation exposure with the O-arm during foot surgery is less than that with a conventional CT scan of the foot postoperatively.

Furthermore, additional costs for equipment and staff are associated with the use of intraoperative CT and navigation systems. Many institutions may already have this equipment for neurosurgery and other services, and it could be shared for use in foot and ankle surgery. The cost would then be reduced to the sterile draping material and the technician required to operate the equipment.\textsuperscript{23} Also, intraoperative CT negates the need for postoperative CT, thus offsetting some costs. The real benefit of intraoperative imaging and navigation is to reduce intraoperative complications and improve surgical outcomes, minimizing the need for secondary procedures. Three-dimensional imaging modalities may help a surgeon overcome the steep learning curve in foot and ankle surgery, since the difficult articular geometry and anatomy can more easily be visualized.\textsuperscript{7}

**CONCLUSION**

Intraoperative 3-D CT and navigation are a substantial added value in foot and ankle surgery. The drawbacks are small, and the advantages more than substantial. This is on track to become the gold standard in foot and ankle surgery.

**REFERENCES**

18. Hsu AR, Gross CE, Lee S. In-


