Original Article
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Safe Optimal Tear Drop View for Spinopelvic Fixation Using a Three-Dimensional Reconstruction Model of the Pelvis

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Background: Spinopelvic fixation (SPF) has been a challenge for surgeons despite the advancements in instruments and surgical techniques. C-arm fluoroscopy-guided SPF is a widely used safe technique that utilizes the tear drop view. The tear drop view is an image of the corridor from the posterior superior iliac spine to the anterior inferior iliac spine (AIIS) of the pelvis. This study aimed to define the safe optimal tear drop view using three-dimensional reconstruction of computed tomography images.

Methods: Three-dimensional reconstructions of the pelvises of 20 individuals were carried out. By rotating the reconstructed model, we simulated SPF with a cylinder representing imaginary screw. The safe optimal tear drop view was defined as the one embracing a corridor with the largest diameter with the inferior tear drop line not below the acetabular line and the lateral tear drop line medial to the AIIS. The distance between the lateral border of the tear drop and AIIS was defined as tear drop index (TDI) to estimate the degree of rotation on the plane image. Tear drop ratio (TDR), the ratio of the distance between the tear drop center and the AIIS to TDI, was also devised for more intuitive application of our simulation in a real operation.

Results: All the maximum diameters and lengths were greater than 9 mm and 80 mm, respectively, which are the values of generally used screws for SPF at a TDI of 5 mm and 10 mm in both sexes. The TDRs were 3.40 ± 0.41 and 3.35 ± 0.26 in men and women, respectively, at a TDI of 5 mm. The TDRs were 2.26 ± 0.17 and 2.14 ± 0.12 in men and women, respectively, at a TDI of 10 mm.

Conclusions: The safe optimal tear drop view can be obtained with a TDR of 2.5 to 3 by rounding off the measured values for intuitive application in the actual surgical field.

Keywords: *Pelvis, Spinal fusion, Tear drop view, Spinopelvic fixation, Three-dimensional*

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Spinopelvic fixation (SPF) is indicated for long arthrodesis extending to the sacrum, unstable sacral fractures, high-grade spondylolisthesis, pelvic obliquity correction, and lumbosacral deformities requiring corrective osteotomy.[1-4] Despite the advances with respect to surgical techniques and instruments, SPF remains challenging for surgeons because of pseudarthrosis and fixation failure.[1,5,6] Poor bone quality of the sacrum, complex anatomy, considerable biomechanical loading at the lumbosacral junction, and the large cantilever effect of the long construct have been suggested as reasons for the high rates of these complications.[3]

There has been a continuous development of SPF techniques. The Galveston technique is considered the most fundamental of modern SPF techniques utilizing the pelvis for the anchoring of spinal constructs.[1,7] An L-shaped contoured rod is inserted at the posterior superior iliac spine (PSIS) and advanced into the ilium, located just above the sciatic notch. The iliac screw (IS), one of the most popular techniques in the modern era, is an improved method of the Galveston technique that uses iliac bolts instead of rods. This technique has been reported to be biomechanically stable and have favorable outcomes, high fusion rates, and a low incidence of fixation failure compared with previous techniques.[8-10] However, it has also been documented to be associated with screw prominence, wound problems over the screw heads, substantial muscle dissection, gluteal pain, and difficult hardware linkage with spinal constructs.[2,6,9] The S2-alar-iliac screw (S2AIS), a modification of IS, was introduced in 2007 to overcome these problems and has been documented to have lower rates of complications and fixation failures than IS.[2,6,11]

Several studies have described SPF techniques, including freehand based on bony landmarks, C-arm fluoroscopy-guided, and navigated or robot-supported techniques.[12-16] The C-arm fluoroscopy-guided technique, generally utilizing the tear drop view, is a reliable and safe method that is essential for patients with anatomical variations, trauma, or tumors.[13] The tear drop view is an overlapped image of the anterior and posterior columns of the pelvis, showing the corridor from the PSIS to the anterior inferior iliac spine (AIIS).[16] However, to our knowledge, there is a paucity of literature suggesting the optimal tear drop view and definite landmarks in fluoroscopic images to obtain this view. Therefore, this study aimed to define the optimal tear drop view using three-dimensional (3D) reconstruction of computed tomography (CT) images.

METHODS

The Institutional Review Board of Korea University Guro Hospital approved the current study, and a waiver of consent was obtained (No. 2020GR0420). We collected data from randomly selected 20 individuals (10 men and 10 women) who visited our institution and underwent pelvis CT (Aquilion ONE) with axial images at an interval of 1 mm in 2020, after excluding those with a history of fracture, infection, tumors, or congenital deformity of the spine or pelvis. One attending staff member (JHY) and a resident (TCH) reviewed the medical records and pelvis CT scans. Using the Digital Imaging and Communications in Medicine files of CT scans, 3D reconstruction of the pelvis was performed using the Mimics software (Materialise NV).

Acquisition of the Tear Drop View and Simulation of SPF Using a 3D Pelvis Model

Upon rotating the reconstructed 3D model around the AIIS, which is a target of the screw trajectory and readily recognizable on the C-arm fluoroscopy and adjusting its transparency according to the accumulated bone density through the axis mimicking the fluoroscopic beam, we identified the moment representing the tear drop view, consistent with that on fluoroscopy (Fig. 1). The screw trajectory was set up along the perpendicular axis passing through the center point of the tear drop, which is the intersection point between a vertical line drawn from the apex of the tear drop and the transverse line with the longest length (Fig. 2).

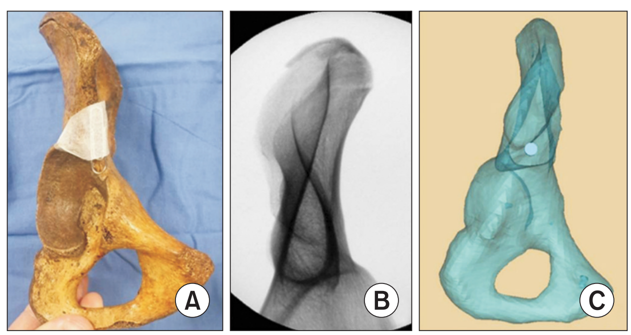

Fig. 1. Simulation of the tear drop view with a dry pelvic bone and three-dimensional (3D) pelvis model. (A) Positioning of the dry pelvic bone to simulate the tear drop view. (B) C-arm fluoroscopic image of the dry pelvic bone, representing the tear drop view. (C) Simulation of the tear drop view with a 3D pelvis model.

Definition of Optimal Tear Drop View

Several previous studies have documented that screws with a larger diameter and a longer length could provide greater fixation strength.[17-19] Accordingly, the optimal tear drop view in the current study was defined as a view allowing the insertion of the screw, represented as a cylinder in our simulation, with a maximum acceptable diameter and length without any intra-articular and intrapelvic protrusion or cortical breakage. Thus, the prerequisites for defining a safe tear drop view were as follows (Fig. 3): (1) the inferior tear drop line should not be below the acetabular line to prevent violation of the acetabular rim, and (2) the lateral border of the tear drop line should be medial to the AIIS to avoid intrapelvic protrusion. Cortical breakage or protrusion was checked while increasing the diameter of the cylinder by 1 mm (Fig. 4).

Measurement of Indexes

For the preliminary validation, several parameters were measured using a 3D pelvis model. The distance between the lateral border of the tear drop and AIIS was defined as the tear drop index (TDI) (Fig. 5). We defined the TDI as a surrogate for the index of the plane image because it is impossible to estimate the degree of rotation on the plane fluoroscopic image. While rotating the 3D model with a TDI of 5 mm (Fig. 6), the maximum acceptable diameter was measured at each rotation. The maximum acceptable length was also measured with a cylinder representing an

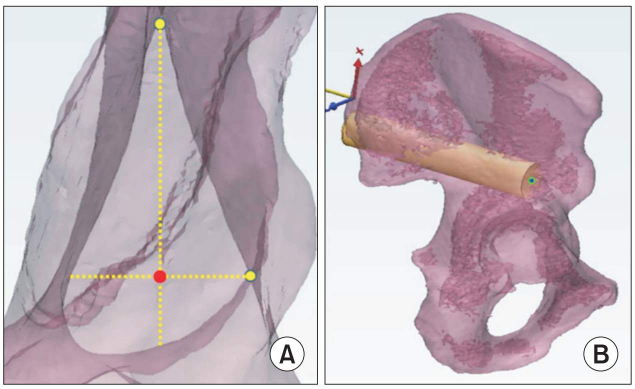

Fig. 2. Simulation of screw insertion. (A) Center point of the tear drop. (B) Screw trajectory along the perpendicular axis passing through the center point of the tear drop.

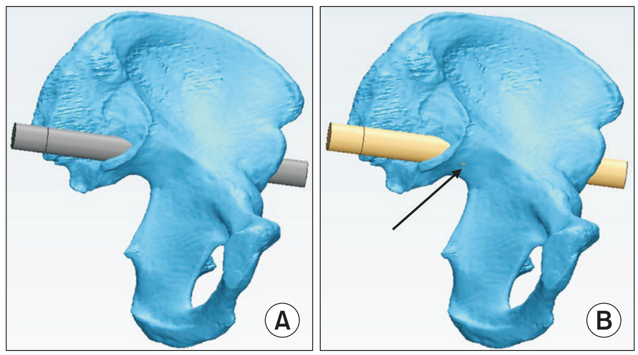

Fig. 4. Simulation of spinopelvic fixation (SPF) while increasing the diameter of the cylinder by 1 mm. (A) Simulation of SPF using a cylinder with a diameter of 16 mm without cortical breakage. (B) Cortical breakage (black arrow) in the simulation of SPF using a cylinder with a diameter of 17 mm.

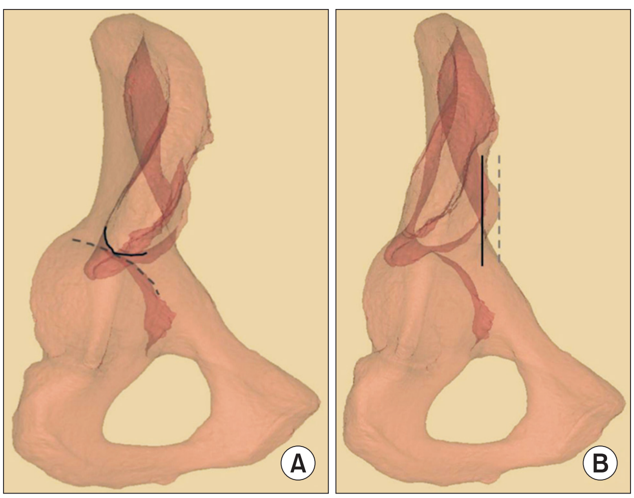

Fig. 3. Safe tear drop to prevent any intra-articular and intrapelvic protrusion. (A) Inferior tear drop line (black line) not below the acetabular line (gray dashed line). (B) Lateral tear drop line (black line) medial to the anterior inferior iliac spine (gray dashed line).

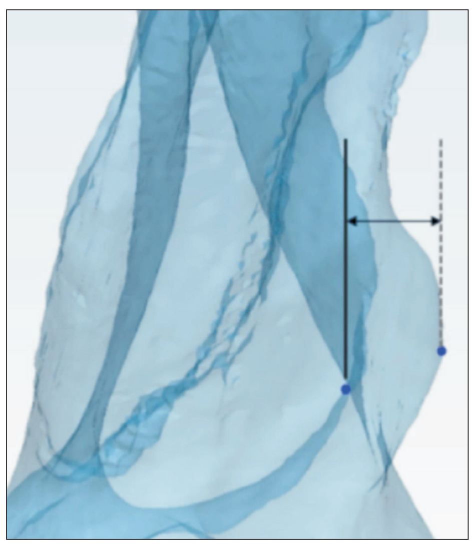

Fig. 5. Tear drop index. The distance between the lateral border of the tear drop (black line) and anterior inferior iliac spine (gray dashed line).

imaginary screw with a diameter of 9 mm, which is considered large enough to secure stability and thicker than that of generally used screws in actual SPF surgeries.[3,20] As a corridor did not appear at TDI values of 0 and 15 mm in several patients, these measurements were performed at TDI values of 5 and 10 mm.

However, it is difficult to measure the TDI on fluoroscopic images in an actual operation. Therefore, we devised the tear drop ratio (TDR), which was defined as the ratio of the distance between the tear drop center point and the AIIS to TDI, to apply our simulation in a more intuitive manner in a real operation (Fig. 7).

Statistical Analysis

The maximum acceptable diameter was compared depending on the laterality of the pelvis, the amount of rotation, and sex using the Mann-Whitney test; comparisons of the maximum acceptable length was also performed in the same manner. The values are presented as median (interquartile range). The statistical significance was set at $p < 0.05$. All statistical analyses were performed using IBM SPSS statistics ver. 26.0 (IBM Corp., Armonk, NY, USA).

RESULTS

Overall, 40 pelvises from 20 individuals were included. The mean age of the individuals was 30.45 ± 7.33 years without significant difference between sexes.

Maximum Acceptable Screw Diameter and Length

All the maximum acceptable diameters and lengths were more than 9 mm and 80 mm, respectively, which are the values of the diameter and length of screws generally used for SPF, respectively, regardless of the TDI in both sexes (Tables 1 and 2). There was no significant difference in the diameter and length depending on the laterality of the pelvis.

Comparisons of Acceptable Screw Diameter and Length Depending on the Sex and Amount of Rotation

A comparison of the maximum diameter and length between a TDI of 5 mm and 10 mm showed no statistically significant differences, except for the maximum length in men (Tables 1 and 2). The maximum acceptable length of a cylinder at a TDI of 5 mm was significantly longer than that at a TDI of 10 mm in men on both sides. The maximum acceptable screw diameter in men was significantly larger than that in women at every rotation. The maximum acceptable screw length in men was larger than that in women, but it was statistically insignificant (Tables 1 and 2).

Tear Drop Ratio

The TDRs, the ratio of TDI and the distance between the tear drop center point and the AIIS, at a TDI of 5 mm were 3.40 ± 0.41 and 3.35 ± 0.26 in men and women, respectively. The TDRs at a TDI of 10 mm were 2.26 ± 0.17 and 2.14 ± 0.12 in men and women, respectively (Table 3).

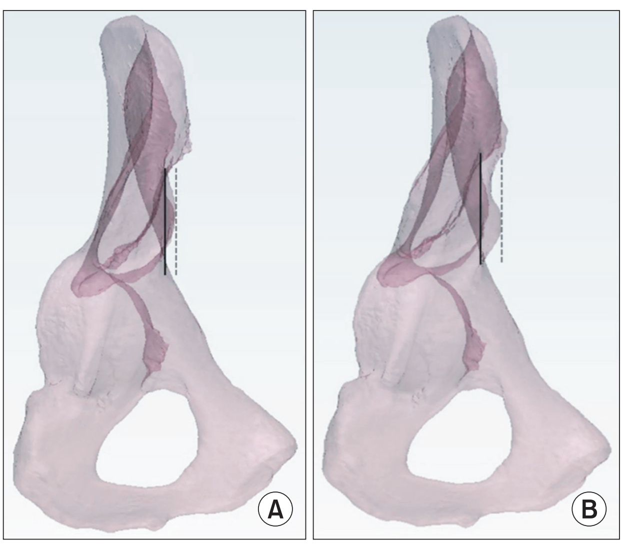

Fig. 6. Tear drop views with different tear drop index values (TDI). The TDI, which refers to the distance between the lateral border of the tear drop (black line) and the anterior inferior iliac spine (gray dashed line), was 5 mm (A) and 10 mm (B).

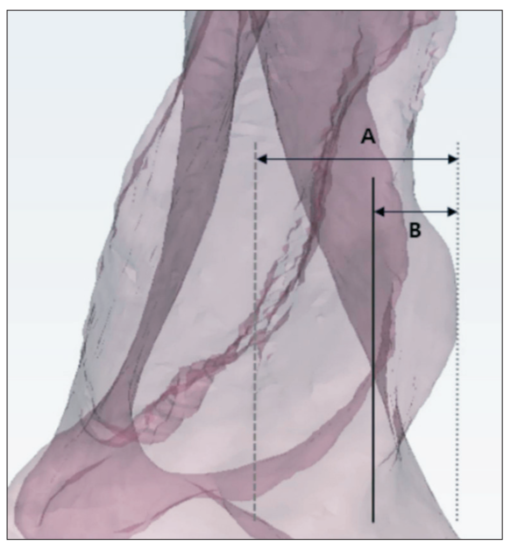

Fig. 7. Tear drop ratio (A/B). The ratio of the distance between a vertical line (gray dashed line) over the center point of the tear drop and the anterior inferior iliac spine (AIIS; gray dotted line) to that between a vertical line (black line) over the lateral border of the tear drop and the AIIS (gray dotted line).

Table 1. Maximum Acceptable Diameter (mm) Depending on TDI (5 mm and 10 mm)

Variable	Right pelvis			Left pelvis		
	TDI of 5 mm	TDI of 10 mm	*p*-value*	TDI of 5 mm	TDI of 10 mm	*p*-value*
Male	16.5 (14–20.3)	17.5 (16.3–20.3)	0.538	17.5 (16–19.3)	18.4 (15.8–21.5)	0.469
Female	13.5 (13–16)	14 (14–15)	0.451	14.5 (13–17)	14.5 (12.8–17)	0.939
p-value†	0.012	0.003		0.020	0.022	

Values are presented as median (interquartile range).
TDI: tear drop index.
*Comparison between TDI of 5 mm and 10 mm (Mann-Whitney test). †Comparison between sexes (Mann-Whitney test).

Table 2. Maximum Acceptable Length (mm) Depending on TDI (5 mm and 10 mm)

Variable	Right pelvis			Left pelvis		
	TDI of 5 mm	TDI of 10 mm	*p*-value*	TDI of 5 mm	TDI of 10 mm	*p*-value*
Male	122.02 (116.58–128.52)	113.73 (109.31–121.37)	0.028	124.45 (118.81–127.29)	115.00 (109.41–119.55)	0.010
Female	107.05 (100.31–127.35)	111.73 (107.20–129.23)	0.226	104.20 (85.87–131.71)	113.19 (105.90–126.58)	0.406
p-value†	0.082	0.762		0.151	0.821	

Values are presented as median (interquartile range).
TDI: tear drop index.
*Comparison between TDI of 5 mm and 10 mm (Mann-Whitney test). †Comparison between sexes (Mann-Whitney test).

Table 3. Tear Drop Ratio Depending on TDI (5 mm and 10 mm)

Sex	TDI of 5 mm	TDI of 10 mm
Male	3.40 ± 0.41	2.26 ± 0.17
Female	3.35 ± 0.26	2.14 ± 0.12

Values are presented as mean ± standard deviation.
TDI: tear drop index.

DISCUSSION

Although the free-hand technique has been reported to be a safe and effective method for SPF, such as IS or S2AIS insertion,[12,14,21] it was observed that radiological guidance would be required for pathological extremes, such as trauma, tumor, and anatomical variations.[13] The tear drop view, a passage from the PSIS to the AIIS, is used to secure the trajectory for the insertion of the IS or S2AIS.[16] Although the tear drop view is a widely used radiographic view for SPF or acetabular surgery,[20,22] there is a lack of literature documenting a definition of the standard tear drop view and guidelines to obtain this view intuitively. Therefore, if a reliable standard for the ideal tear drop view is established, it would be possible not only to ensure the correct direction of screws, but also to decrease the number of radiographs taken to obtain this view, reducing subsequent radiation exposure to both surgeons and patients. Moreover, the current study is the first to suggest guidelines that surgeons can utilize in the actual surgical field.

It has been reported that screws with a larger diameter and longer length achieve greater fixation strength, leading to lower loosening rates and higher fusion rates.[17-19] Therefore, IS or S2AIS with a larger diameter and a longer length would be preferable for those requiring SPF. Accordingly, an optimal tear drop view was defined as enabling the safe insertion of larger and longer screws in this study. Using reconstruction software, we rotated the 3D reconstructed CT images to find the view guiding the larger and longer screws and converted the 3D images into plane images to mimic intraoperative C-arm fluoroscopy.

The median maximum diameter was not significantly different between the TDI of 5 and 10 mm in both sexes. While the median maximum acceptable length at a TDI of 5 mm was significantly longer than that at a TDI of 10 mm in men, the median maximum acceptable length of 10 mm TDI tended to be longer than 5 mm TDI in women without significant difference. Therefore, the rotation degree that provides an optimal corridor for SPF could differ between men and women. This difference might originate from the anatomical differences of the pelvis between the sexes. Several previous studies have documented differences in the insertion angle of screws for SPF between the sexes. Zhu et al.[23] reported that the trajectory of S2AIS in women was 5° more caudal than that in men in the Asian population. Funao et al.[24] also documented that the insertion angle of S2AIS was significantly different between men and women. Thus, we suggest that the anatomical differences between the sexes should be considered when determining the screw size and insertion angle pre- and intraoperatively.

Despite the difference in the rotation degree providing the maximum length between the sexes, the measured maximum length of the corridor, all longer than 80 mm, was generally sufficient to secure a satisfactory length, regardless of the amount of rotation. Therefore, it is reasonable to assume that a corridor with sufficient length can be obtained as long as a corridor for screw insertion can be secured. This situation can be achieved when the shape of the tear drop is clearly visible while rotating the C-arm fluoroscopy. Accordingly, a tear drop view with the largest acceptable diameter would be considered as a safe and optimal tear drop with a spacious corridor providing an enough permissible range of insertion trajectory in SPF. Both TDI values of 5 and 10 mm appear to be acceptable, as they can embrace a corridor with a sufficiently large diameter without significant difference.

Although we introduced the TDI to facilitate the estimation of the amount of rotation in the plane image, it is still difficult to measure the TDI by millimeters on fluoroscopic images intraoperatively. Moreover, it can vary depending on the degree of magnification or reduction of the intraoperative fluoroscopic images. Instead, we assumed that it would be more practical to evaluate the TDI as a ratio compared to another related parameter. Therefore, the concept of TDR was adopted to assess the degree of rotation on the plane image in an easier manner, and relatively constant values were obtained at each TDI. For intuitive application to the actual surgical field, we suggest rounding off the measured values to a TDR of 2.5 to 3. However, because our sample size was too small and TDR is an unofficial parameter, further studies are necessary to verify TDR as a reliable parameter. In addition, although adjusting the rotation of the C-arm fluoroscopy within this range of TDR intraoperatively seems feasible, it is still far from pinpoint accuracy. Therefore, another parameter that represents rotation better than TDR may be developed in the future.

The maximum acceptable screw diameter in men was significantly larger than that in women at every rotation. In addition, there was a tendency for the maximum acceptable length in men to be longer than that in women, although this was not statistically significant. These results are consistent with those of previous studies. In Funao et al.'s report [24] using 3D CT analysis, the maximum length and minimal intraosseous area on the perpendicular plane of the S2AIS pathway were significantly longer and larger in men and women. Wang et al.[25] also indicated that the modified sacroiliac screws, measured on the 3D pelvis model, were thicker and longer in men than in women, suggesting that it would stem from the anatomical differences between the sexes.

Forty pelvises from randomly selected 20 individuals were included to evaluate the general anatomy of the pelvis rather than extreme variations. Although the anatomy and alignment of the lumbosacral area can be different between healthy individuals and patients requiring SPF, the sacropelvic anatomy, a key of SPF, would not change much with the advancement of degeneration. In addition, the number of samples was relatively small to generalize the measured values of the maximum acceptable diameter and length in this study. However, it was shown that the defined optimal tear drop view would provide a satisfactory screw diameter and length for sufficient stability of SPF. Moreover, the authors performed several SPF surgeries using this concept and confirmed satisfactory results in postoperative CT (Fig. 8); however, the number of cases performed was too small to support our principle impeccably. A subsequent future study with a larger number of patients will be required to validate the results of this study and provide more reliable values.

Three-dimensional reconstruction techniques have been extensively utilized in various medical fields, includ-

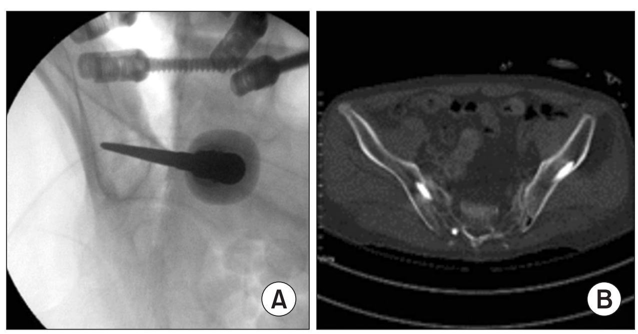

Fig. 8. A 63-year-old male patient who underwent spinopelvic fixation for long arthrodesis extending to the sacrum. (A) Intraoperative C-arm fluoroscopic image showing an instrument targeting toward the center of the tear drop. (B) Postoperative computed tomography scan showing the appropriate location of spinopelvic fixation screws.

ing spinal surgery and SPF.[26] Several authors have utilized a 3D pelvis model or CT images to analyze the parameters and angles for various SPF techniques.[23-25,27,28] In addition, Bow et al.[16] reported the efficacy of a 3D-printed simulator and teaching module for S2AIS. It is meaningful that the results of our study can be utilized not only in preoperative planning, but also intuitively in the actual surgical field, since we simulated the situation of the SPF procedure with intraoperative C-arm fluoroscopy.

This study has several limitations. First, since we included only the Korean population, it is unreasonable to generalize our results to non-Asian populations. Second, the sample size for the pilot validation was relatively small, as described above. Third, although our results suggesting the optimal tear drop view could help to readily find the view in the actual surgical field, the SPF procedure itself is still challenging. Thus, a technique that enables surgeons to easily target the center of the tear drop needs to be developed. Despite these limitations, we suggested the basic prerequisites of the tear drop view allowing safe SPF and validated the realizability of our concepts by simulation with a 3D pelvis model. In addition, it was confirmed that a corridor with a satisfactory diameter and length could be acquired from our defined optimal tear drop view. Consequently, this study is the first to suggest the optimal tear drop view for surgeons operating on the spine to implement intuitionally in the real surgical field using C-arm fluoroscopy, allowing the insertion of screws with maximum diameter and length to secure sufficient stability of SPF.

The safe optimal tear drop view could be the one providing a corridor with the largest diameter with the inferior tear drop line not below the acetabular line and the lateral tear drop line medial to the AIIS. This view can be acquired with a TDR of 2.5 to 3 by rounding off the measured value for intuitive applications. Notably, a thorough preoperative evaluation of an appropriate screw diameter and length and consideration of anatomical differences between the sexes are essential for safe SPF surgery.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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