Utility of 3-Dimensional Intraoperative Imaging in Pelvic and Acetabular Fractures
A Network Meta-Analysis

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Abstract

Background: Successful surgical management of pelvic ring and acetabular fractures requires technical expertise to achieve an accurate reduction and stable fixation. The use of 3-dimensional (3D) intraoperative imaging (3DIOI) as an assessment tool has led to improved reduction and placement of implants. The purpose of this study was to assess the utility of using 3DIOI in the management of acetabular and pelvic fractures on the basis of outcomes reported in the literature.

Methods: A literature search was performed using PubMed, the Cochrane Database of Systematic Reviews (CDSR), and Google Scholar using key terms. A network meta-analysis conducted using the frequentist approach allowed for statistical analysis of reported outcomes regarding screw position (in mm), fracture reduction (in mm), and complications.

Results: A total of 9 studies were included in this analysis. When compared with conventional radiography, the mean radiation dose (in cGy·cm²) was significantly higher in 3DIOI (mean difference, 82.72; 95% confidence interval [CI], 21.83 to 143.61; \( p = 0.007 \)). Use of 3DIOI yielded a 93% lower risk of developing medical complications (odds ratio [OR], 0.07; 95% CI, 0.02 to 0.35; \( p = 0.014 \)). Use of 3DIOI yielded higher odds of achieving accurate screw placement (OR, 4.21; 95% CI, 1.44 to 12.32; \( p = 0.008 \)) and perfect reduction (OR, 2.60; 95% CI, 1.19 to 5.68; \( p = 0.016 \)). In ranking the imaging modalities, 12 of the 13 parameters analyzed were in favor of 3DIOI over conventional fluoroscopy and 2D navigation imaging.

Conclusions: Current literature supports the use of 3DIOI because of the decreased rates of misplaced implants, malreduced fractures, complications, and subsequent revision operations. The use of 3DIOI allows for improved visualization of pelvic anatomy when repairing pelvic and acetabular fractures, and helps surgeons to achieve favorable surgical outcomes.

Level of Evidence: Therapeutic Level III. See Instructions for Authors for a complete description of levels of evidence.

The management of pelvic and acetabular fractures is challenging and technically demanding because of the complex anatomy of the pelvis. Assessment of intraoperative reduction can be difficult without proper visualization. Although preoperative imaging can help with surgical planning of fracture reduction, the intraoperative visualization of the fracture

Disclosure: The authors indicated that no external funding was received for any aspect of this work. The Disclosure of Potential Conflicts of Interest forms are provided with the online version of the article (http://links.lww.com/JBJSREV/A710).
reduction and position of the implant is critical for optimizing the outcome of the surgery.

Many studies have found that conventional fluoroscopy is unable to detect clinically important step-offs, acetabular roof incongruencies, and marginal impactions. Additionally, the standard postoperative anteroposterior and oblique Judet radiographs cannot detect articular malreduction and screws protruding into the joint. The same is true regarding malreduction and malpositioning of implants for pelvic ring fractures. Postoperative computed tomography (CT) is capable of detecting these errors; however, revisions will require additional operations.

The pelvic and acetabular anatomy is better visualized through 3-dimensional (3D) intraoperative imaging (3DIOI) as it better assesses pelvic and acetabular fracture reduction and positioning of implants, especially in fractures involving weight-bearing articular surfaces. The devices allow for improved visualization and imaging with more anatomical details that can be reviewed intraoperatively by the surgeon. This ultimately may decrease malreduction of the fracture and malpositioning of implants. The goal of this study was to assess the utility of 3DIOI in improving the outcomes of operative fixation of pelvic and acetabular fractures. We hypothesized that 3DIOI will yield better surgical outcomes overall and fewer revisions than other forms of intraoperative imaging.

**Materials and Methods**

**Study Design and Search Methods**

An electronic literature search was conducted during November 2019 using PubMed, the Cochrane Database of Systematic Reviews (CDSR), and Google Scholar. Studies were found using various combinations of the following keywords: “3D imaging,” “intraoperative imaging,” “pelvic fractures,” “acetabular fractures,” “O arm,” “3D,” “computed tomography”, and “CT”.

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**Fig. 1**

Flowchart of the stepwise literature screening process used to identify articles from specific resources and screen them for inclusion in the study.
TABLE I Summary of Studies Included in the Current Review of 3D Intraoperative Imaging for Pelvic and Acetabular Fracture Fixation*

<table>
<thead>
<tr>
<th>Study</th>
<th>Study Type</th>
<th>Sample Population</th>
<th>Surgery</th>
<th>Type of Injury</th>
<th>Site of Surgery</th>
<th>Operative Time (min)</th>
<th>Mean Radiation Dose (cGy·cm²)</th>
<th>Complications</th>
<th>Revisions/Screw Replacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Behrendt, 2012</td>
<td>Comparative (control vs. 3D)</td>
<td>16 pelvises (plastic, cadaver) 102 screws</td>
<td>Perc. screws</td>
<td>NR</td>
<td>Posterior pelvic ring</td>
<td>6.3 ± 1.2 (fluoro)†</td>
<td>10.9 ± 3.5 (fluoro)†</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Eckardt, 2015</td>
<td>Comparative (control vs. 3D)</td>
<td>114 patients</td>
<td>Perc. screws</td>
<td>Posterior wall, posterior column, anterior wall, anterior column, transverse, T-type, both column, unclassifiable</td>
<td>Acetabulum</td>
<td>168 ± 89 (fluoro)†</td>
<td>NR</td>
<td>Surgical site infections: 1 deep wound infection, 3 superficial wound infections.</td>
<td></td>
</tr>
<tr>
<td>Gras, 2012</td>
<td>Comparative (control vs. 3D)</td>
<td>20 synthetic hemipelvis 80 screws</td>
<td>Perc. screws</td>
<td>ORIF</td>
<td>Acetabulum</td>
<td>63 ± 3.22 (2D)‡</td>
<td>497 ± 84.3 (3D)</td>
<td>No revisions</td>
<td></td>
</tr>
<tr>
<td>Groosterlinden, 2011</td>
<td>3D navigation assessment</td>
<td>5 cadaver pelves 40 screws</td>
<td>Perc. screws</td>
<td>ORIF</td>
<td>Acetabulum (1 A1, 1 A2, 2 A3, 1 B1, 0 B2, 3 B3, 1 C1, 9 C2, 2 C3) 24 screws</td>
<td>25.8 ± 3.0 (3D)</td>
<td>NR</td>
<td>4/40 (2D)†</td>
<td></td>
</tr>
<tr>
<td>Keil, 2018</td>
<td>3D navigation assessment</td>
<td>20 patients</td>
<td>ORIF</td>
<td>Pelvic ring</td>
<td>Acetabulum</td>
<td>250 ± 103.7 (3D)</td>
<td>NR</td>
<td>3/10 (supraacetabular group)††</td>
<td></td>
</tr>
<tr>
<td>Kendoff, 2008</td>
<td>Comparative (control vs. 3D)</td>
<td>12 cadaver pelves 24 acetabuli 24 screws</td>
<td>Perc. screws</td>
<td>ORIF</td>
<td>Acetabulum (OTA 62 B1) Acetabular impaction (at articular surface)</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
<td></td>
</tr>
<tr>
<td>Oberoi, 2012</td>
<td>Comparative (control vs. 3D)</td>
<td>68 patients 7 screws</td>
<td>Perc. screws</td>
<td>ORIF</td>
<td>Acetabulum</td>
<td>264 ± 100 (2D)‡</td>
<td>NR</td>
<td>No iatrogenic complications</td>
<td></td>
</tr>
<tr>
<td>Ochs, 2010</td>
<td>Comparative (control vs. 3D)</td>
<td>32 pelvises (15 synthetic, 17 cadaver) 210 screws</td>
<td>Perc. screws</td>
<td>ORIF</td>
<td>Acetabulum</td>
<td>7.8 ± 2.9 (fluoro)†§§</td>
<td>NR</td>
<td>NR</td>
<td></td>
</tr>
<tr>
<td>Takao, 2014</td>
<td>3D navigation assessment</td>
<td>6 patients 12 screws</td>
<td>Perc. screws</td>
<td>Pelvic ring (2 SI dislocation, 2 Denis Zone I, 2 Denis Zone II) Posterior pelvic ring</td>
<td>65 (3D)</td>
<td>NR</td>
<td>NR</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*NR = not reported. †Represents conventional protocol: plain 2D fluoroscopy without navigation. ‡Represents 2D-navigated protocol: plain 2D fluoroscopy with navigation. §Significantly different from the conventional group. ‡‡Significantly different from the 2D group. **3 deep wound infections, 1 superficial wound infection. ††1 deep wound infection, 3 superficial wound infections. †††The 3 study groups were supraacetabular (10 screws), superior rami (10 screws), and iliosacral (20 screws). §§§Represents results from synthetic pelvis only. ##Represents results from human cadaver pelvis only.

**Study Selection and Eligibility Criteria**

Only full-text published studies in the English language were considered for inclusion. Studies were included if they contained 1 or more of the following predefined outcome measures: accuracy of screw placement, quality of resection and congruity of the joint, postoperative implant-related failures (reoperations and/or revisions), and procedural measures (for 3DIOI versus conventional fluoroscopy).

**Study Selection Process**

A literature search was conducted by 3 authors (J.J.P., R.K., and S.A.S.). Each author screened titles and abstracts. Full-length manuscripts were read when necessary to determine eligibility on the basis of the selection criteria. Discrepancies were resolved through discussion among all of the authors.

A total of 224 articles were identified through PubMed and Google Scholar. After removing duplicate studies, 203 studies were screened. Sixty-six of the studies were selected for full-text assessment, and of these, 10 were not in the English language and 47 focused on...
Fig. 2

**Figs. 2-A, 2-B, and 2-C** Comparisons of operative characteristics (operative time, radiation dose, and medical complications). Forest plots of the various imaging modalities (Fluoro — conventional 2D fluoroscopy without navigation, 2D — plain 2D fluoroscopy with a navigation protocol, and 3D — intraoperative 3D imaging) are shown, with associated league tables showing direct evidence (upper triangle) and indirect evidence (lower triangle) for the pairwise comparisons. Significantly better outcomes are reported in green, and significantly worse outcomes are reported in red. **Fig. 2-A** Mean operative time in minutes. Data are reported as the mean difference (MD) and 95% confidence interval (CI). **Fig. 2-B** Mean radiation dose in cGy·cm². Data are reported as the mean difference (MD) and 95% CI. **Fig. 2-C** Risk of developing medical complications. Data are reported as the odds ratio (OR) and 95% CI.
the use of 3DIOI for other indications not related to pelvic and acetabular fractures. These studies were excluded, leaving 9 studies eligible for assessment and analysis (Fig. 1).

Data Collection Process
In a predesigned Excel (Microsoft) spreadsheet, 2 reviewers (J.P. and R.K.) extracted the following types of information from each included study: (1) general manuscript data (authors, year of publication, and journal name), (2) study characteristics (study period and sample size), (3) participants (number of participants in each group, sex, and follow-up period), (4) operative characteristics (surgical site, surgery type, 3D software, operative time, and mean radiation dose per surgery), and (5) postoperative outcomes: (a) parameters of operative success (number of accurately placed screws and number with perfect fracture reduction), (b) parameters regarding operative failures (inaccurately placed screws, poor or imperfect fracture reduction, articular perforation, deviation of actual from planned screw placement [in mm], and revisions and/or screw replacements), (c) diagnostic accuracy measures (largest visible gap, largest visible step-off, ability to detect the position of the implant, misplaced screws, fracture incongruity, and articular impaction), and (d) risk of developing medical complications (acute respiratory distress syndrome [ARDS], infection, neurologic injury, and thromboembolism).

Summary Measures
All statistical analyses were performed using R (version 4.0.2; R Foundation for Statistical Computing) and RStudio (version 1.3.1056) by a statistician with a PhD degree. A network meta-analysis was conducted according to a frequentist approach with weighted least squares based on a multivariate regression with random effects using the R package netmeta function. This approach enables adequate consideration of multiple-arm studies and includes restricted maximum-likelihood estimation. For each test procedure, mean differences (MDs) or standardized mean differences (SMDs) with corresponding 95% confidence intervals (CIs) were calculated for quantitative outcomes. Odds ratios (ORs) with 95% CIs were estimated for dichotomous end points. Contrast-based forest plots were created for all comparisons. League tables were generated using the netleague and netsplit functions to split pooled networks into direct and indirect effects.

Ranking Treatments
All of the measured parameters from each imaging modality were ranked on the basis of the frequentist analogue of the surface under the cumulative ranking line (SUCRA) using the netrank function of netmeta. SUCRA values give the percentage efficacy of each individual parameter for the treatment currently being evaluated in comparison with control or standard treatment. The P-score of a parameter, which may range from 0 to 1, measures the extent of certainty that the parameter in 1 intervention (in this case, 1 imaging modality) is better than in another intervention.

Results
The 9 studies included in this analysis were published between 2008 and 2018. Six studies compared 3DIOI with 2D navigation or conventional fluoroscopy (comparative study type), and the 3 remaining studies compared 3DIOI with gold-standard CT or only presented 3D data without a direct comparison with control or standard treatment. The P-score of a parameter, which may range from 0 to 1, measures the extent of certainty that the parameter in 1 intervention (in this case, 1 imaging modality) is better than in another intervention.

In total, 476 screws and 293 pelves (i.e., cadaver, synthetic, and patient pelves) were included for review (Table I). The type of surgery ranged from percutaneous screw placement to open reduction and internal fixation (ORIF) of the posterior pelvic ring and acetabulum. Injuries in the studies included variants of sacroiliac (SI) dislocations and acetabular fractures (Table I).

General characteristics such as operative time, radiation dose, and associated complications and revisions varied widely among the studies. Operative time was longer with 3DIOI in some studies, while other studies found that operative time was similar or shorter with 3DIOI (Table I). Overall, there were no significant differences in operative time among the different imaging modalities of conventional fluoroscopy, 2D navigation, and 3D imaging (Fig. 2-A). Although not all studies measured the mean radiation dose, the available results showed greater reported doses in the 3DIOI groups (Table I). In our analysis, the mean radiation dose (in cGy·cm²) was significantly greater with 3DIOI (MD, 82.72; 95% CI, 21.83 to 143.61; p = 0.007) (Fig. 2-B). Lastly, a majority of the studies reported no iatrogenic complications or revisions, but overall, more complications were found in the conventional fluoroscopy and 2D-navigated groups (Table I). In our analysis, 3DIOI yielded a 93% reduced risk of developing medical complications (OR, 0.07; 95% CI, 0.02 to 0.35; p = 0.014) (Fig. 2-C).

Seven studies compared the utility of different imaging modalities by measuring various parameters of operative success and errors. Parameters included accuracy and misplacement rates for screw insertion, postoperative fracture reduction, and the ability to assess fracture step-offs and gaps. Five of the 7 studies found more favorable outcomes in the 3DIOI groups (Table II). Use of 3DIOI yielded higher odds of achieving accurate screw placement (OR, 4.21; 95% CI, 1.44 to 12.32; p = 0.008) and perfect reduction (OR, 2.60; 95% CI, 1.19 to 5.68; p = 0.016). In contrast, 2D navigation imaging yielded results that were not significantly different from those achieved with conventional fluoroscopy (Fig. 3-A). Four studies also found a decrease in the number of cortical perforations (OR, 0.32; 95% CI, 0.13 to 0.80; p = 0.014) and number of poor reductions (OR, 0.28; 95% CI, 0.10 to 0.75; p = 0.010) in the 3DIOI groups (Fig. 3-C, Table II). In contrast, 2D navigation showed no significant
<table>
<thead>
<tr>
<th>Study</th>
<th>Site of Surgery</th>
<th>3D Device</th>
<th>Navigation Software</th>
<th>Study Results</th>
</tr>
</thead>
</table>
| Behrendt, 2012<sup>15</sup> | Posterior pelvic ring | Ziehm Vision FD Vario 3D | BrainLAB Spine and Trauma Fluoro 3D | Operative Success/Primary Outcome:
6/36 (fluoro)*
14/33 (2D)<sup>†</sup>
20/33 (3D)
Operative Error/Secondary Outcome:
Cortical perforation:
10/36 (fluoro)*
7/33 (2D)<sup>†</sup>
2/30 (3D)<sup>‡</sup> |
| Eckardt, 2015<sup>19</sup> | Acetabulum | Medtronic O-Arm | None | No. of perfectly reduced fractures (<1 mm):
17/42 (fluoro)*
46/72 (3D)
No. of perforations of osseous cortices:
7/70 (fluoro)*
11/70 (2D)<sup>†</sup>
3/70 (3D) |
| Grossterlinden, 2011<sup>13</sup> | Acetabulum, posterior pelvic ring | Siemens 3D C-arm ARCADIS Orbic | VectorVision Fluoro 3D Navigation | Correct screw placement by surgeon experience:
53% low volume (fluoro)*
90% low volume (3D)
87% high volume (fluoro)*
95% high volume (3D) |
| Gras, 2012<sup>16</sup> | Acetabulum | Siemens ISOC3D | VectorVision Fluoro 3D Navigation | No. of perfectly placed screws:
29/40 (2D)<sup>†</sup>
37/40 (3D)
No. of screws with correct positions (grade 0 = 0 mm perforation):
18/24 (2D)*
23/24 (3D)
24/24 (CT) |
| Kendoff, 2008<sup>2</sup> | Acetabulum | Siemens ISOC3D | None | Ability to detect intra-articular position of screw:
19/24 (2D)*
23/24 (3D)
24/24 (CT) |
| Oberst, 2012<sup>17</sup> | Acetabulum | Siemens ISOC3D | VectorVision Fluoro 3D | Postoperative fracture step (mm):
1.5 ± 3.1 (2D)*
0.3 ± 0.7 (3D) |
| Ochs, 2010<sup>12</sup> | Acetabulum | Siemens ISOC3D | VectorVision Fluoro 3D | Number of screws with correct positions (grade 0 = 0 mm perforation):
60/70 (fluoro)*
56/70 (2D)<sup>†</sup>
65/70 (3D) |

*Represents conventional protocol: plain 2D fluoroscopy without navigation.
†Represents 2D navigated protocol: plain 2D fluoroscopy with navigation.
‡3 screws were removed from the original group as deviation was inevitable in preoperative planning.
§Misplaced screws led to revision/replacement of screws.
Figs. 3-A through 3-D Comparisons of various parameters of operative success and errors (accurately placed screws, perfect reduction, screw deviation, inaccurately placed screws, perforation, poor reduction, and screw revisions). Forest plots of the imaging modalities (Fluoro = conventional 2D fluoroscopy without navigation, 2D = plain 2D fluoroscopy with a navigation protocol, and 3D = intraoperative 3D imaging) are shown, with associated league tables showing direct evidence (upper triangle) and indirect evidence (lower triangle) for the pairwise comparisons. Data for operative success (Fig. 3-A) and operative errors (Figs. 3-B, 3-C, and 3-D) are reported as the odds ratio (OR) or mean difference (MD) and 95% confidence interval (CI). Significantly better outcomes are reported in green.

### Operative Success parameters

#### Accurately placed screws

<table>
<thead>
<tr>
<th></th>
<th>2D</th>
<th>OR</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluoro</td>
<td>3.45 (1.21, 7.99)</td>
<td>4.09 (1.33, 12.56)</td>
<td></td>
</tr>
<tr>
<td>2D</td>
<td>3.14 (1.25, 7.94)</td>
<td>2D</td>
<td></td>
</tr>
<tr>
<td>3D</td>
<td>4.21 (1.44, 12.32)</td>
<td>1.34 (0.48, 3.76)</td>
<td></td>
</tr>
</tbody>
</table>

### Operative failure parameters

#### Deviation At screw entry points

<table>
<thead>
<tr>
<th></th>
<th>2D</th>
<th>MD</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluoro</td>
<td>-0.80 (-1.71, 0.11)</td>
<td>-0.40 (-1.33, 0.51)</td>
<td></td>
</tr>
<tr>
<td>2D</td>
<td>-1.10 (-1.57, 0.28)</td>
<td>0.40 (-0.95, 1.75)</td>
<td></td>
</tr>
<tr>
<td>3D</td>
<td>-1.40 (-2.33, -0.47)</td>
<td>-0.30 (-1.34, 0.74)</td>
<td></td>
</tr>
</tbody>
</table>

#### Deviation At screw at critical zones

<table>
<thead>
<tr>
<th></th>
<th>2D</th>
<th>OR</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluoro</td>
<td>-2.00 (-3.47, -0.73)</td>
<td>-2.20 (-3.78, -0.62)</td>
<td></td>
</tr>
<tr>
<td>2D</td>
<td>-2.50 (-3.87, -0.72)</td>
<td>0.10 (-1.59, 1.78)</td>
<td></td>
</tr>
<tr>
<td>3D</td>
<td>-2.20 (-3.76, -0.67)</td>
<td>0.30 (-1.39, 1.98)</td>
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</tr>
</tbody>
</table>

### Inaccurately placed screws

<table>
<thead>
<tr>
<th></th>
<th>2D</th>
<th>OR</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluoro</td>
<td>0.32 (0.09, 1.17)</td>
<td>1.68 (0.33, 8.48)</td>
<td></td>
</tr>
<tr>
<td>2D</td>
<td>0.33 (0.09, 1.29)</td>
<td>1.45 (0.76, 20.13)</td>
<td></td>
</tr>
<tr>
<td>3D</td>
<td>1.46 (0.31, 6.96)</td>
<td>4.41 (0.06, 20.36)</td>
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</tbody>
</table>

### Imperfect Reduction

<table>
<thead>
<tr>
<th></th>
<th>2D</th>
<th>OR</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluoro</td>
<td>0.83 (0.35, 1.96)</td>
<td>0.83 (0.35, 1.96)</td>
<td></td>
</tr>
<tr>
<td>2D</td>
<td>0.83 (0.35, 1.96)</td>
<td>0.83 (0.35, 1.96)</td>
<td></td>
</tr>
<tr>
<td>3D</td>
<td>0.83 (0.35, 1.96)</td>
<td>0.83 (0.35, 1.96)</td>
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</table>

### Poor Reduction

<table>
<thead>
<tr>
<th></th>
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<th>OR</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluoro</td>
<td>0.28 (0.10, 0.75)</td>
<td>0.28 (0.10, 0.75)</td>
<td></td>
</tr>
<tr>
<td>2D</td>
<td>0.28 (0.10, 0.75)</td>
<td>0.28 (0.10, 0.75)</td>
<td></td>
</tr>
<tr>
<td>3D</td>
<td>0.28 (0.10, 0.75)</td>
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### Perforation

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<th>OR</th>
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<tbody>
<tr>
<td>Fluoro</td>
<td>0.29 (0.12, 0.71)</td>
<td>0.33 (0.13, 0.83)</td>
<td></td>
</tr>
<tr>
<td>2D</td>
<td>0.29 (0.12, 0.71)</td>
<td>0.33 (0.13, 0.83)</td>
<td></td>
</tr>
<tr>
<td>3D</td>
<td>0.32 (0.13, 0.90)</td>
<td>1.10 (0.55, 2.20)</td>
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</tbody>
</table>

### Revisions / Screw Replacement

<table>
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<th></th>
<th>2D</th>
<th>OR</th>
<th>95% CI</th>
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<tbody>
<tr>
<td>Fluoro</td>
<td>-5.58 (-33.97, 0.92)</td>
<td>2D</td>
<td></td>
</tr>
<tr>
<td>2D</td>
<td>-5.58 (-33.97, 0.92)</td>
<td>2D</td>
<td></td>
</tr>
<tr>
<td>3D</td>
<td>-5.58 (-33.97, 0.92)</td>
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**Fig. 3**
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<thead>
<tr>
<th>Study</th>
<th>Site of Surgery</th>
<th>3D Device</th>
<th>Navigation Software</th>
<th>Study Type</th>
<th>Parameter Compared with CT Imaging</th>
<th>Mean Deviation of Actual from Planned Screw Placement (mm)</th>
<th>Study Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Keil, 201811</td>
<td>Acetabulum</td>
<td>Siemens C-arm Aarcus Orbic</td>
<td>None</td>
<td>3D navigation assessment</td>
<td>Mean value of largest visible step, axial (mm): 1.14 ± 1.8 (3D) 2.87 ± 2.7 (CT) Relative difference: −1.73 Absolute difference: 1.96**</td>
<td>NR†</td>
<td>NR†</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mean value of largest visible gap, sagittal (mm): 2.02 ± 3.9 (3D) 5.87 ± 3.6 (CT) Relative difference: −3.85 Absolute difference: 4.57†</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kendoff, 20082</td>
<td>Acetabulum</td>
<td>Siemens ISO-3D</td>
<td>None</td>
<td>Comparative (control vs. 3D) and 3D navigation assessment</td>
<td>Ability to detect extra-articularly placed screws (n): 19/24 (2D)§ 23/24 (3D) 24/24 (CT) Ability to detect articular incongruity (n): 19/24 (2D)§ 23/24 (3D) 24/24 (CT) Ability to detect articular impaction injury (n): 15/24 (2D)§ 19/24 (3D) 22/24 (CT)</td>
<td>NR†</td>
<td>NR†</td>
</tr>
<tr>
<td>Ochs, 201012</td>
<td>Acetabulum</td>
<td>Siemens ISO-C3D</td>
<td>Vector Vision Fluoro 3D</td>
<td>Comparative (control vs. 3D)</td>
<td>AC screw#: 3.6 ± 2.6 (fluoro)§ 3.9 ± 2.4 (2D)** 3.6 ± 2.3 (3D) PC screw††: 5.8 ± 2.9 (fluoro)§ 6.3 ± 3.3 (2D)** 5.4 ± 2.9 (3D) AC screw#: 4.9 ± 2.6 (fluoro)§ 4.7 ± 2.7 (2D)** 3.6 ± 1.9 (3D) PC screw††: 6.0 ± 3.6 (fluoro)§ 5.7 ± 2.9 (2D)** 4.0 ± 2.1 (3D)</td>
<td>NR†</td>
<td>NR†</td>
</tr>
<tr>
<td>Takao, 20144</td>
<td>Posterior pelvic ring</td>
<td>Ziehm Vision FD Vario 3D</td>
<td>Stryker Navigation System II-Cart</td>
<td>3D navigation assessment</td>
<td>AC screw#: 11.2 ± 4.4 (fluoro)§ 9.7 ± 4.8 (2D)** 8.2 ± 4.4 (3D) PC screw††: 8.8 ± 5.8 (fluoro)§ 10.0 ± 6.7 (2D)** 7.4 ± 3.6 (3D)</td>
<td>NR†</td>
<td>NR†</td>
</tr>
</tbody>
</table>

*Significant (p < 0.0024). †Significant (p < 0.001). ‡NR = not reported. §Represents conventional protocol: plain 2D fluoroscopy without navigation. #Anterior column screw. **Represents 2D-navigated protocol: plain 2D fluoroscopy with navigation. ††Posterior column screw.
difference compared with fluoroscopy for all parameters (Fig. 3-C).

Two studies directly compared 3DIOI against CT by evaluating their ability to assess for fracture step-offs and gaps, cortical perforations, and articular incongruities\textsuperscript{2,11}. The study results showed that 3DIOI underestimated step-offs and gaps, but performed similarly to CT in detecting extra-articularly placed screws and articular incongruities (Table III). No statistical analysis was able to be performed for these 2 studies.

The mean deviation of actual from planned screw placement (in mm) at different points in the screw trajectory was measured in 2 studies (Table III)\textsuperscript{1,12}. Use of 3DIOI was associated with less deviation at the critical zone (MD, \(-2.1.40\); 95% CI, \(-2.33\) to \(-0.47\); \(p = 0.003\)) and at the screw end points (MD, \(-2.2.20\); 95% CI, \(-3.70\) to \(-0.70\); \(p = 0.003\)) (Fig. 3-B).

Overall, in ranking of the imaging modalities, 3DIOI outperformed conventional fluoroscopy and 2D navigation in 12 of the 13 parameters statistically analyzed in our study. For 8 of the 13 parameters, 3DIOI had P-scores of >0.80. Conventional fluoroscopy only scored superior to 3DIOI with regard to mean radiation dose, with a P-score of 0.96 (Fig. 4).

**Discussion**

Pelvic and acetabular fractures are challenging injuries to manage. Surgical fixation of these injuries requires technical expertise for accurate reduction, stable fixation, and prevention of neurovascular damage\textsuperscript{13}. Computer navigation and advanced imaging techniques have yielded superior results in pedicle and iliosacral fractures because of their ability to improve the accuracy of placing intraosseous screws\textsuperscript{12}.

To our knowledge, previous systematic reviews have only reported on malpositioning and revision rates of screws for iliosacral fixation\textsuperscript{14}. The present systematic review sought to elucidate the utility and operative outcomes associated with 3DIOI for the fixation of pelvic ring and acetabular fractures. The primary outcomes and adverse outcomes assessed in each comparative and assessment study demonstrated the utility and benefits provided by advanced imaging. Although the measured outcomes differed among the studies, collectively they supported our hypothesis. Overall, our study found that 3DIOI was superior to conventional fluoroscopy and 2D navigation, but comparable with CT.

**Types of Studies**

This systematic review included both comparisons of 3DIOI with other imaging modalities and assessments of only 3DIOI. The assessment studies were included because the data from these studies provided valuable information regarding the utility of 3DIOI relative to CT imaging. The primary subjects of each study varied on the basis of the primary outcomes measured. The primary outcomes included screw misplacement rates, deviations of actual from planned screw paths, ability to assess articular incongruities, and ability to perfectly reduce fractures. Additional outcomes were also measured in each study, but only outcomes used in >1 study are reported in this review. Because of the differences in measured outcomes, not all studies provided patient demographic data, as many of them used cadaver or synthetic.
Utility of 3-Dimensional Intraoperative Imaging in Pelvic and Acetabular Fractures

Screw Accuracy and Placement
Three studies found a higher accuracy or a higher correct screw placement rate (<1 mm from the target and 0 mm of cortical perforation) in the 3DIOI compared with the 2D navigation and conventional fluoroscopy groups, with rates of correct screw placement with 3DIOI ranging from 60.1% to 92.8%12,15,16. The increased accuracy could be attributed to the improved visualization and dynamic, variable-slice images provided by 3DIOI17. Two studies investigated the mean deviation (in mm) of actual from planned screw placement at different positions1,12. Collectively, they compared conventional fluoroscopy, 2D navigation, and 3DIOI. The study by Ochs et al. was more robust as it assessed the accuracy of percutaneous periacetabular screw placement among all of these imaging modalities. The researchers found a higher rate of grade-0 (<3.25-mm) deviations at the critical zones and end points (35.7% and 27.1%, respectively), and a lower rate of cortical perforations, in the 3D navigation group. This was true even for retrograde screw placement in the posterior column, which requires longer screws and more technical skill12. Takao et al. found the mean deviation between the planned and the inserted screw position to be 1.8 mm at the area around the nerve root tunnels, with a maximal margin of error of 3 mm, when using 3D imaging1.

The ability of conventional fluoroscopy and 3DIOI in assessing screw placement was also assessed against that of CT imaging. CT imaging is considered the gold standard for evaluating pelvic fractures, as it provides more accurate and detailed information regarding the anatomy.18 The ability of conventional fluoroscopy and 3DIOI to assess screw placement was also compared against that of CT imaging. Use of 3DIOI was superior to conventional fluoroscopy in its ability to detect intra-articular and extra-articular screw placement, but it was not superior to CT imaging2.

Articular Displacement
Imaging techniques were also evaluated on the basis of their ability to assist in reducing fractures via ORIF or percutaneous screws. Two studies found better reduction with 3DIOI than with conventional fluoroscopy17,19. Researchers attributed these findings to increased recognition of residual step-offs and gaps that can remain undetected with intraoperative conventional fluoroscopy19. Use of 3DIOI as well as 2D imaging was also assessed against CT. Overall, use of 3DIOI improved visualization of the pelvis compared with conventional fluoroscopy; however, the study by Keil et al. showed that the mean fracture step-offs and gaps were underestimated with 3DIOI when not combined with postoperative CT11. Kendoff et al. also assessed the ability of 3DIOI to detect articular incongruity and an articular impaction injury. Use of 3DIOI was superior to conventional fluoroscopy in detecting impaction; however, it had no superiority in evaluating articular incongruities2. This was likely because fracture lines can be missed or overlooked using the individual slice images collected in 3DIOI and CT imaging2. These studies show the continued need for postoperative CT scans as a diagnostic tool to ensure quality reductions and implant placement2,11.

Another benefit of 3DIOI is the opportunity to operate on high-risk patients more safely17. ORIF is an invasive procedure and elderly patients with multiple comorbidities are at increased risk for surgical complications. Nonoperative management of acetabular fractures is not often feasible because of the increased risks of pneumonia and thromboembolism due to the weeks of required immobilization17. By using 3DIOI for closed reduction and percutaneous screw fixation of acetabular fractures, the surgeon provides better fracture reduction and gains earlier mobilization of the patient.

Operative Time
Operative times varied greatly among the studies. Four studies reported shorter operative times in the 3DIOI group, while 1 study reported longer operative times12,15,17,19. It is important to consider that a comparison of operative times in this review is difficult because of the diverse types of procedures and pelvic ring and acetabular injuries included among the studies. Some researchers simply experimented with passing a single screw, while others attempted to reduce fractures as well. In 1 study, researchers found a shorter operative time per screw in the 3DIOI group, which they attributed to shorter instrumentation times associated with 3D navigation19. In contrast, another study found that after excluding percutaneous screws, skin-to-skin operative times (in minutes) were significantly greater in the 3DIOI group than in the fluoroscopy group (264 ± 100 and 365 ± 95, respectively; p < 0.001)17. Researchers hypothesized that the difference was not likely due to the procedure, but rather to increased detection of misplaced screws and unsatisfactory reductions17. In the study by Ochs et al., although the operative times (in minutes) were similar among the 2D navigation and 3DIOI groups (10.5 ± 3.7 and 11.6 ± 3.6, respectively), the time in the control group using conventional fluoroscopy was only 7.2 ± 4.412. They proposed that this operative time difference when using navigation was due to the time needed for image acquisition and for preparation (fixation of the reference tracker)12.

The time spent acquiring the images is an important component of the operative time. For conventional fluoroscopy, individual 2D images are
reported complications, a majority of the studies reported no complications as many used cadavers and synthetic pelvises. Furthermore, there was a decreased number of screw revisions in the 2D-navigated and 3DIOI groups as enhanced imaging guidance improved screw placement.

One disadvantage of 3DIOI, secondary to the non-continuous acquisition of image data, is that implants can distort 3D image construction due to metal artifact. In 1 study, researchers explained that metal artifact was likely the reason for underestimated valuation of fracture steps and gaps compared with CT imaging (Table III). The use of metal artifact reduction (MAR) in 3DIOI is sparse in the literature, but 1 study found improved image quality using MAR for pedicle screw placement in spine surgery. No studies currently focus on MAR in 3DIOI for acetabular and pelvic fractures, and this should be investigated in further studies.

**Financial Viability of 3DIOI Devices**

The costs of these imaging devices should be considered, as the initial investment can be approximately $260,000 more than for a conventional C-arm. For example, the Ziehm Vision RFD 3D device can range from $425,000 to $600,000, and the Medtronic O-Arm can range from $784,000 to $860,000. Prices are subject to changes as each device has modifications (lasers, WiFi integration, and navigation integration) and specialty packages (cochlear, vascular, and orthopaedic trauma) that can be added at the time of purchase. Ancillary equipment such as a power table, Sterile-Z drapes (TIDI Products), and Medtronic Sterile Tube Drapes are additional expenses.

A major factor that influences the return on investment (ROI) for a 3DIOI device is its ability to decrease monetary, time, and opportunity costs. To our knowledge, no cost-benefit analysis of 3DIOI has been conducted in orthopaedic trauma, but in spine surgery the cost of revision of a lumbar pedicle screw is approximately $9,600. The expected benefits such as improved accuracy, decreased revisions, and overall better health-care quality and safety are reasons why these devices may provide a good ROI. They can also be used in a multitude of specialties, including otolaryngology, vascular surgery, neurosurgery, orthopaedic trauma, and spinal surgery. Each specialty may use different CPT (Current Procedural Terminology) codes (and associated charges) for 3DIOI, but CPT code 76377 (3D rendering with interpretation and reporting of CT, MRI, ultrasound, or other tomographic modality) was used at our institution in the case example below.

**Impact in the Operating Room Environment**

Adaptable physical space is needed to accommodate the size of the devices. The only major size difference between a 3DIOI device, such as the Ziehm Vision RFD 3D, and a conventional C-arm fluoroscope is the flat-panel detector that takes the place of the standard image intensifier on a C-arm. However, the Medtronic O-Arm is larger (110.5 in [280.6 cm] × 32 in [81.3 cm] × 79.6 in [202.2 cm]) as it completely encloses the patient. An estimated 2.5 m² should be allocated to a single O-Arm, and a minimum room size of 35 m² is needed to accommodate the mobile units.

There are no major differences regarding the device operators. No additional personnel are required to operate the devices, as hospital radiology technicians are normally trained to operate the equipment by the manufacturer. Maintaining a sterile field is imperative, and should be a concern when introducing these large devices into the operating room. When using the Ziehm device, it is recommended to drape the patient instead of the device using a Sterile-Z drape. The O-Arm uses a special sterile tube drape to maintain sterility.

Radiation exposure should also be considered. Four studies in our review discussed this point, but only 2 studies directly compared the mean radiation dose. In 2 studies, the radiation dose of a 3D-navigated procedure was
estimated to be 5 times and 8.6 times higher than that of the conventional procedure. The increased dose-area product in 3DIOI is explained by the automated image acquisition. Although 3DIOI uses more radiation, the improved visualization of fractures and screw placement is a major advantage. Moreover, the radiation exposure is actually less for the operating team because they can leave the operating room during the scan. Some studies, in the setting of pediatric pedicle screw placement, have found that the radiation intensity of the O-Arm can be reduced by 89% and still produce images of adequate quality.

**Case Example**

We were able to test the utility of 3DIOI in a patient with a left sacroiliac joint diastasis and left anterior column acetabular fracture (Figs. 5-A through 5-D). Fracture reduction and fixation was initially performed with percutaneous sacroiliac screws under conventional 2D fluoroscopy (Figs. 5-E and 5-F). Using this imaging modality, we determined that we had achieved acceptable reduction with appropriate screw placement. We then used the Medtronic O-Arm to verify the positioning, and we found that the screw in S1 had indeed been accurately placed (Fig. 5-G) but the distal S2 screw was displaced anteriorly (Fig. 5-H). The screw in S2 was subsequently repositioned using 3DIOI to ensure proper placement. Using the O-Arm afforded our team improved visualization of the pelvic anatomy, the fracture, and screw position. Importantly, we ultimately decreased the risk of cortical perforation or iatrogenic neurovascular injury by using this imaging modality.

**Limitations**

This review has some limitations. We sought to compile data associated with the various intraoperative imaging techniques from multiple studies. However, all of the studies differed with respect to the variables and parameters assessed, making it difficult to directly compare their results. The types of subjects also differed among the studies. In 1 study, researchers used both synthetic and cadaver pelves, and they reported increased rates of malpositioning in the cadaver pelves as they had more complex anatomy and poor-quality osseous structures. Additionally, we could not control for confounding variables such as differences in patient types and comorbidities. Variability in bone quality and fracture pattern, surgeon experience, and technique will also have had a direct effect on the reported study results. In addition, the substantial learning curve issues associated with both pelvic fracture surgery and utilization of 3DIOI were not discussed in any of the studies.

**Overview**

In summary, the rates of misplaced implants, malreduced fractures, complications, and subsequent revision surgeries decreased with the use of 3DIOI. Intraoperative imaging affords surgeons improved visualization of screw trajectories, fracture lines, and the dimensions of the pelvis. Comparing the imaging techniques indicated that 3DIOI was superior to conventional fluoroscopy and 2D navigation but comparable with CT. Using 3DIOI was particularly helpful for pelvic ring disruptions with sacral dysmorphism and acetabular fractures, as it gave surgeons a better understanding of the pelvic anatomy.
Although 3DIOI is associated with a greater mean radiation dose, it is regarded as a viable option for operative fixation of acetabular and pelvic ring fractures because of the overall benefits of decreased complications, perforations, and malpositioned implants.

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