The Asymmetric Profile of the Acetabulum

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Abstract Despite the curvaceous profile of the acetabulum, orthopaedic surgeons have continued to implant hemispheric cups since the introduction of total hip arthroplasty. The geometric discrepancies between the natural acetabulum and implant can result in painful iliopsoas impingement attributable to prosthetic overlap at the anterior acetabular ridge over which the iliopsoas tendon extends to leave the pelvis. We expanded on previous in vitro observations of acetabular morphology using a large in vivo sample and quantified the dimensions of the psoas valley. We studied computed tomographic scans of 200 healthy hips from 50 men and 50 women. The acetabular ridges were digitized on three-dimensional bone reconstructions and their coordinates were manipulated in spreadsheets to deduce acetabular diameter, anteversion, and inclination and to plot the rim profile. Our results

confirm the acetabular rim is an asymmetric succession of three peaks and three troughs. The psoas valley has the following shape distribution: 79% curved, 11% angular, 10% irregular, and 0% straight. The mean depth of the psoas valley is 5 mm and the latitude of its trough is on average 6 mm below the acetabular equator. The use of side-specific cups that replicate the curvaceous acetabular profile could prevent prosthetic overlap and reduce the incidence of iliopsoas impingement.

Introduction

To overcome the complex anatomy of the acetabulum, implant manufacturers have approximated the shape of acetabular cups to a simple hemisphere. Thus, for more than 50 years, orthopaedic surgeons have implanted hemispheric cups for THA. The geometric discrepancy between implant and anatomy often results in partial prosthetic overlap of the acetabular rim (Fig. 1), notably at the anterior iliopubic junction, which features a depression to allow passage of the iliopsoas tendon as it leaves the pelvis.

A well-known complication of anterior cup overlap after THA is iliopsoas impingement caused by chronic friction between the iliopsoas tendon and the rim of the implant [3, 5, 16, 21, 27, 33]. A review of the scarce literature on the syndrome suggests an incidence of approximately 5% of all THAs [3, 5]. The incidence is difficult to estimate because the syndrome takes various clinical forms and because the diagnosis criteria vary among authors [3, 5, 16, 21, 33]. In our experience, the syndrome can occur with all acetabular implants, but it is observed more frequently in cases in which the implant is oversized, insufficiently anteverted, or protrudes as a result of insufficient reaming.

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Fig. 1A–B Anteroposterior photographs of cadaver acetabulum show (A) the curvaceous profile of the acetabular rim and (B) prosthetic overlap at the anterior valley leading to iliopsoas impingement.

Some protruded acetabular implants such as dual-mobility cups with a supplementary cylindrical rim portion are designed with a notch to allow passage of the iliopsoas tendon and therefore prevent impingement.

The dimensions of the anterior acetabular ridge have never been specifically analyzed in the literature. The morphologic features of the anterior ridge were analyzed qualitatively by Maruyama et al. [23] who visually identified four different shape configurations on dry cadaver specimens. The dimensional variations of this anterior depression were reported more recently by Vandenbussche et al. [37] henceforth naming it the psoas valley, using surgical navigation equipment on fresh cadaver pelvis.

The aims of our study were to (1) quantify the dimensions of the acetabular rim with particular regard to the psoas valley, (2) investigate the interindividual and intra-individual variations in acetabular diameter, anteversion, inclination, and depth of the psoas valley, and (3) determine whether the shape or depth of the psoas valley is related to age, gender, acetabular diameter, or anteversion.

Materials and Methods

We studied 100 abdominopelvic computed tomography (CT) scans taken on patients for examination of nonorthopaedic conditions. The scans were selected from a large preexistent radiographic database at our center. We ensured all patients had normal and healthy hips, and we excluded specimens with evidence of hip osteoarthritis, skeletal deformities, or a history of pelvic or femoral trauma. We selected specimens to form two comparable groups: 50

women (mean age, 55.6 ± 21.0 years; range, 18–88 years) and 50 men (mean age, 55.0 ± 19.1 years; range, 18–82 years). Two hundred scanned hips were available for analysis.

All patients had been scanned following an identical protocol using a 64-slice multidetector scanner (General Electric, Waukesha, WI). The CT scans were taken with a contiguous thickness of 1.25 mm, from the top of the ilium to below the lesser trochanter, with settings of 12 kV and 70 to 120 mA depending on patient size. Each CT scan contained 150 to 200 DICOM images and was recorded on a separate CD-ROM.

We used image processing software dedicated to DICOM images, OsiriX (open-source software; <http://homepage.mac.com/rossetantoine/osirix>), to generate three-dimensional (3-D) bone reconstructions of the CT scans [28]. It benefits from the extremely fast and optimized 3-D graphic capabilities of the OpenGL graphic standard optimized for exploiting any available hardware graphic accelerator boards [29]. The 3-D bone reconstructions were created using the surface rendering function in OsiriX with the default software settings (pixel value, 300; medium resolution, 0.50; smooth iterations, 20). The use of 3-D reconstructions of medical images for descriptive anatomic studies or for examination of pathologic lesions is well documented [1, 2, 6, 7, 13, 17, 18]. The novelty of our method is, however, the digitization of specific points, or regions of interest, on 3-D bone surfaces and the exportation of their coordinates to spreadsheets for additional data processing.

On each pelvis, we (EV) digitized and named the anterior superior iliac spines and pubic symphysis to define

Fig. 2 The frontal pelvic plane and the pelvic coordinate system is defined by four anatomic landmarks on the pelvis, the left and right anterior superior iliac spines (L-ASIS and R-ASIS) and the left and right pubic tubercles (L-PT and R-PT).

the frontal pelvic plane [22, 24]. The pelvic coordinate system is thus established with the origin at the midpoint between the anterior superior iliac spines (Fig. 2), and thereafter, the rotation axis (z) was used to define anteversion, the circumduction axis (y) for inclination, and the flexion axis (x) for position along the acetabular rim.

On each acetabulum, the articular surface was digitized with a minimum of 10 dispersed points and the acetabular rim was digitized with approximately 80 points (Fig. 3). The acetabular notch was not digitized as part of the acetabular rim, but a landmark was placed at the inferior margin of the acetabular notch to provide a standard

reference for all acetabular rims. All points were digitized by the same author (EV).

For each CT scan, the coordinates of digitized points were exported using OsiriX to a file as comma-separated variables. Geometric analysis software, 3D Reshaper[®] (Technodigit, Gleizé, France), was used to deduce the coordinates of the center of rotation for each acetabulum and to calculate its anteversion and inclination angles. The software deduced the center of acetabular rotation by fitting a sphere through the points on the articular surface and calculated anteversion and inclination by fitting a plane through the points on the acetabular rim in both cases using the method of least squares.

The point coordinates were further manipulated in spreadsheets using Microsoft[®] Excel[®] (Microsoft Corp, Redmond, WA) to represent each acetabular rim as a two-dimensional profile following a previously published method [37]. The acetabular rim coordinates and center of rotation were treated as one data set and the three following mathematical manipulations were applied: (1) translation of the data set such that the center of acetabular rotation coincides with the origin of the pelvic coordinate system; (2) rotation of the data set such that the mean acetabular plane coincides with the y–z plane of the pelvic coordinate system; and (3) transformation of the coordinate system from Cartesian to cylindrical such that x,y,z are represented as x,r,θ.

To make all the acetabular profiles directly comparable, the inferior margin of the acetabular notch was set at 0° along the θ axis for all acetabula. The profiles of left acetabula were mirrored to become superposable over those of right acetabula. We observed the two-dimensional plot of each acetabulum individually and each point of inflexion was labeled and its coordinates were noted

Fig. 3A–B The points digitized on the acetabular rim and on the articular surface illustrate the position of (A) the inferior margin of the acetabular notch, which was used as a reference point, and (B) the poas valley, which is at the anterior rim of the acetabulum

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Fig. 4A–B Photographs of cadaver acetabulum show identified points of inflection. IMAN = inferior margin of the acetabular notch. (A) View taken perpendicular to acetabular equator and (B) view taken inferior to the acetabulum.

Fig. 5 A two-dimensional acetabular profile indicates points of inflexion. The inferior margin of the acetabular notch (IMAN) is set to zero on the θ axis. Points A, B, and C correspond to the peaks and the trough of the posterosuperior depression. Points C, D, and E correspond to the peaks and the trough of the psoas valley.

(Figs. 4, 5). For each acetabulum, the shapes of the posterosuperior depression and the psoas valley were described as curved, angular, irregular, or straight [23, 37]. In addition, we calculated the depths of the posterosuperior depression and the psoas valley from coordinates of their respective points of inflection. All depths were quantified in millimeters and in degrees. Particular attention was drawn to the distance between the trough of psoas valley (D) and the mean acetabular equator (θ axis), which also was quantified in millimeters and in degrees.

We compared the morphometric data (age, diameter, anteversion, inclination, depth of psoas valley, depth of posterosuperior depression) between men and women using unpaired t tests. Comparisons from right to left acetabula were made with paired t tests. Correlations between variables were calculated using the Pearson product moment coefficient of correlation (r). The significance level was set at 0.05. We used Microsoft® Excel® and its statistical software (Microsoft Corp).

Results

The acetabular rim profile was an asymmetric succession of three peaks and three troughs with variable amplitude in

each individual (Fig. 5). The shape of the posterosuperior depression had the following distribution in the population: 57% curved, 28% irregular, and 15% straight. The shape of the psoas valley had the following distribution in the population: 79% curved, 11% angular, 10% irregular, and 0% straight. The average depth of the psoas valley was 5 mm (range, 2–10 mm) and the latitude of its trough was approximately 6 mm below the acetabular equator (3 mm above to 15 mm below). Curved valleys were most often symmetric, resembling a sombrero, whereas angular valleys were marked by a sharp indentation, and irregular valleys were mostly asymmetrically S-shaped with a prominent superior convexity and a small inferior concavity.

We identified several acetabular dimensions related to gender: diameter, anteversion, and depth of psoas valleys (in millimeters) (Table 1). In contrast, inclination was not related to gender, and when measured as an arc of sphere, the depth of the psoas valley (in degrees) appeared similar in men and women. The psoas valley depth was thus proportional to the acetabular diameter and not directly related to gender.

The intraindividual acetabular differences (Table 2) indicated substantial asymmetry between right and left sides of the same patient. Most notably, the difference

Table 1. Morphometric acetabular data

Parameter	Total group (n = 200)		Male acetabulae (n = 100)		Female acetabulae (n = 100)		p Value*
	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range	
Age (years)	55.3 $\pm$ 20.0	18–88	55.0 $\pm$ 19.1	18–82	55.6 $\pm$ 21.0	18–88	0.897
Diameter (mm)	48.5 $\pm$ 4.4	40.0–59.5	51.9 $\pm$ 3.1	44.6–59.5	45.1 $\pm$ 2.2	40.0–51.2	< 0.0001
Anteversion (degrees)	16.9 $\pm$ 5.5	5.2–34.2	15.1 $\pm$ 4.9	5.8–28.1	18.8 $\pm$ 5.4	5.2–34.2	< 0.0001
Inclination (degrees)	38.7 $\pm$ 4.8	26.8–48.8	39.0 $\pm$ 4.7	26.8–48.8	38.4 $\pm$ 4.8	28.2–48.0	0.375
PV depth (mm)	4.9 $\pm$ 1.6	2.0–10.3	5.4 $\pm$ 1.7	2.0–10.3	4.4 $\pm$ 1.3	2.0–8.4	< 0.0001
PV depth (degrees)	11.6 $\pm$ 3.5	4.5–21.8	11.9 $\pm$ 3.6	4.5–21.8	11.3 $\pm$ 3.4	5.1–21.4	0.206
PV trough (mm)	−6.3 $\pm$ 3.2	−14.7–3.4	−6.7 $\pm$ 3.7	−14.7–1.0	−5.8 $\pm$ 2.6	−11.2–3.4	0.054
PV trough (degrees)	−14.7 $\pm$ 7.1	−30.2–9.1	−14.6 $\pm$ 7.8	−30.2–2.4	−14.8 $\pm$ 6.5	−27.8–9.1	0.839
PSD depth (mm)	5.4 $\pm$ 2.7	−3.4–13.8	6.1 $\pm$ 2.7	−1.4–13.8	4.7 $\pm$ 2.6	−3.4–9.7	0.0001
PSD depth (degrees)	12.8 $\pm$ 6.4	−8.6–32.4	13.6 $\pm$ 6.0	−3.1–32.4	12.0 $\pm$ 6.7	−8.6–25.4	0.071

* p values less than 0.05 are significant; SD = standard deviation; PV = psoas valley; PSD = posterosuperior depression.

Table 2. Intraindividual acetabular differences

Parameter	Total group (n = 100)		p Value*
	Mean $\pm$ SD	Range	
Diameter (mm) [†]	1.14 $\pm$ 1.00	0.03–4.86	< 0.0001
Anteversion (degrees) [‡]	2.70 $\pm$ 1.82	0.11–8.20	< 0.0001
Inclination (degrees) [§]	2.40 $\pm$ 2.20	0.05–11.24	< 0.0001
PV depth (mm)	1.08 $\pm$ 0.95	0.00–4.70	< 0.0001
PV depth (degrees)	2.55 $\pm$ 2.23	0.02–11.90	< 0.0001
PV trough (mm)	1.48 $\pm$ 1.22	0.00–5.40	< 0.0001
PV trough (degrees)	3.32 $\pm$ 2.73	0.04–10.79	< 0.0001
PSD depth (mm)	1.76 $\pm$ 1.70	0.00–9.65	< 0.0001
PSD depth (degrees)	4.14 $\pm$ 4.11	0.07–24.42	< 0.0001

* p values less than 0.05 are significant; [†]diameter greater than 2 mm in 17% of patients; [‡]anteversion greater than 5° in 11% of patients; [§]inclination greater than 5° in 13% of patients; SD = standard deviation; PV = psoas valley; PSD = posterosuperior depression.

Table 3. Parametric correlations in total group (n = 200)

Correlated parameters	R*
Age versus PV depth (mm)	0.07
Age versus PV depth (degrees)	0.03
Age versus PSD depth (mm)	−0.12
Age versus PSD depth (degrees)	−0.15
Diameter versus anteversion	−0.32
Diameter versus PV depth (mm)	0.34
Diameter versus PV depth (degrees)	0.07
Diameter versus PSD depth (mm)	0.23
Diameter versus PSD depth (degrees)	0.06
Anteversion versus PV depth (mm)	−0.28
Anteversion versus PV depth (degrees)	−0.20

* R = Pearson's product moment coefficient; 0.25 < |R| < 0.49 indicates a low correlation; |R| < 0.25 indicates little or no correlation; PV = psoas valley; PSD = posterosuperior depression.

between contralateral acetabular diameters was greater than 2 mm in 17% of patients. Moreover, the shape of the contralateral psoas valley was different in 12% of patients, and the shape of the contralateral posterosuperior depression was different in 8% of patients.

The dimensions of the psoas valley and of the posterosuperior depression were unrelated to patient age, but they were related to acetabular diameter and anteversion (Table 3). The negative correlation between diameter and anteversion was consistent with the observation that women have smaller acetabula but higher anteversion angles. The negative correlation between psoas valley depth and anteversion was unexpected but follows logically from anatomic considerations in that more anteverted acetabula allow better iliopsoas passage and hence need shallower psoas valleys.

Discussion

Geometric discrepancies between implants and anatomy can result in prosthetic overlap at the anterior acetabular ridge and lead to iliopsoas impingement after THA. We studied the morphologic features of the acetabulum with high precision to suggest means of preventing iliopsoas impingement by improving surgical technique or implant design. Our study aimed to (1) quantify the dimensions of the acetabular rim and particularly the psoas valley, (2) investigate the interindividual and intraindividual variations in acetabular features, and (3) determine whether the shape or depth of the psoas valley is related to age, gender, acetabular diameter, or anteversion.

The use of 3-D reconstruction CT has numerous advantages over studies on cadaver specimens. The number

of subjects available is greater and their demographic data are accessible. The digitization of relevant points using a computer screen renders the process more accurate because the reconstructed pelvis is viewed with the ideal magnification and spatial orientation. Once digitized, points remain clearly marked and their placement may be corrected a posteriori if need be. The strengths of this study therefore can be summarized as precision of measurements, selection of suitable subjects, and ethnic diversity of the sample, because the scans were performed at a major hospital in a cosmopolitan city. The weaknesses of the study include uncertainty about the exact accuracy of 3-D bone reconstructions of DICOM images, inability to assess the interoperator or intraoperator repeatability in digitization of relevant points, and the choice not to investigate possible relationships between ethnic origin and morphology.

Our data from a large in vivo sample confirm findings of recent in vitro studies [23, 37]. The acetabular rim profile is an asymmetric succession of three peaks and three troughs, the latter corresponding to junctions between the three bones that fuse at the acetabulum (ilium, ischium, pubis), which starts prenatally in the embryonic period [34, 35] and continues well beyond puberty [26]. At birth, the pelvis is still partly cartilaginous, notably the entire iliac crest, the acetabular floor, and its inferior margin. The acetabulum is still a triradiate stem forming a Y-shaped epiphyseal articular surface but continues to grow and adapt structure to function until maturity [26, 30, 38].

In a previous work, the term *psoas valley* was introduced to refer to the depression in the anterior acetabular ridge [37], as this name indicates involvement of the iliopsoas tendon in this region during THA. The *psoas valley* provides passage for the iliopsoas tendon and changes its direction just as a pulley changes the course of a cord. Its shape is ill-defined, probably because of the complexity of the acetabular architecture and orientation. Some authors suggested the anterior ridge has different shapes simply because of anatomic variations [11, 20]. Maruyama et al. [23] distinguished four anterior ridge configurations: curved, angular, irregular, and straight. The precise data of our present study affirm only the first three configurations actually exist. We have never observed a truly straight *psoas valley*, although some may appear straight on visual observation; the minimum dip calculated is 2 mm.

When positioning a cup in THA, it is just as important to consider the latitude of the *psoas valley* trough with respect to the acetabular equator as it is to consider the depth of the *psoas valley* relative to its adjacent peaks. Prosthetic cups most often are medialized and elevated during THA by approximately 4 mm each way depending on the extent and direction of acetabular reaming [8, 10, 15]. Although medialization and elevation enable deeper burial of the cup

in the acetabulum, the prosthetic overlap may well persist depending on the depth and relative latitude of the *psoas valley*. In other words, an acetabulum with a relatively lateralized center of rotation and a deep *psoas valley* is most susceptible to iliopsoas impingement.

The posterosuperior depression was mentioned briefly but not analyzed by Maruyama et al. [23]. We observed three configurations for this depression, most often curved but occasionally straight or irregular. A junior surgeon performing THA using a posterior approach, unaware of the existence of a posterosuperior depression, tends to overincline the cup, aiming to insert it fully in bone and avoiding any overlap of the posterosuperior ridge. This is mistaken because it involuntarily induces an incorrect inclination as evident on postoperative radiographs. A more experienced surgeon, however, would allow a slight prosthetic overlap at this depression, particularly if seeking a 40° inclination.

Our measurements confirm results of previous anatomic studies. The acetabular inclination is slightly less than 40° [4, 23, 24, 31, 36, 37], and the angle of 45° imposed by traditional ancillary instruments is not justifiable. The acetabular anteversion differs considerably according to gender, approximately 15° in men compared with 19° in women. The definition of anteversion differs among anatomists, surgeons, radiologists, and engineers. The so-called functional anteversion depends on the effective tilt of the pelvis under the spine [9, 19, 25, 32, 39].

Whatever the definition of anteversion, the shape variations of the *psoas valley* must be known in case of periacetabular osteotomy or in case of radiographic measurement of anteversion. The planning and results of periacetabular osteotomy are based on CT scans [12, 14, 31] and inevitably are influenced by the shape of the *psoas valley*. We suspect the anteversion indicated by radiologists and surgeons for THA often is based on the assumption that the acetabulum is hemispheric and that its profile is planar, the level at which the transverse section used for this calculation could coincide with the *psoas valley*, in which case the calculated anteversion will be incorrect.

We confirmed and quantified the asymmetry of the acetabular rim. The gradual evolution of joint implants rendered side-specific implants a standard requirement for large joints, including the shoulder, elbow, and knee. Some recent knee implants are designed to be gender-specific ostensibly to provide better anatomic fit and bone coverage. We believe it would be important for implant manufacturers to provide side-specific acetabular cups replicating the asymmetric acetabular profile. Such implants are expected to reduce the incidence of painful iliopsoas impingement after THA and would be particularly desirable in the case of dual-mobility cups, which have a protrusive rim portion to address issues of dislocation.

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