The Anatomy of the Acetabulum

What is Normal?

Viktor Krebs MD, Stephen J. Incavo MD,
William H. Shields BS

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Abstract Published studies of the human hip make frequent reference to the normal pelvis and acetabulum. However, other than qualitative descriptions we found no clinically applicable published references describing a normal pelvis and acetabulum; such information is important for designing certain kinds of implants (eg, reconstruction cages). We describe a method to quantify, average, and apply data gathered from normal human specimens to create a standard representation of the ilium and ischium. One hundred healthy hemipelves from 50 human skeletons were evaluated. We measured angles and distances between major anatomic landmarks in the pelvis. The data collected were analyzed for variance and averaged to create a normal topographic map. Finally, we examined several commercially available acetabular reconstruction

cages to determine the fit to the anatomically determined normal pelvis. These results provide a representation of true acetabular geometry and may serve as the basis for future acetabular reconstruction cage design.

Introduction

An estimated 160,000 to 170,000 primary hip arthroplasties and 29,000 revision hip arthroplasties are performed annually in the United States [1]. Despite this, little published information exists concerning the anatomic features of the human pelvis. Several anthropomorphic studies have discussed variability of the shape and size of the human pelvis, but we have found no quantitative analysis of the periacetabular bony anatomy [3, 4, 6, 15].

Topographic features of the ilium, ischium, and pubis as they relate to the acetabulum and its center are important for properly reconstructing the hip [4, 10, 15]. The angular relationships of these bones are important for implant fixation. These relationships are even more important in implant revisions where the normal anatomy often is altered or damaged and is virtually devoid of the reference points seen in the minimally compromised, or normal, hip.

In quantitatively describing normal anatomy, we posed four specific questions: (1) What is the pelvic bone topography (outer table) and how does it relate to acetabular orientation (abduction and anteversion)?; (2) What bone is available and best suitable for fixation in the region of the acetabular dome and anterior and posterior columns?; (3) Do gender and/or race differences exist in pelvic anatomy?; and (4) Do currently available acetabular cages match normal pelvic anatomy?

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Each author certifies that his or her institution has approved or waived the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research.

V. Krebs
Division of Reconstructive Surgery, Cleveland Clinic,
Cleveland, OH, USA

S. J. Incavo
Weill Cornell Medical College of Cornell University, New York,
NY, USA

S. J. Incavo (✉)
Adult Reconstructive Surgery, The Methodist Hospital,
6550 Fannin, 25th Floor, Houston, TX 77030, USA
e-mail: sjincavo@tmhs.org

W. H. Shields
Stryker Orthopaedics, Mahwah, NJ, USA

Materials and Methods

To create a standard representation of the periacetabular bone, a topographic map of the bone surfaces was created in relation to the acetabular cavity. We then characterized and mapped anatomically distinct acetabular regions used for acetabular fixation (superior dome, anterior and posterior columns). Finally, we compared the shapes of commercially available reconstruction cages to that of the modeled normal acetabular structure.

One hundred hemipelves from 50 specimens were measured. All measurements were taken on specimens in the Hamann-Todd Osteologic Collection at the Cleveland Museum of Natural History [4, 12]. The collection is the largest of its kind in the world and contains more than 3100 modern human skeletons from the unclaimed dead of Cleveland, OH, from 1912 to 1938. Only healthy pelvises in good condition were used in this study; degraded specimens or those with evidence of pelvic abnormality or disorders were excluded. All specimens in this study also were measured in a previous anatomic study using the collection [10], and the specimen demographics in the current study were similar.

Selection was based on the population receiving THAs in the United States. Specimen age and race were weighted. Four specimens were younger than 40 years, six were between 40 and 49 years, 14 were between 50 and 59 years, 16 were between 60 and 69 years, and 10 were 70 years or older. The average age was 58.8 years (standard deviation, 12.1 years; range, 28–82 years). In each age group, half of the specimens were male and half were female. The race ratio of the specimens was 1:4, 20% African-American and 80% Caucasian. The Hamann-Todd collection does not contain a substantial number of specimens from any other race; therefore, no other races were included in this study.

The method for preparing the specimens for topographic measurement was similar to that used by Maruyama et al. [10]. The hemipelvis and sacrum of each specimen were assembled using rubber bands. Small pieces of foam replaced the cartilage in each joint. The pelvis then was mounted and secured on a measurement table. The anterior superior iliac spine (ASIS) and crest of the pubis were in contact with the horizontal table, establishing the coronal plane. The crest of each ilium was in contact with the vertical backboard, establishing the transverse plane (Fig. 1). The reference point for all measurements was the spherical center of the acetabulum. The center of rotation is the focal point on the pelvic side of the hip and, therefore, our reference point for all measurements.

We placed appropriately sized acetabular trials in the native, unreamed acetabulum. Several different cup sizes were used, the average cup size of 54 mm is similar to the

Fig. 1 The measurement setup we used to determine the topography of the pelvis is shown.

average hemispheric shell used in primary THA. To collect the topographic data, a depth gauge was mounted on a shaft that rotated about the axis of the acetabulum. One end of this device held an acetabular window trial (Stryker Orthopaedics, Mahwah, NJ). The largest window trial that bottomed out in the acetabulum was secured with its face parallel to the face of the acetabulum, making the anteversion and abduction of the window trial equal to that of the native acetabulum. Anteversion of the window trial was measured from the established coronal plane, and abduction was measured from the established transverse plane.

To collect the data points, the depth gauge was swept rotating around the pelvis from the midline of the ischium to the ASIS. We chose the midportion of the ischium as the starting point (0°) because it was easy to identify in all specimens and it is an easily identifiable landmark during surgery. During each sweep, the depth gauge was fixed at a predetermined radius from the center of the acetabulum. Every 10°, the depth gauge was extended down to the bone, collecting a data point. After each sweep, the depth gauge was returned to the 0° mark and was moved out an additional 10 mm from the center of the acetabulum (increasing the sweep radius by 10 mm). Another sweep then was performed. We repeated this process five to six times on each hemipelvis, depending on specimen size and bony anatomy. The collected points created a topographic map of the ilium, from the rim of the acetabulum to beyond the ASIS, and a map of the posterior aspect of the ischium.

A take-off angle, α , was measured that describes the angle between the acetabular opening and the posterior pelvic bone (including the ilium and ischium) 10 to 15 mm from the acetabular rim. These angles were determined by using the second arc from the pelvic curvature map.

We made angle measurements using a custom-made goniometer attached to an acetabular window trial (Stryker

Fig. 2 A pelvic specimen shows the axes used for angular measurements: S1 = superior angle 1, the angle between the top of the sciatic notch and the most prominent ridge on the ilium; S2 = superior angle 2, the angle between the most prominent ridge on the ilium and the ASIS; P = posterior angle, the angle between the top of the sciatic notch and the line bisecting the ischium; I = inferior angle, the angle between the ischial bisection and the superior pubic ramus; and A = anterior angle, the angle between the ASIS and the superior pubic ramus.

Orthopaedics). The face of the trial was placed parallel to the native acetabular rim/opening. The measurements were made in reference to a line that bisected the ischium 1 cm distal to the posteroinferior acetabular rim (Fig. 2). This allowed angular measurements between the specific landmarks. Owing to its importance for acetabular fixation, the superior quadrant was divided into two subregions by the superior iliac column, S1 and S2. This allowed for more detailed analyses of the size, position, and topography of each region. Angular measurements included: superior angle 1 (S1), the angle between the top of the sciatic notch and the most prominent ridge on the ilium; superior angle 2 (S2), the angle between the most prominent ridge on the ilium and the ASIS; posterior angle (P), the angle between the top of the sciatic notch and the line bisecting the ischium; inferior angle (I), the angle between the ischial bisection and the superior pubic ramus; and anterior angle (A), the angle between the ASIS and the superior pubic ramus.

We made all length measurements with digital calipers (Mitutoyo, Kawasaki, Japan). Eight measurements were

Fig. 3 A pelvic specimen shows the length measurements: H = height of acetabulum from the rim at the ischium to the ASIS; W = width of acetabulum from the rim at the pubic ramus to the sciatic notch; PC₁ = posterior column thickness above the ischial spine; PC₂ = posterior column thickness from the deepest point on the sciatic notch; AC₁ = anterior column thickness at the teardrop; AC₂ = anterior column thickness at the junction of the iliac wing; D₁ = distance from the sciatic notch to the anteroinferior iliac spine; and D₂ = distance along the prominence of the iliac wing from the acetabular rim to the superoanterior end of the ilium.

taken on each hemipelvis ($n = 100$) to determine differences between the specified demographics. Length measurements included: height of acetabulum from the rim at the ischium to the ASIS (H), width of acetabulum from the rim at the pubic ramus to the sciatic notch (W), posterior column thickness above the ischial spine (PC₁), posterior column thickness from the deepest point on the sciatic notch (PC₂), anterior column thickness at the teardrop (AC₁), anterior column thickness at the junction of the iliac wing (AC₂), distance from the sciatic notch to the anteroinferior iliac spine (D₁), and distance along the prominence of the iliac wing from the acetabular rim to the superoanterior end of the ilium (D₂) (Fig. 3).

Cross-sectional reconstructions of 10 hemipelves, left and right from five specimens, were created at five intervals from the ischium to the ASIS (0°, 110°, 130°, 140°, and 160°). To create each cross section, the thickness of each pelvis was measured at a series of points along each predetermined interval (0°, 110°, etc.). The thickness measurements then were converted into a smooth curve representing the inner table of the pelvis.

The cross sections were taken at predetermined angles corresponding to the screw hole pattern of multiple commercially available acetabular shells. Each cross-sectional reconstruction was analyzed to determine the acceptable length of dome and rim screws. We based screw positioning on neutral orientation; the axis of the screw is parallel to the axis of the screw hole. The screw length was recorded when it reached either the outer or inner cortex depending on the screw angulation. A 10-mm safety factor also was included. Different screw angles of insertion were not taken into account.

Six commercially available acetabular cage designs were evaluated to determine if and how these designs match the normal pelvis. The acetabular designs tested were DePuy Protrusio (DePuy, Warsaw, IN, USA), Smith and Nephew Contour (Smith and Nephew, Memphis, TN, USA), Sulzer Burch Schneider (Zimmer, Warsaw, IN, USA), Link Partial Pelvis (Link, Hamburg, Germany), Biomet Recovery (Biomet, Warsaw, IN, USA), and Stryker Gap II (Stryker, Mahwah, NJ, USA). Measurements of take-off angles, α , of the implants were compared with the measured acetabular α angles in 10° increments.

To analyze the topographic data, a best-fit line was created using a third-order polynomial regression through the data points collected at each 10° -increment on each hemipelvis. All best-fit lines from the 100 hemipelves were combined and averaged through another third-order polynomial regression to establish the normal topography of the periacetabular bone. Each normal curve was imported into a computer-assisted design program (Pro/ENGINEER® Wildfire 2.0; Parametric Technology Corp, Needham, MA), creating a three-dimensional normal model of the pelvis from the midline of the ischium to the ASIS.

The mean and standard deviation of the angular acetabular regions and length measurements were calculated. We analyzed gender and race differences using an analysis of covariance with age and window trial size treated as continuous variables. The analysis of covariance combined analysis of variance and regression, fitted linear regression models to each group and compared regression groups using the precision of the comparisons of the group means using SAS® software (SAS Institute Inc, Cary, NC). The fit of cage designs were compared by measuring the take-off angles, α , of the implants about the circumference of the acetabulum and comparing these values with the anatomically measured α angles in 10° -increments.

Results

A topographic map was created of the pelvic bones, as determined by measured α angles, and showed a relatively flat anterior topography changing to a more angled

Fig. 4 A topographic map of the pelvic bones surrounding the acetabulum from the ischium to the ASIS is shown. The location of the five cross sections ($\theta = 0^\circ, 110^\circ, 130^\circ, 140^\circ$, and 160°) is identified.

topography moving posteriorly (Fig. 4). Much of the superior and posterior walls of the acetabulum showed substantial angulation producing acetabular anteversion and abduction. This was seen during examination of the α angles that generally ranged from 60° to 80° , except in the most inferior aspects of the acetabulum, which had substantially less angulation (Table 1). The highest angles were in the region of the sciatic notch. Average natural anteversion of the face of the acetabulum was 20.7° (SD 3.8), and average natural abduction was 39.8° (SD 7.0).

The superior acetabular region of the pelvis subtended an average angle of 77° (S1 + S2). The other regions were 95° for angle A, 88° for angle I, 100° for angle P, 49° for S1, and 28° for angle S2 (Table 2). The most prominent portion of the ilium was identified visually as the division between the subquadrants S1 and S2 (49° anterior to the sciatic notch). The cross section (and therefore the area available for screw fixation) was widest between 110° and 160° (Fig. 3). Anterior and posterior column thickness averaged 34.4 and 44.6 mm respectively (Table 3). At 110° , our data showed the inner and outer tables converge somewhat (but never closer than 21 mm), making this an ideal location to place a long screw between the inner and outer walls of the ilium (Fig. 5). The acceptable range of dome and rim screws for a 54-mm acetabular shell ranges from 25 to 50 mm (Fig. 6).

When looking at race differences in absolute terms, PC₁ was 3.3 mm greater ($p = 0.01$) for African-Americans (47.5 mm, SD 6.0 mm) than for Caucasians (44.2 mm, SD 5.3 mm). Race had an effect on Angle S2, and was greater ($p = 0.024$) for African-Americans (an absolute difference of 1.8° larger). Male and female specimens differed, even after window trial size was taken into account to control for

Table 1. The mean take-off angle, α

Location on pelvis	Normal pelvis	Ilioischial spanning cages				Iliac flange with inferior hook	
		A	B	C	D	E	F
Ischium fixation zone							
0°	11° sd = 9	9.5	2.5	7.5	−18	−	−
10°	12° sd = 9	13	4	10	−17	−	−
20°	25° sd = 14	14.5	0	13	−11.5	−	−
30°	59° sd = 15	15	0	14	0	−	−
40°	69° sd = 9	16	0	15	0	−	−
50°	73° sd = 11	25.5	0	15	0	−	−
60°	77° sd = 14	30	0	15	0	−	−
70°	79° sd = 13	30	0	15	0	−	−
80°	77° sd = 12	31	0	15	0	−	−
90°	75° sd = 12	32	0	15	0	−	−
100°	76° sd = 9	36	0	15	0	−	−
Ilium fixation zone							
110°	74° sd = 8	34	0	15	0	−	
120°	70° sd = 9	28	9	15	19	30	9
130°	63° sd = 10	20	9	16	10	28	9
140°	52° sd = 11	14	6	13	4	24	9
150°	41° sd = 11	19	2	16	−	−	−
160°	25° sd = 14	−	1.5	13	14	−	10
170°	15° sd = 11	−	4	8.3	26	−	9
180°	10° sd = 7	−	−	−	32		−

Table 2. Angle measurement means and standard deviations

Average angle (degrees)			
Angle	Men	Women	p Value
P	96 sd = 8.3	104 sd = 7.2	0.002
S1	51 sd = 7.4	47 sd = 6.3	0.03
S2	28 sd = 5.3	28 sd = 4.4	ns
A	97 sd = 7.1	93 sd = 5.4	0.02
I	88 sd = 5.0	88 sd = 6.3	ns

ns = not significant.

Table 3. Length measurement means and standard deviations

Length	Average length (mm)		p Value
	Men	Women	
H	53.7 sd = 3.47	47.0 sd = 2.47	ns
W	52.4 sd = 3.44	45.5 sd = 2.44	0.01
PC1	48.3 sd = 4.68	41.4 sd = 4.02	0.01
PC2	40.8 sd = 3.70	35.6 sd = 2.68	ns
AC1	30.1 sd = 2.91	24.1 sd = 2.74	0.001
AC2	38.7 sd = 5.12	32.7 sd = 6.09	ns
D1	104.1 sd = 5.55	96.7 sd = 5.91	ns
D2	99.9 sd = 8.63	92.6 sd = 5.62	ns

ns = not significant.

Fig. 5 The diagram overlaying the photograph shows a representative pelvic cross section at 110°. To create each cross section, the thickness of each pelvis was measured at a series of points along each predetermined interval (0°, 110°, etc) identified in Figure 2. The thickness measurements then were converted to a smooth curve representing the inner table of the pelvis. A cross-sectional graph shows 0°, 130°, 140° and 160°, and take-off angle α .

specimen size. Men had smaller ($p = 0.002$) angle P, larger ($p = 0.03$) angle S1, and larger ($p = 0.02$) angle A than women. The average absolute difference between men and women was 8.2° for P, 4.2° for S1, and 3.5° for A.

The α angles of none of the commercially available cage designs matched the measured pelvic α angles, although some designs came closer than others (Table 1). In general,

Fig. 6 The acceptable range of dome and rim screws are shown in a left hip for a 54-mm acetabular shell. Screw lengths are based on the cross-sectional reconstructions at 0°, 110°, 130°, 140°, and 160°. The screw hole pattern is based on multiple commercially available acetabular shells. All lengths are given in millimeters and a 10-mm safety factor is included.

cages had lower α angles than the normal pelvis; this would lead to a less anteverted and abducted position of the acetabulum when compared with the outer table of the pelvis.

Discussion

Understanding the measurements used to create a topographic map of normal periacetabular bone could help surgeons obtain better acetabular fixation and more easily locate the hip center of rotation in complex cases. Additionally, these data could provide the basis for more anatomically driven implant designs such as revision acetabulum components, acetabular reconstructive cages, augments, and pelvic bone fixation plates [7, 13]. The superior and posterior aspects of the acetabulum have increasingly steep walls which ultimately result in 40° acetabular abduction and 21° anteversion (Fig. 7).

We acknowledge the specimens used for this study represent two races only. The averages of the same measurements taken on specimens from other races might be different. Also, the sample size used to calculate suitable screw placement in the acetabulum is small (10 hemipelves from five specimens). Screw positioning was based on neutral orientation to the screw hole, and intraoperative screw angulation was not taken into account. Although the dome screw lengths included in Figure 6 represent the distance to the nearest cortex, angulation of screws to remain in the ilium cortexes can result in much longer screw lengths being safely placed.

The chosen topographic measurement method provides numerous advantages over digital reconstructions from CT or MRI. It is easier to establish the frontal and coronal planes and are no problems attributable to artifact or from segmentation. Physically measuring each specimen also allows for collection of only desired data, simplifying subsequent analysis of the data. The obvious disadvantage to physical measurement is that it is not possible on live patients. If the limitations with diagnostic imaging can be overcome.

Several articles describe safe screw placement for acetabular fixation [2, 8, 11, 16]. The anatomically based topographic maps and cross sections we generated allowed us to define an acceptable range of screw lengths at different positions around the hemisphere when anatomically positioned. The most prominent portion of the ilium was identified visually as the division between the subquadrants S1 and S2 (49° anterior to the sciatic notch). Although the relatively flat surface topography in the S2 subregion appears ideal for superior fixation, the bone thins rapidly as the inner and outer tables converge. Even though the S1 region has a more complex surface topography, the cross section is thicker, which makes it better suited for implant fixation. This information may help the surgeon position screws and/or plates for optimal fixation. It also is important that implants be designed to match the complex topography of the S1 region, allowing the surgeon to gain fixation in that area.

Our acetabular orientation measurements are within the acceptable range of anteversion ($15^\circ \pm 10^\circ$) and abduction ($40^\circ \pm 10^\circ$), identified by Lewinnek et al. [9], but less than the ideal implant abduction of 45° to 55° identified by D'Lima et al. [5].

The angles we measured are independent of patient size, indicating the angles between anatomically designed features on implants (screw holes, flange placement on an acetabular reconstruction cage, etc) do not need to change with implant size. This suggests there is no need to modify implant and screw positions depending on the size of the patient. There were differences between angle and length measurements for male and female pelves, as described previously [4, 15]. When normalized for size, some measurement differences between men and women remained; however, it is unlikely the relatively small differences would have any clinical importance. Therefore, although the concept of gender-specific implants is of recent interest, our findings do not support the need for such implants in the acetabulum. It also is unlikely the differences between races would have any importance, which negates the need for race-specific implants.

Length measurements will help determine the quantity of bone loss in revision cases [14] and can help the surgeon more readily conceptualize the quantity of bone available

Fig. 7A–D Four different orientations of the pelvic topography map are shown: (A) in the same orientation as the cadaveric pelvis overlay (Fig. 2), (B) as viewed from directly above the acetabulum, (C) as

viewed from behind the ischium looking toward the ASIS, and (D) as viewed from the sciatic notch.

for fixation in each region. For example, the anterior column increases in thickness from 25 to 35 mm in the inferior to superior direction, whereas the posterior column increases from 35 to 45 mm in the superior to inferior direction.

Comparison of commercially available reconstruction cages is important for several reasons. The take-off angles did not necessarily match those of most currently available implants, and future implant designs could incorporate a higher take-off angle. The clinical implication of this is that placement of the cage on the superior ilium will result in a retroverted position relative to the native acetabulum and

the ischial portion of the plate will not have bone contact. If the cage is placed on the bone inferiorly, there will be a gap between the superior flange and the bone. Even when a posterior buildup is present on the cage, insufficient anteversion may result.

When used clinically, reconstructive cages often are placed vertically and in a retroverted position. This must be compensated for by cementing a polyethylene liner in a more desirable position. However, if a reconstructive cage could match the acetabular anatomy, then it would serve several purposes. Bending or contouring of cages, which may weaken and predispose a cage to fatigue failure,

would be unnecessary. A well-fitting implant can be designed for bone ingrowth, a feature not available with current designs. Ingrowth may prevent cage loosening and subsequent fatigue failure. If a cage can accurately fit and native acetabular opposition can be reproduced, then standard polyethylene inserts with secure locking mechanisms can be used. Potential design features should focus on maximizing ilium fixation in the S1 region, a high angulation of the superior and posterior acetabulum in the region of the posterior column, flattening of this angulation at the ischial level, screw holes placed to obtain purchase in the widest portion of the ilium (110°), and ischial and pubis screw holes located 100° apart.

The surface topography, pelvic angular measurements, column depths, and screw placement data are helpful for further refinement of acetabular surgical techniques and future design of implants for reconstruction of acetabular and pelvic anatomy.

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