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Review

Intraoperative 3D-imaging in foot and ankle trauma - clinical examples and study results

Intraoperative 3D-Bildgebung beim Fuß- und Sprunggelenkstrauma - klinische Beispiele und Studienergebnisse

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KEYWORDS
3D radiographic imaging;
ISO-C-3D;
ARCADIS-3D;
Fracture;
Correction

Summary

Background: Intraoperative 3D radiographic imaging in foot and ankle (trauma) surgery was introduced more than ten years ago. This review was performed to specify the potential benefit.
Methods: The previous literature dealing with intraoperative 3D-imaging was reviewed and summarized, and case reports were added.
Results: Imperfect reduction and/or implant position was detected in more than one third of operatively treated foot and ankle injuries through intraoperative visualization with 3D radiographic imaging. The second device generation allows for faster scanning and image interpretation time and halved radiation dose. 3D radiographic imaging leads to cost reduction through avoiding revision surgery.
Conclusions: Intraoperative 3D radiographic imaging improves the intraoperative visualization of fracture reduction and implant position in comparison with 2D-imaging.

SCHLÜSSELWÖRTER
3D-Röntgenbildgebung;
ISO-C-3D;
ARCADIS-3D;
Fraktur;
Korrektur

Zusammenfassung

Hintergrund: Die intraoperative 3D Röntgenbildgebung für die Traumaversorgung an Fuß und Sprunggelenk wurde vor über 10 Jahren vorgestellt. Dieses Review soll den potentiellen Benefit spezifizieren.
Material und Methoden: Die bisherige Literatur, die sich mit der intraoperativer 3D Röntgenbildgebung bei der Traumaversorgung an Fuß und Sprunggelenk befasst wurde gesichtet und zusammengefasst und einige Fallbeschreibungen wurden angefügt.
Ergebnisse: Durch die verbesserte intraoperative Visualisierung mittels 3-D-Röntgenbildgebung wurde bei der Versorgung von Verletzungen an OSG/Fuß

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jeweils in mehr als einem Drittel der Fälle verbesserungsbedürftige Reposition/Korrektur und/oder Implantatlage erkannt. Die zweite Gerätegeneration erlaubt eine schnelleren Scan und Bildanalyse als die erste Generation bei halbierter Strahlenbelastung. Der Einsatz der intraoperativen 3D-Röntgenbildgebung führt zur Kostenersparnis durch Vermeidung von Revisionen.
Schlußfolgerungen: Die intraoperative 3D-Röntgenbildgebung verbessert die intraoperative Visualisierung von Knochen(-fragment-)positionen und Implatatlagen im Vergleich zur 2D-Röntgenbildgebung.

Introduction

When using intraoperative fluoroscopy in foot and ankle surgery, incorrect position of bones, bone fragments and/or implants frequently remains undiscovered, and is only recognized on postoperative computed tomography (CT) scans [1—4,10,11].

A mobile C-arm with three-dimensional imaging (ISO-C-3D Siemens, Erlangen, Germany) was developed to better enhance the intraoperative recognition of problems with fracture reduction and fixation [2—4,10]. The conclusions of the first clinical experience using this device was that the intraoperative three-dimensional visualization with

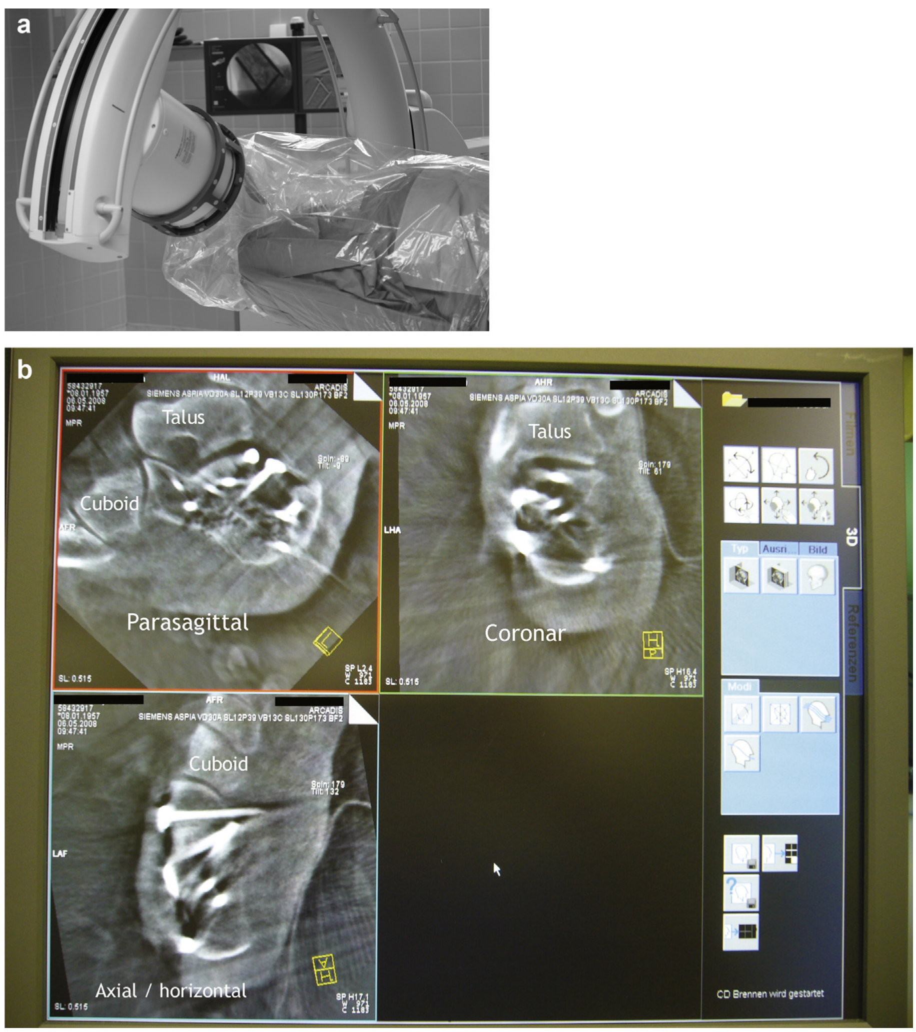

Figure 1a-b. Figure 1a shows the ARDACIS-3D during intraoperative scan. The lower leg, ankle and foot are placed on a splint which is covered by a sterile plastic bag to maintain a neutral foot and ankle position during the scan. Then, the entire table with lower legs, ankles and feet is covered with a second sterile plastic bag to maintain sterility. During the scan, the entire staff leaves the area of radiation contamination. Figure 1b shows a monitor view of ARCADIS-3D device showing multiplanar reformations of a calcaneus after open reduction and internal fixation with a plate and screws. The axial/horizontal reformation shows a screw which is too long in the distal part of the calcaneus close to the calcaneocuboid joint which was not visible with 2D radiographic imaging.

Table 1 Cases with ISO-C-3D use [11]. ORIF (open reduction and internal fixation); CRIF (closed reduction and internal fixation).

Diagnosis (numbers)	Number of changes after ISO-C-3D use			Description of procedures and of changes after ISO-C-3D use
	In total	Implant position	Reduction	
Fractures (n = 50)				
Pilon (11)	4/11	2/11	3/11	All cases ORIF with plates & screws Case 1, one screw that penetrated ankle corrected Case 2, one screw that penetrated ankle corrected & step in joint line corrected Case 3, 4, step of the ankle joint line corrected
Weber C (7)	3/7	2/7	2/7	All cases CRIF with syndesmosis screw Case 1, reduction of distal fibula corrected Case 2, syndesmosis screw corrected Case 3, reduction of distal fibula & syndesmosis screw corrected
Dorsal Volkmann (1)	1/1	-	1/1	CRIF with two screws Step and gap in joint line corrected
Talus (3)	1/3	1/3	-	All cases ORIF with screws, one screw that penetrated ankle joint corrected
Calcaneus (20)	7/20	5/20	3/20	ORIF with plate & screws Case 1, 2, 3, one screw that penetrated posterior facet corrected Case 4, one screw that penetrated calcaneocuboid joint corrected Case 5, 6, step in the posterior facet corrected Case 7, one screw that penetrated posterior facet and step in the posterior facet corrected
Navicular (1)	1/1	1/1	-	CRIF with screw One screw that penetrated talonavicular joint medially and plantarly corrected
Cuboid (1)	-	-	-	ORIF with screws
Lisfanc-fracture-dislocation (6)	2/6	1/6	1/6	2 cases ORIF with tricortical bone autograft, plate & screw, 4 cases ORIF with screws/wires Case 1, one screw that penetrated talonavicular joint corrected Case 2, reduction of 3rd metatarsal corrected to reduce flattening of the transverse arch
Posttraumatic osteoarthritis at the hindfoot with or without deformity (n = 12)				
Subtalar osteoarthritis (2)	1/2	1/2	-	Open cartilage removal, cancellous bone autograft, 7.3 mm screws One screw that penetrated the ankle joint corrected
Subtalar osteoarthritis with deformity (10)	4/10	3/10	2/10	Open cartilage removal, correction, tricortical bone autograft, 7.3 mm screws Case 1, one screw that penetrated the ankle joint corrected Case 2, one screw that penetrated joint between cuboid and 4th metatarsal corrected Case 3, hindfoot varus corrected Case 4, one screw that penetrated joint between cuboid and 4th metatarsal corrected; hindfoot varus correted
In total (62)	24/62 (39%)	16/62 (26%)	12/62 (19%)	

the ISO-C-3D could provide useful information in foot and ankle trauma care that cannot be obtained from plain films or conventional C-arms alone [10]. The ISO-C-3D appeared to be most helpful in procedures with closed reduction and internal fixation, and/or when axial reformations provide information that is not possible with a conventional C-arm and/or direct visualization during open reduction and internal fixation. The ISO-C-3D had the possibility of replacing a postoperative Computer tomography (CT) scan as two-dimensional images for documentation can also be performed [10]. The radiation contamination that corresponded to 39 seconds fluoroscopy time with a conventional

Table 2 Cases with ARCADIS-3D use [11]. ORIF (open reduction and internal fixation); CRIF (closed reduction and internal fixation).

Diagnosis (numbers)	Number of changes after ARCADIS use			Description of procedures and of changes after ARCADIS use
	In total	Implant position	Reduction	
Fractures (n = 50)				
Pilon (8)	2/8	2/8	0/8	All cases ORIF with plates & screws Case 1, one screw that penetrated ankle corrected Case 2, one screw that penetrated ankle the distal tibiofibular joint corrected
Weber C (10)	4/10	4/10	4/10	All cases ORIF with syndesmosis screw All cases, reduction of distal fibula & syndesmosis screw corrected
Dorsal Volkmann (1)	0/1	-	-	CRIF with two screws
Talus (3)	1/3	1/3	-	All cases ORIF with screws, one screw that penetrated subtalar joint corrected
Calcaneus (20)	6/20	4/20	3/20	ORIF with plate & screws Case 1, 2, 3, one screw that penetrated posterior facet corrected Case 4, one screw that penetrated calcaneocuboid joint corrected Case 4, 5, 6, step in the posterior facet corrected
Navicular (1)	1/1	1/1	-	CRIF with screw One screw that penetrated talonavicular joint medially and plantarly corrected
Cuboid (1)	-	-	-	ORIF with screws
Lisfanc-fracture-dislocation (6)	2/6	1/6	1/6	All cases ORIF with screws/wires Case 1, one screw that penetrated talonavicular joint corrected Case 2, reduction of 1st and 2nd metatarsal corrected to reduce flattening of the transverse arch
Posttraumatic osteoarthritis at the hindfoot with or without deformity (n = 12)				
Subtalar osteoarthritis (2)	1/2	1/2	-	Open cartilage removal, cancellous bone autograft, 7.3 mm screws One screw that penetrated the ankle joint corrected
Subtalar osteoarthritis with deformity (10)	4/10	2/10	2/10	Open cartilage removal, correction, tricortical bone autograft, 7.3 mm screws Case 1 and 2, one screw that penetrated the ankle joint corrected Case 3 and 4, hindfoot varus corrected
In total (62)	21/62 (34%)	16/62 (26%)	10/62 (15%)	

digital C-arm, and the time spent with 440 seconds interruption of the surgical procedure have been criticized [10]. The second generation device has been developed to minimize these problems and to improve handling. The aim of a second study was to assess the clinical use of the new device (ARCADIS-3D, Siemens) in comparison with earlier experience with the first generation device (ISO-C-3D, Siemens). In this study, reconstructive procedures were also included in addition to trauma cases [11]. This clinical study was performed in a level I trauma center, which is also a university hospital (ISO-C-3D group, institution A), and a level II trauma center, which is also a university teaching hospital (ARCADIS-3D group, institution B). The surgical staff involved in the study consisted of experienced orthopaedic surgeons as well as interns, residents and fellows in training. The devices were always used after reduction/correction and positioning of implants was judged to be correct by the surgeon using a conventional C-arm. When incorrect reduction and/or implant positions were detected with the conventional C-arm, a correction of the reduction/correction and/or implant was performed.

Technical equipment

ISO-C-3D/ARCADIS-3D (Siemens) are motorized mobile C-arms that provide fluoroscopic images during a 190 degree orbital rotation, resulting in a 119 mm data cube (Figure 1a). Multiplanar and two-dimensional reconstructions can be obtained from these 3D data sets (Figure 1b).

Study results

On average, the operation was interrupted for 440 seconds in the ISO-C-3D group (120 seconds, on average, for the scan and 210 seconds, on average, for evaluation of the images by the surgeon). In the ARCADIS-3D group, the operation was interrupted for 320 seconds on average (60 seconds, on average, for the scan and 180 seconds, on average, for evaluation). The net radiation time during a 100-image scan was 39.3 seconds for the ISO-C-3D and 19.6 seconds for ARCADIS-3D. Using the ISO-C-3D scan, the position of the implant alone was corrected in 26% of cases (16 of 62), the reduction alone was corrected in 19% of cases (12 of

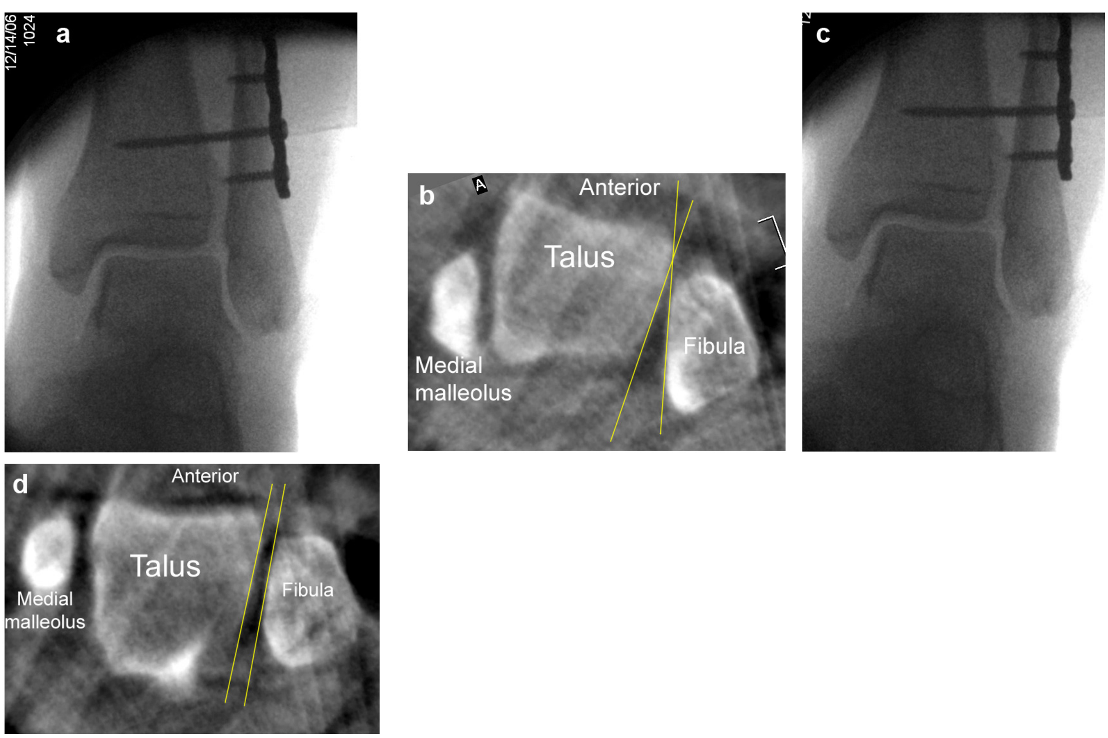

Figure 2a-d. Weber-C ankle from the ARCADIS-3D group. Figure 2a shows a C-arm image after ORIF including syndesmosis screw. The ARCADIS-3D-scan shows a massive internal rotation of the distal fibula leading to inconcruency of the ankle joint (Figure 2b). This was not recognized with the 2D radiographic imaging (Figure 2a). After correction of the ORIF, the 2D radiographic imaging showed no detectable difference (Figure 2c). The ARCADIS-3D shows a correct rotation of the distal fibula and anatomic congruency of the ankle joint (Figure 2d).

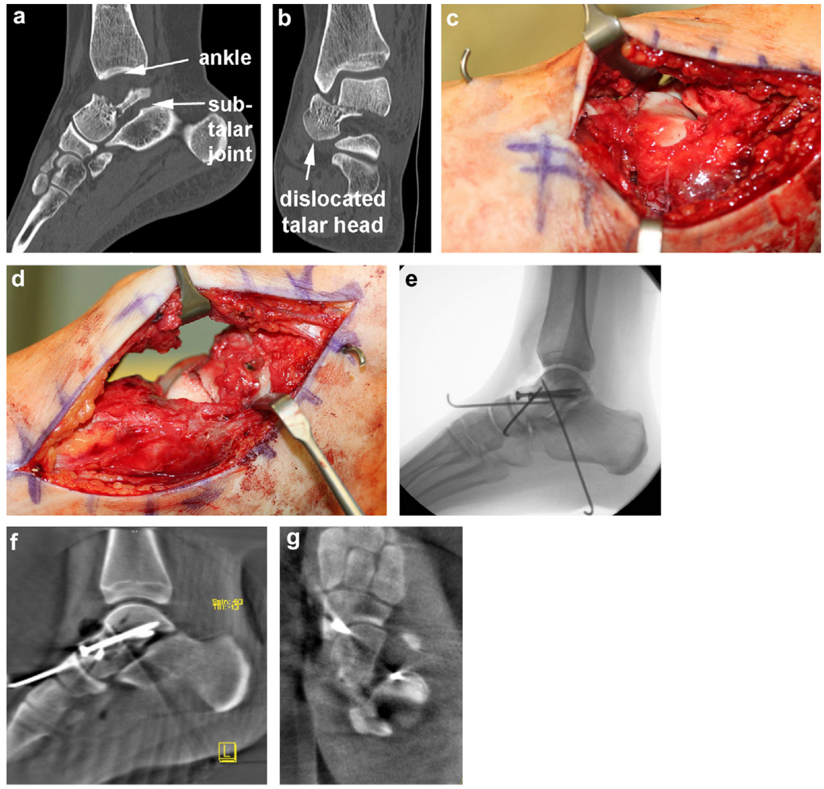

Figure 3a-3g. Hawkins IV talar fracture with dislocation of ankle (Figure 3a), subtalar (Figure 3a), and talonavicular (Figure 3b) joints. ORIF with screws through anterolateral (Figure 3c) and anteromedial (Figure 3d) approaches. The reduced but instable subtalar and talonavicular joints were additionally transfixed (Figure 3e). The intraoperative 3D radiographic imaging approves an optimal reduction and implant position (Figure 3f and 3g) which was not visible with 2d radiographic imaging.

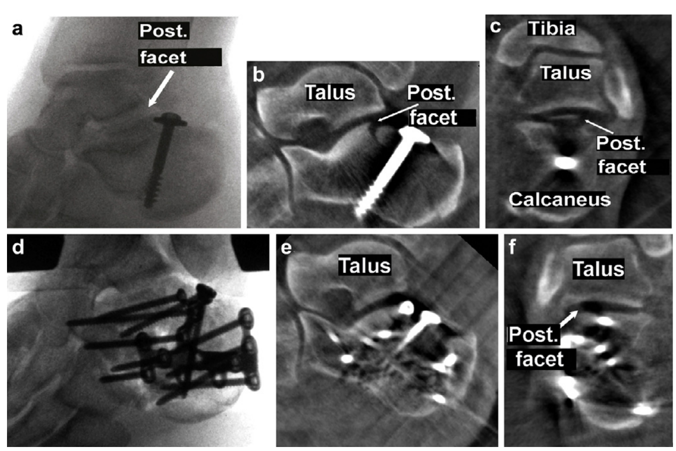

Figure 4a to 4f. Insufficient closed reduction and conversion to open reduction of a Sanders 2B fracture. The fracture pattern is special with a fracture line running far posterior in the posterior joint facet. Based on this fracture morphology and especially due to a missing flattening of the Boehler's angle, a closed reduction and internal screw fixation with washer (7.3 mm) was performed. The 20°-Broden's view shows step less reduction of the posterior facet (Figure 4a). In contrast, the intraoperative 3D radiographic imaging shows a significant step in the posterior facet (Figure 4b, parasagittal reformation; Figure 4c, paracoronar reformation). In the same surgical procedure, an open reduction and internal screw and plate fixation through an extensile lateral approach (as described in the text) followed. The 20°-Broden's view again shows step less reduction of the posterior facet (Figure 4d) which was proved by the intraoperative 3D radiographic imaging (Figure 4e, parasagittal reformation; Figure 4f, paracoronar reformation).

62), and both implant position and reduction were corrected in 7% of cases (4 of 62) (Table 1). A second ISO-C-3D scan was performed in 12 cases after the corrections (50% of cases in which corrections were performed) (Table 1). In none of those 12 cases were further corrections made after the second scan (Table 1). Using the ARCADIS-3D scan, the position of the implant alone was corrected in 26% of cases (16 of 62), the reduction alone was corrected in 15% of cases (10 of 62), and both implant

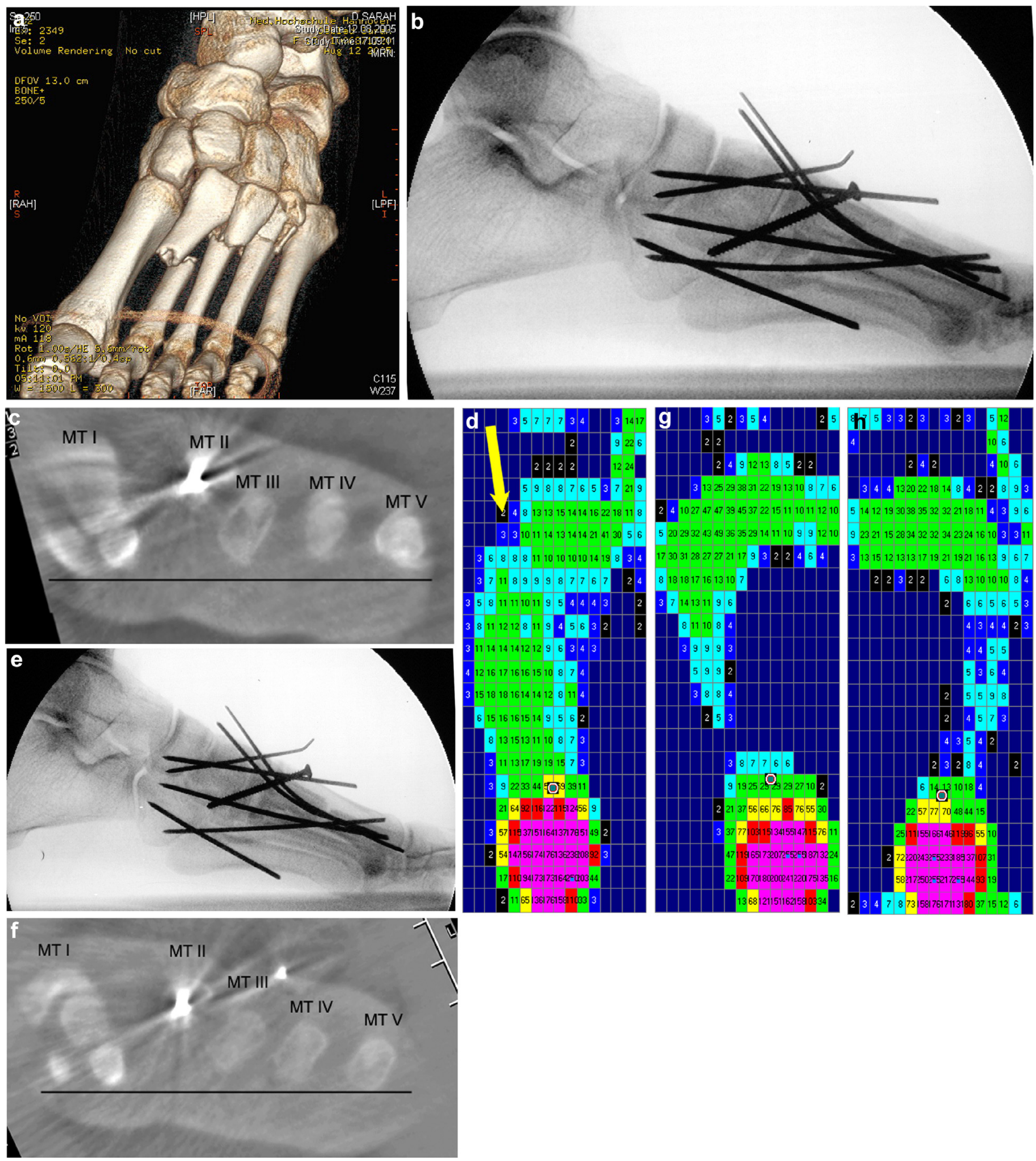

Figure 5a to 5h. Homolateral lateral Lisfranc-fracture-dislocation (Figure 5a). Figure 5b shows the lateral fluoroscopic image after ORIF and Figure 5c axial reformations of the intraoperative 3D radiographic imaging that shows a malorientation of the 3rd metatarsal (too far plantar). Figure 5d shows the corresponding image of an intraoperative pedography with the maximum forces showing a massively decreased force percentage under the 4th and 5th metatarsal heads (arrow). ORIF of the 3rd ray was repeated (figures 5e-h). Figure 5g shows the maximum force pattern in comparison which is similar as the uninjured contralateral side (figure 5h) [12].

position and reduction were corrected in 8% of cases (5 of 62) (Table 2). A second ARCADIS-3D scan was performed in 14 cases after the corrections (66% of cases in which corrections were performed) (Table 2). In none of those 14 cases were further corrections were made after the second scan (Table 2). The level of surgeon experience did not differ between the ISO-C-3D and ARCADIS-3D group (Chi2-test, $p > .05$). The percentage of correction did not significantly differ between groups with different experience (head department, attending surgeon, senior resident and junior resident, and ISO-C-3D versus ARCADIS-3D; Chi2-test, $p > 0.05$).

Discussion

In the described landmark studies, the intraoperative use of the ISO-C-3D/ARCADIS-3D in foot and ankle fracture care and in corrections of post-traumatic deformities in the hindfoot region led to changes of reduction/correction and/or implant position in more than one third of the cases [11]. Other studies have shown the same effect [5,8]. In those institutions where an ISO-C-3D/ARCADIS-3D is available it will be used intraoperatively as described despite the questionable impact on the outcome [11]. Hufner et al performed a cost analysis and concluded that intraoperative 3D radiographic imaging lead to cost reduction through avoiding revision surgery [7]. The goal of the surgical procedure is to achieve anatomic reduction and optimal implant position [11]. Insufficient reduction/correction and intraarticular implant position is tried to avoid and the ISO-C-3D/ARCADIS-3D is helpful for this purpose [11]. Especially the possibility to obtain axial reformations was found to be extremely helpful, for example in Weber-C fractures. We recognized rotational malpositions of the distal fibula when using the ISO-C-3D/ARCADIS-3D intraoperatively and were able to correct the reduction in the same procedure [11]. Another important finding in this study was the high percentage of screws penetrating joints when open reduction and internal fixation of calcaneus fractures was performed [11]. Although the posterior facet and the calcaneocuboid joint were visible from the lateral side, we frequently found screws penetrating these joints medially when we performed an intraoperative ISO-C-3D/ARCADIS-3D-scan [11]. Both joints are oblique and the posterior facet is especially difficult to visualize with a C-arm (Broden's view) [6,9]. Significant steps in the joint line of the posterior facet were also recognized with ISO-C-3D/ARCADIS-3D only, and correction at the same operative procedure was possible [11]. A major concern for new technical devices is always the time factor. In our studies, the use of the ISO-C-3D/ARCADIS-3D was not considerably time consuming [11]. The operation was interrupted for 7.20 minutes in average for the ISO-C-3D/ARCADIS-3D use.

In summary, the ISO-C-3D/ARCADIS-3D most helpful in closed procedures and/or when axial reformations provide information which are not possible to obtain with a C-arm or with direct visualization [11].

Figures 2—5 show clinical examples.

Conflict of interest

Regarding the manuscript **Intraoperative 3D-imaging in foot and ankle trauma - clinical examples and study results**, I state that myself or my institution did not receive funding in relation to the content of the manuscript. I am consultant of Curvebeam, Stryker, Ulrich and Intercus, proprietor of R-Innovation, and joint proprietor of First Worldwide Orthopaedics.

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