

Comparison of Acetabular Morphology Changes After Pediatric Pelvic Osteotomies Using Patient-Specific 3-D Models

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Abstract:

Background: Surgical management to improve hip joint morphology in immature patients with acetabular dysplasia includes Pemberton, Dega, San Diego, and Salter acetabular osteotomies. This study evaluates acetabular morphology between these osteotomies using patient-specific 3-D printing technology.

Methods: Preoperative computed tomography scans (CTs) from patients with acetabular dysplasia were rendered into 3-D printable formats. Quadruplicate pelvis models for each patient received Pemberton, Dega, San Diego, and Salter osteotomies. CTs were obtained of each model before and after osteotomy. Acetabular volume and regional coverage angles were computed and compared before and after each osteotomy.

Results: Fourteen hips (14 patients) were included: 1 male, 13 female, age 5.4±1.3 years (3.9-7.5 years). Acetabular volume decreased following each osteotomy (Pemberton by 14%, Dega by 19%, San Diego by 19%, and Salter by 6%), with a smaller volume reduction for Salter than the others ($p<0.05$). Volume change was similar between Pemberton, Dega, and San Diego ($p=0.32$). Pemberton increased coverage in Superior and Anterior regions; Dega increased coverage in Superior, Superior-Anterior, and Anterior regions; San Diego increased coverage in Posterior, Superior-Posterior, and Superior regions; and Salter increased coverage in Superior region ($p<0.05$).

Conclusions: Acetabular volume changes found in this study support the convention that redirectional osteotomies such as Salter are more volume neutral than incomplete osteotomies such as Pemberton, Dega, and San Diego. However, even the Salter decreased acetabular volume. This study re-demonstrated that each osteotomy studied,

changes acetabular coverage in different regions. Based on this, a surgeon's osteotomy decision should be based on the dysplastic acetabulum morphology.

Level of Evidence: Level III: Case-control study

Key Concepts:

- Redirectional osteotomies, such as the Salter, are more volume neutral than incomplete osteotomies such as the Pemberton, Dega, and San Diego.
- The Salter decreases acetabular volume.
- Each osteotomy used for correction of hip dysplasia changes acetabular coverage in different regions.
- Differences in volume changes and acetabular coverage between osteotomies should be taken into account during surgical planning to optimize patient-specific dysplasia.

Introduction

Developmental dysplasia of the hip (DDH) is a pediatric disorder that encompasses a spectrum of hip joint abnormalities in which the femoral head and acetabulum have an abnormal anatomical relationship.¹⁻⁴ Incidence of DDH ranges from 1 to 34 cases per 1,000 live births.¹ Development of the hip joint is determined by the presence of a reduced femoral head within the acetabulum and interactions between the acetabulum and femoral head.⁵⁻⁸ An abnormal anatomical relationship can result in a flattened acetabular morphology, with resulting hip instability leading to gait and functional abnormalities.⁵⁻⁸ Untreated acetabular dysplasia can lead to hip pain and early-onset osteoarthritis of the joint.³

Treatment for acetabular dysplasia focuses on concentric reduction of the hip joint allowing for improved acetabular development.⁴ First-line treatment in children under 6 months of age is Pavlik harnessing or other nonsurgical means of maintaining the hip joint dynamically immobilized in a flexed and abducted position.⁴ Children that fail treatment with a Pavlik harness or other nonsurgical means may require closed or open reduction followed by casting or further bracing. If dysplasia persists following reduction, treatment includes acetabular re-orientation as is done with pelvic osteotomies.⁷ Children with open triradiate cartilage

are often treated with a Pemberton, Dega, or San Diego osteotomy, all of which are incomplete or reshaping osteotomies which hinge the acetabulum through the flexible triradiate cartilage to improve acetabular coverage of the femoral head (Figure 1).⁹ In contrast, the Salter osteotomy uses a complete or redirectional osteotomy to increase coverage, which has traditionally been considered to be volume neutral.⁹

Three-dimensional (3-D) printing technologies have enabled use of patient-specific models in research and clinical care. Specifically, several studies have demonstrated improved surgical and trauma outcomes when preoperative planning includes patient-specific 3-D printed models.¹⁰⁻¹⁸ A major benefit of 3-D printing technology is enabling comparative analysis of surgical outcomes where it was not possible. Specifically, 3-D printing technology allows for replicate models from the same patient to undergo multiple procedures, whereas previous studies were limited in that a single patient can only undergo one procedure. This allows for direct comparison of morphological or radiologic outcomes of different procedures. The purpose of the current study is to compare the morphological 3-D outcomes of the Pemberton, Dega, San Diego, and Salter osteotomies with mock surgeries on patient-specific 3-D printed

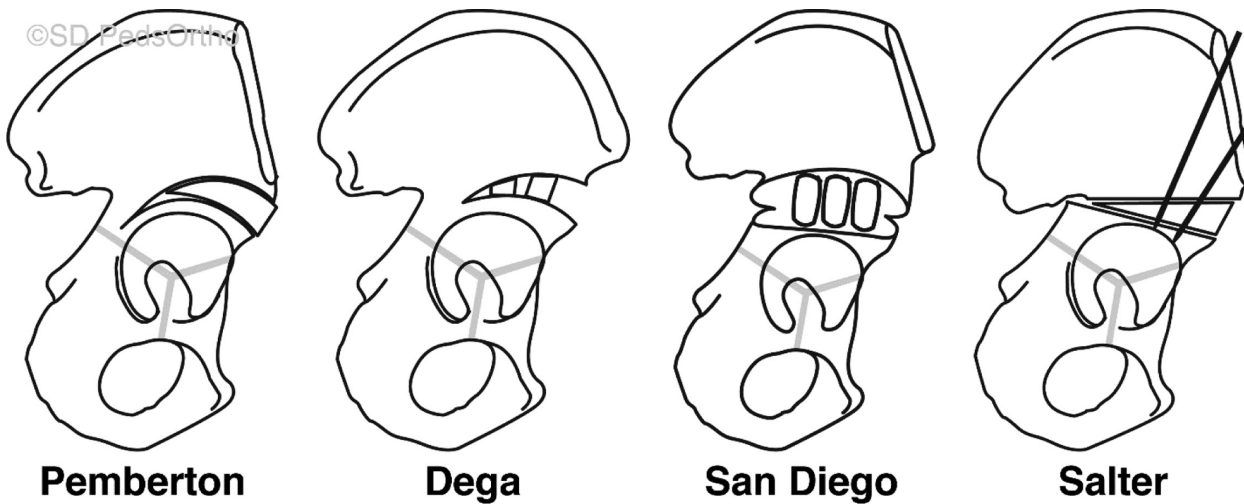


Figure 1. Pelvic osteotomies used to treat residual acetabular dysplasia in children.

dysplastic pelvic models, testing the null hypothesis that all the osteotomies would result in equivalent changes in acetabular coverage and volume.

Materials and Methods

This single-center retrospective cohort study was approved by our Institutional Review Board before initiation. This study included patients with a diagnosis of acetabular dysplasia and a preoperative pelvic CT scan from 2007 to 2015. These patients were treated with an acetabuloplasty (Pemberton, Dega, San Diego, or Salter). Subjects were excluded in this study if they did not have a preoperative computed tomography (CT) scan or their CT scan had insufficient resolution for 3-D reconstruction. For patients with bilateral dysplasia, only the right hip was included in this study.

Each CT scan was processed into a 3-D printable format as described in Caffrey et al.¹⁹ Briefly, for each patient CT scan, bone and cartilage tissues were separately processed into a 3-D printable format (G-code) using Mimics version 19.0 (Materialise, Leuven, Belgium) and Simplify3D software (Simplify3D, Cincinnati, OH).

3-D Model Printing

A quadruplicate set of pelvises were 3-D printed from the G-code files for each patient using a dual-extrusion printer (TAZ 4; Lulzbot, Loveland, CO). Dual extrusion

allowed for simultaneous and interlaced printing of stiff and flexible materials into a single object. Rigid acrylonitrile butadiene styrene (ABS) material was used to simulate bone and a flexible thermoplastic polyurethane (TPU) material was used to simulate the triradiate cartilage and pubic symphysis (Figure 2). Triangular fill pattern at 20% volume fill for bone and 0% volume fill for cartilage were selected to best mimic the cutting properties of bone and the flexibility of the cartilage based on qualitative assessment by the senior surgeon after performing mock osteotomies on printed blocks with multiple fill pattern and fill volume combinations. Pre-mock surgery CT scans of each 3-D print were acquired in a similar fashion to patient preoperative CT imaging.

Mock Surgery

Mock Pemberton, Dega, San Diego, and Salter osteotomies were performed on the quadruplicate set of 3-D prints for each patient by a fellowship-trained pediatric orthopaedic surgeon using the originally described surgical technique for each osteotomy (Figure 3 top). The osteotomies were started with an oscillating saw. Once the outer cortex had been breached, straight and curved osteotomes were used to complete the bending acetabuloplasties. The Pemberton osteotomy was performed through the medial and lateral cortex of

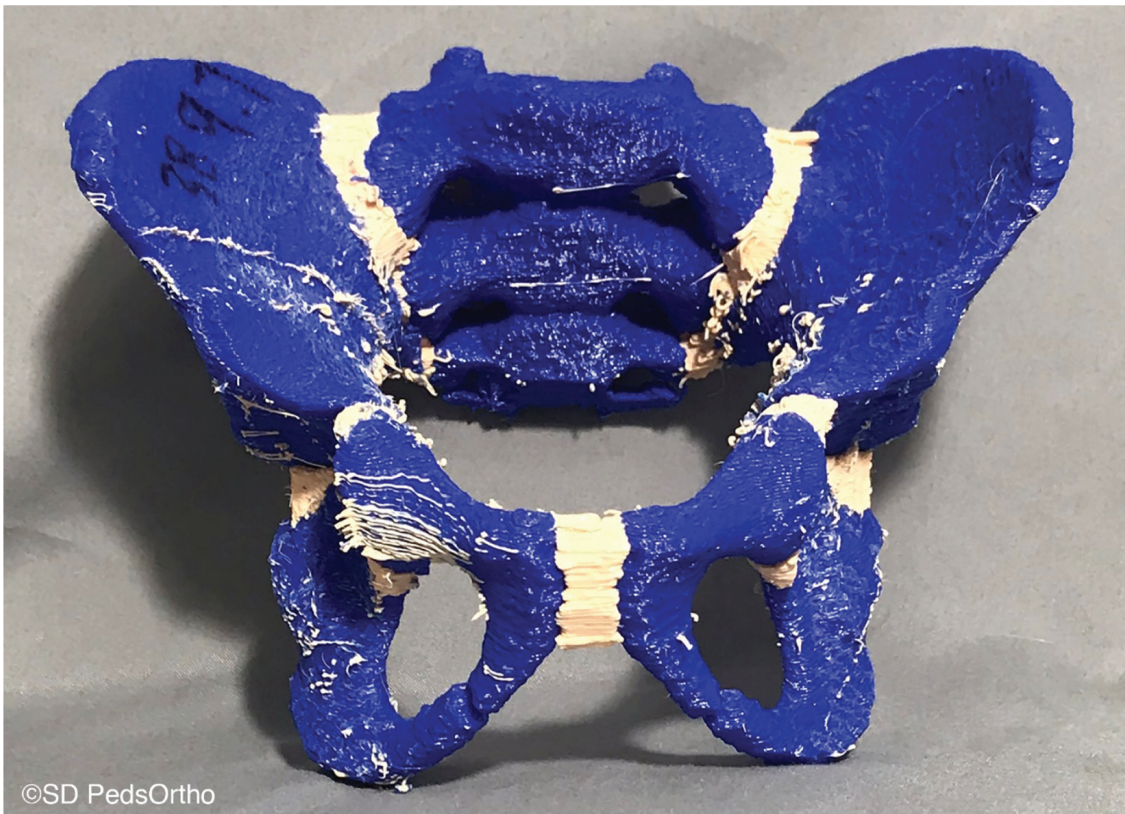


Figure 2. 3-D printed pelvis with rigid ABS for bone (blue) and more flexible TPU (tan) for cartilage.

the ilium starting between the anterior superior iliac spine (ASIS) and anterior inferior iliac spine (AIIS), extending the cut posteriorly and ending by curving inferiorly toward the transverse limb of the triradiate cartilage, stopping just short of the cartilage. The Dega osteotomy was performed through the lateral cortex of the ilium, starting between the ASIS and AIIS but stopped 1 cm short of the greater sciatic notch. The San Diego osteotomy was performed by cutting the medial and lateral cortex of the ilium at the AIIS and greater sciatic notch. Between these two structures, the lateral cortex was hinged open. The Salter osteotomy was performed by dividing the ilium from the greater sciatic notch to the AIIS. A standardized triangular 3-D printed bone graft measuring 10 mm × 20 mm × 20 mm (height × width × depth) was used for all models to ensure a similar magnitude of correction for all patients and surgical approaches. Post-mock surgery CT scans were acquired for each 3-D print.

Morphological Evaluation

Acetabular volume and octant coverage angles were measured and quantified on the operative side from preoperative and postoperative CT scans of the 3-D prints as described previously.^{20,21} Each CT scan was reconstructed using Mimics software (Figure 4A) and evaluated using a custom MATLAB algorithm (MATLAB R2014; MathWorks, Natick, MA), which was previously validated.^{20,21} Briefly, acetabular articular surfaces on the pelvic reconstructions were automatically identified and a best-fit sphere utilizing least-squares regression was used to approximate the acetabulum center of rotation and to calculate the volume of the acetabulum (Figure 4B). Specifically, acetabular volume was calculated as the hemispheric volume of a best-fit sphere. Coverage angles were defined and measured as the angle between a line connecting the edge of the acetabulum with the center of rotation of the acetabular best-fit sphere and a line connecting the centers of

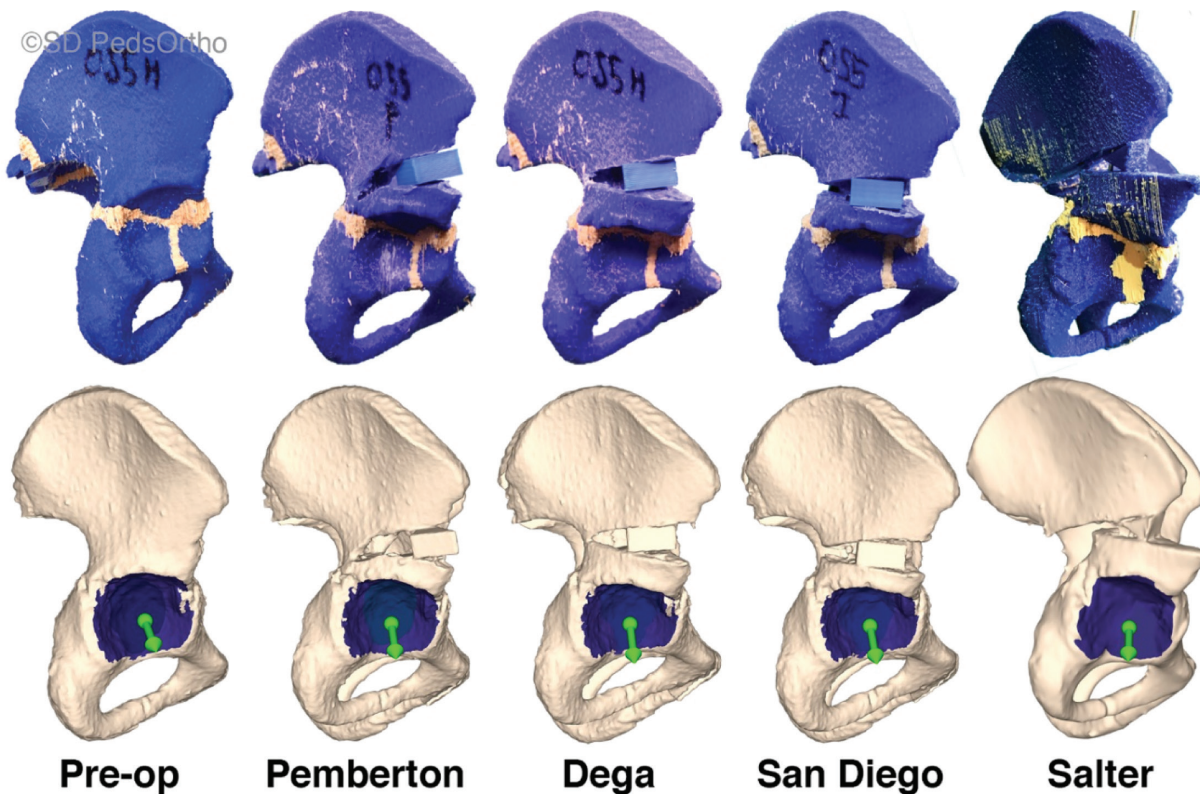


Figure 3. Top: 3-D printed hip with dysplasia and after Pemberton, Dega, San Diego and Salter osteotomies showing placement of triangular bone graft (10 x 10 x 20 mm). Bottom: Corresponding 3-D renderings from CT images of each printed model showing acetabular surface area (blue) and acetabular direction vector (green arrow).

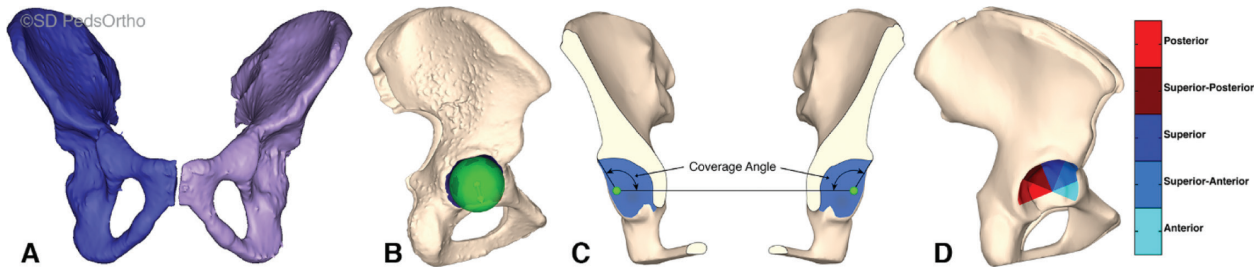


Figure 4. A) reconstruction from the CT scan showing the right and left hemipelvis segmented. B) 3-D rendering of CT scan showing best-fit sphere, acetabulum center of rotation and acetabular direction vectors. C) Coronal cross section of 3-D model illustrating coverage angle calculation. D) Diagram of the five clinically pertinent coverage angle octants of the acetabulum.

rotation of the right and left acetabulum best-fit spheres (Figure 4C). The five weight-bearing octants were measured and classified as superior (S), superior anterior (SA), anterior (A), posterior (P), and superior posterior (SP) regions (Figure 4D). The three inferior regions (IA, I, and IP) were not included in analysis as they do not provide weight-bearing coverage and are therefore not clinically relevant.

Statistical Analyses

Previous work defined normal acetabular coverage by sex (male and female) and age (8 to 17 years old);²⁰ however, the current evaluation included patients less than 8 years of age, so comparisons were not made to normal values but rather change in coverage angle and acetabular volume within and between osteotomy groups. Pre- to postoperative changes for each procedure

were compared using repeated measures ANOVA (for normally distributed data) or the Friedman test (for non-normally distributed data). When evaluating the magnitude of the postoperative change among procedures, ANOVA with the Bonferroni post hoc test or the Kruskal-Wallis and Mann-Whitney tests were used for normal and non-normal data, respectively. Analysis was performed using IBM SPSS (version 26; IBM, Armonk, NY). Significance was set at $\alpha=0.05$ for all tests. Data are reported as mean \pm SD.

Results

Fourteen hips in 14 patients were included, mean age 5.4 ± 1.3 years (range: 3.9 to 7.5 years, Table 1). Acetabular volume decreased significantly from the preoperative volume in all cases: Pemberton ($-1375 \pm 1330 \text{mm}^3$, -14%), Dega ($-1816 \pm 1328 \text{mm}^3$, -19%), San Diego ($-1877 \pm 1238 \text{mm}^3$, -19%), and Salter ($-537 \pm 934 \text{mm}^3$, -6%) (Table 2). Acetabular

volume decrease for the Salter was less than each other osteotomy ($p < 0.05$). The changes in acetabular volume for the Pemberton, Dega, and San Diego were not significantly different from each other (Table 3).

Compared to preoperative mean coverage angles, the postoperative mean coverage angles varied across several regions ($p < 0.05$ all comparisons). The San Diego had greater coverage in the posterior (P) ($75.4^\circ \pm 8.8^\circ$ to $79.0^\circ \pm 7.4^\circ$, $+3.6^\circ$ change), superior-posterior (SP) ($81.9^\circ \pm 9.5^\circ$ to $92.6^\circ \pm 9.3^\circ$, $+10.7^\circ$ change), and superior (S) ($98.6^\circ \pm 9.2^\circ$ to $111.1^\circ \pm 12.8^\circ$, $+12.5^\circ$ change) regions. The Salter had greater coverage in the S region ($98.6^\circ \pm 9.2^\circ$ to $102.6^\circ \pm 7.3^\circ$, $+10.7^\circ$ change). The Pemberton increased coverage in the S ($98.6^\circ \pm 9.2^\circ$ to $106.6^\circ \pm 9.7^\circ$, $+8.0^\circ$ change), superior-anterior (SA) ($74.0 \pm 12.1^\circ$ to $91.0^\circ \pm 16.7^\circ$, $+17.0^\circ$ change), and anterior (A) ($45.8^\circ \pm 8.9^\circ$ to $50.7^\circ \pm 11.7^\circ$, $+4.9^\circ$ change) regions. The Dega increased coverage in the S ($98.6^\circ \pm 9.2^\circ$

Table 1. Clinical Cohort Characteristics

Subject	Side	Sex	Age*	Previous	Volume	Posterior	Superior-	Superior	Superior-	Anterior
				Treatment	(mm^3)		Posterior		Anterior	
1	R	F	5.0	PH	7887.3	84.9°	92.6°	102.7°	58.5°	42.5°
2	R	F	4.6	HAB, CR, HAB	9680.5	64.8°	78.3°	93.0°	57.8°	39.3°
3	R	F	6.4	CR, HAB	11094.9	71.7°	78.4°	99.1°	80.5°	56.8°
4	R	F	3.9		6727.9	65.4°	63.5°	74.3°	68.6°	32.9°
5	R	F	7.5	CR, HAB	9981.4	90.1°	97.2°	106.6°	88.1°	60.7°
6	R	F	6.0	PH, HAB	9345.6	82.2°	89.0°	108.8°	92.1°	58.8°
7	L	F	5.7		7721.2	70.5°	73.1°	92.0°	73.9°	35.4°
8	R	F	5.2	PH, CR, HAB	9511.2	65.8°	68.4°	90.3°	61.6°	38.8°
9	R	F	6.9		12976.1	80.9°	85.3°	102.3°	81.0°	48.1°
10	R	F	6.7	PH	9613.3	79.1°	85.6°	110.0°	87.3°	54.0°
11	R	M	5.0	CR	7886.5	84.8°	93.0°	102.7°	57.9°	42.3°
12	R	F	7.3	OR, VDRO, HAB	12612.7	62.0°	79.4°	95.9°	74.1°	38.3°
13	R	F	4.1	HAB, CR, HAB	8241.3	78.4°	81.8°	102.4°	85.9°	48.7°
14	R	F	7.1	PH, HAB	13117.7	74.6°	81.1°	99.7°	68.6°	44.8°

*Age in years at time of CT, CR=Closed Reduction, HAB=Hip Abduction Brace, OR=Open Reduction, PH=Pavlik Harness, VDRO=Varus Derotational Osteotomy.

Table 2. Pre- to Postoperative Volume Difference By Osteotomy

	Mean±SD	% different	Median	Sig.*
Pemberton	-1375.2±1329.9	14%	-1428.4	0.009
Dega	-1816.3±1328.1	19%	-1932.6	0.004
San Diego	-1876.7±1238	19%	-2149.0	0.002
Salter	-537.3±934.2	6%	-589.2	0.016

*Difference between pre- and postop value.

Table 3. Comparison of Pre- to Postoperative Volume Differences Between Osteotomies

Reference	Comparison	Mean Difference*	% Change*	Sig.
Salter	Pemberton	837.9	7.6%	0.009
	Dega	1279.0	13.0%	0.001
	San Diego	1339.5	13.3%	0.004
Pemberton	Salter	-837.9	-7.6%	0.009
	Dega	441.2	5.4%	0.352
	San Diego	501.6	5.6%	0.329
Dega	Salter	-1279.0	-13.0%	0.001
	Pemberton	-441.2	-5.4%	0.352
	San Diego	60.4	0.3%	0.91
San Diego	Salter	-1339.5	-13.3%	0.004
	Pemberton	-501.6	-5.6%	0.329
	Dega	-60.4	-0.3%	0.910

*Difference between reference group and comparison.

to 106.9°±12.7°, +8.3° change), SA (74.0°±12.1° to 97.3°±13.6°, +23.3° change), and A (45.8°±8.9° to 53.4°±11.3°, +7.6° change) regions. The percent of postoperative change in coverage is listed in Table 4.

Discussion

Patient-specific 3-D print technology provides a unique opportunity to quantitatively compare the acetabular volume and shape changes between four commonly performed pediatric pelvic osteotomies for acetabular dysplasia²² (Figure 3). Unique material properties and technologies allowed for the printing of patient-specific

skeletally immature pelvis models that could be imaged and operated on similar to a pediatric pelvis. Specifically, ABS, a common plastic material used in additive manufacturing, has been shown to imitate the cutting properties of bone using a surgical oscillating saw¹⁴ and is easily imaged.¹⁹ Additionally, a dual-nozzle printing head allows for ABS to be extruded simultaneously with more flexible materials (TPU) to create composite anatomic models. The rigid features (ABS) allow the models to be cut with a saw (similar to bone) and the flexible cartilage-like features (TPU) allow the use of bending and wedging. Therefore, these models may

Table 4. Percent Postoperative Change in Coverage for Each Procedure in Each Pertinent Region

	Surgery	Mean±SD	Median	Sig.
Posterior	Salter	-3.2±14.1%	2.0%	0.330
	Pemberton	0.4±8.8%	1.5%	0.363
	Dega	-.3±7.8%	2.0%	0.875
	San Diego	5.6±9.4%	6.5%	0.026
Superior-Posterior	Salter	0.6±9.3%	0.0%	1.000
	Pemberton	0.4±9.8%	2.0%	1.000
	Dega	-0.7±9.7%	0.5%	1.000
	San Diego	13.6±10.1%	17.0%	0.002
Superior	Salter	4.5±5.1%	3.5%	0.006
	Pemberton	8.3±6.0%	9.0%	0.002
	Dega	8.4±6.4%	7.5%	0.003
	San Diego	12.7±5.9%	13.5%	0.001
Superior-Anterior	Salter	11.6±16.5%	12.5%	0.171
	Pemberton	24.5±23.7%	25.5%	0.008
	Dega	32.9±16.8%	29.0%	0.000
	San Diego	5.9±26.6%	7.0%	1.000
Anterior	Salter	-2.4±10.0%	-1.5%	1.000
	Pemberton	10.1±12.0%	12.0%	0.020
	Dega	16.9±13.0%	17.0%	0.002
	San Diego	1.1±20.1%	3.0%	1.000

better imitate the mechanical and structural properties of the developing pelvis than a single material rigid print.

The results of this study support the conventional belief that redirection osteotomies such as the Salter are more volume neutral than incomplete osteotomies such as the Pemberton, Dega, and San Diego. However, this study showed that even the Salter osteotomy, a redirection osteotomy, decreased acetabular volume. This is likely due to rotation of the hemi-pelvis through the pubic symphysis, resulting in a more “cup-shaped” acetabulum. The acetabular volume changes observed in this study are dependent on the technique used to measure this change. The volume of the hemisphere that best fit within the

boundaries of the acetabulum was calculated. In a flatter, more dysplastic acetabulum, a larger best-fit sphere would be fitted. In comparison, in a better formed, “cup-shaped” acetabulum, the best-fit sphere would decrease in size, and therefore, volume. Additionally, this study redemonstrated that each osteotomy used for correction of acetabular dysplasia uniquely changed acetabular coverage in the different regions.

Several subtypes of acetabular dysplasia have been described based on the location of acetabular coverage deficiency: most notably global deficiencies and deficiencies in the anterosuperior and posterosuperior regions.^{23,24} Differences in volume changes and

acetabular coverage between osteotomies may have important implications in outcomes for correctional surgery and should influence surgical planning to optimize surgical outcomes of patient-specific dysplasia. Acetabular volume and the specific subtype of coverage deficiency should be specifically identified during surgical planning and an osteotomy should be selected to correct the deficiency. For example, the data suggest that a San Diego osteotomy may better treat posterosuperior deficiencies that are commonly observed in children with cerebral palsy and spastic hip instability. On the other hand, the Pemberton or Dega osteotomies may better treat anterior deficiencies that are commonly observed in children with typical developmental dysplasia of the hip.

While these osteotomies are regularly used as surgical treatment for acetabular dysplasia, the differences in volume and coverage yielded by each surgical technique, specifically the Salter, have not previously been quantified. This study leverages a dual material 3-D printing platform to quantify these differences. Furthermore, these same morphological measurements can be performed on patient CT scans to define coverage deficiencies and volume of dysplastic hips before surgical correction. Combined with the knowledge of postoperative changes, patient specific analysis should ultimately result in the selection of the best procedure that will result in optimal coverage and volume.

This study has some limitations which should be addressed. The two plastic materials used as analogs for bone and cartilage tissues were not biomechanically assessed for similarity to such tissues. Emerging technologies utilizing material jetting, instead of material extrusion, may provide for more realistic and mechanically-validated materials.²⁵ Additionally, this study focused on the bony and cartilage tissues, without the complexity of spanning muscular and ligamentous tissues, which may contribute to postoperative morphological changes. However, this study compares the same models prior and following the surgical procedure, thus allowing a direct comparison between the techniques that would be difficult to mimic, even in an animal model. One study in immature porcine

pelvis tissue found the acetabular volume did not change following Pemberton osteotomy. However, these were not dysplastic acetabuli and the porcine morphology is not shown to be identical to the human child.²⁶ All mock surgeries were performed with identical bone grafts (10 x 10 x 20 mm). While this allowed for standardized comparisons between the four osteotomies, this may not simulate intra-operative techniques. It may be valuable to study the variation in acetabular volume and morphology that occur with different sized grafts for a given surgical technique. Lastly, the surgical techniques used in this study were limited to their original descriptions. Several modifications have been since described to these commonly performed surgeries. For example, the Dega osteotomy can be extended into the sciatic notch, which is thought to give better superior posterior coverage. Similarly, a larger anterior bone graft has been described with the San Diego osteotomy to give better superior anterior coverage.²⁷

The current study directly quantified the differences in acetabular volume and morphology for four commonly performed osteotomies for acetabular dysplasia. We found that all osteotomies decreased acetabular volume, with reshaping osteotomies (Pemberton, Dega, San Diego) resulting in a greater volume decrease compared to the Salter redirection osteotomy. Unique differences in acetabular coverage were observed between the four osteotomies and should be considered during surgical planning to perform patient-specific corrections that more appropriately address each patient's acetabular deficiencies.

Additional Links

- *Comparison of Acetabular Changes in Pediatric Pelvic Osteotomies Using Patient Specific 3D Models*—<https://youtu.be/j1sAPdxE0Nk>
- *Assessment of Three-Dimensional Acetabular Coverage Angles*—<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7605764/>
- *Helen and Will Webster Foundation 3D Innovations Lab at Rady Children's Hospital-San Diego*—<https://www.rchsd.org/programs-services/3d-print-lab/>

Disclaimer

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