Microanatomy of the acetabular cavity and its relation to growth

N. M. Portinaro, D. W. Murray, M. K. D. Benson

From the Istituto Clinico Humanitas, Italy and the Nuffield Orthopaedic Centre, Oxford, England

The anatomy and development of the growing acetabulum are not clearly understood. We dissected and studied histologically two acetabula from the pelvis of a three-month-old infant. Relative rates of growth at the different growth plates were assessed by comparing the height of the proliferative layer with that of the hypertrophic layer.

The three bones which form the acetabulum are surrounded by growth plates on all sides except medially. These face towards the centre of the triradiate cartilage, the limbs of the triradiate cartilage and the articular surface and each may be divided into four distinct areas according to the orientation of its cell columns which reflect the direction of growth.

Growth was particularly rapid at the ischial growth plates directed towards the centre and the articular cartilage, and on both sides of the anterior limb of the triradiate cartilage. These findings may explain the mechanism by which the acetabulum changes orientation and inclination with growth.

J Bone Joint Surg [Br] 2001;83-B:377-83.

Received 26 January 2000; Accepted after revision 4 July 2000

At birth the acetabulum is developing from the growth plates of the ilium superiorly, the ischium posteriorly and the pubis anteriorly. Centrally, the three growth plates are confluent with the thick triflanged hyaline cartilage known as the triradiate cartilage.¹ Laterally, at the margin, the ring apophysis surrounds the acetabular bones and is in continuity with the growth plates of the ilium, ischium and pubis, and with the three flanges of the triradiate cartilage² (Fig. 1).

N. M. Portinaro, MD, MSc, FRCS, Consultant Orthopaedic Surgeon
Istituto Clinico Humanitas, Via Manzoni 56, 20089 Rozzano, Milan, Italy.

D. W. Murray, FRCS Orth, Professor of Orthopaedic Surgery, Consultant Orthopaedic Surgeon

M. K. D. Benson, FRCS, Consultant Orthopaedic Surgeon
Nuffield Orthopaedic Centre, Windmill Road, Headington, Oxford OX3 7LD, UK.

Correspondence should be sent to Mr N. M. Portinaro.

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0301-620X/01/310972 \$2.00

The three primary centres grow in multiple directions allowing the acetabulum to deepen and to expand,² while preserving concentricity and congruity with the fast-growing femoral head.³

The triradiate cartilage is formed by an ilio-ischial flange posteriorly, an iliopubic flange anteriorly, and an ischio-pubic flange inferiorly. Its borders are the three sites of primary growth of the acetabulum and its growth and remodelling ensure that the diameter of the acetabulum enlarges proportionally with the growing femoral head.⁴

The acetabular ring apophysis contributes 25% to 35% to acetabular development by deepening its lateral aspect.^{2,5} It contains the secondary ossific nuclei^{5,6} which start to ossify in early life and fuse completely to form the definitive acetabular margin later in adolescence.^{2,5} The fibrocartilaginous labrum, clearly separate from the capsule, encircles and deepens the acetabulum.

Fig. 1

Photograph of the acetabulum after removal of the soft tissues. The acetabular socket is formed by the three acetabular bones, the ilium (IL), the ischium (IS) and the pubis (PU) with the triradiate cartilage between them. Note the large pulvinar at the centre of the socket.

At birth, both endochondral and membranous ossification is present, although the membranous has preceded the endochondral. Subperiosteal appositional new bone forms rapidly at both the inner and outer sides of the ilium.⁷

The peculiar arrangement of the growing structures of the acetabulum makes it difficult to determine the relative contribution of each component to its overall development.

In the infant it is difficult to determine the orientation of the acetabulum relative to the pelvis. At birth, there are fixed flexion deformities at the hips and the pelvis is flexed on the lumbar spine which is also held in flexion. As the lumbar spine, pelvis and hips 'unwind' the apparent orientation of the acetabulum changes considerably, which explains, in part, why some have considered the perinatal acetabulum to be retroverted or neutral.^{8,9} Shino¹⁰ estimated anteversion at birth as being 19°, Getz¹¹ 38° and Steindler 42°.¹² These discrepancies reflect different methods of assessing pelvic orientation and whether the bones or the cartilage of the acetabulum are being considered.

There have been no previous studies which quantify the rate of growth of the different components of the acetabulum. The contribution of these structures to the overall development and orientation of the acetabulum has only previously been estimated qualitatively.^{2,5,13-15}

Our aim was to determine the microanatomy of the acetabulum and the relative contribution that each component makes to its development.

Materials and Methods

The pelvis of a three-month-old normal male infant who had died in a road accident was obtained at post-mortem after ethical approval. The femoral heads and all the soft

tissues were removed and the pelvis was divided into two hemipelvises and placed in 10% buffered formalin for 48 hours at room temperature. The acetabula were dissected radially on the right, as described by Ponseti⁵ and anatomically on the left.

Radial dissection. The geometrical centre of the acetabulum was determined by inserting a Kirschner (K-) wire in the centre, previously measured on a paper surface laid on the outer border. The acetabulum was then divided, with a 22 scalpel blade for the soft tissue and a 1.2 mm saw blade for the bone, into 12 equal 30° segments centred on the K-wire (Fig. 2).

Anatomical dissection. A K-wire was inserted into the centre of the triradiate cartilage.¹⁶ The acetabulum was divided through the three cartilage flanges into three segments each subtending 120° and containing acetabular bone and its adjacent hyaline cartilage. Each segment was then subdivided into two further 60° segments. These were cut approximately parallel to and about half a centimetre below the acetabular surface. This cut was at about 30° to the plane of the acetabulum (Fig. 3).

Histological examination. Slab radiographs were obtained from each specimen to determine the bone content and shape. Each specimen was then decalcified in 5% nitric acid overnight, dehydrated in graded alcohols, cleared in xylene and embedded in paraffin wax. We obtained sections 3 µm thick from all surfaces using an AO Spencer 820 microtome (American Optics, California). These were stained with haematoxylin and eosin or with Alcian Blue at different molarities of MgCl₂.⁸

The heights of the proliferative and the hypertrophic layers were measured for each growth plate. The ratio between these heights was used as a measure of their relative rates of growth (Fig. 4). These measurements were made using an image-analysis system (Contron Image Ana-

Fig. 2a

Fig. 2b

Figure 2a – Photograph showing the radial dissection of the right acetabulum from the geometrical centre of the socket. The acetabular bones and growth plates may be sectioned obliquely. Figure 2b – Diagram of the radial 30° sections.

Fig. 3a

Fig. 3b

Fig. 3c

Figure 3a – Photograph showing the anatomical dissection of the left acetabulum from the centre of the triradiate cartilage. Each section contains one acetabular bone and its surrounding cartilage. Figure 3b – Diagram of the anatomical section through the triradiate cartilage; Figure 3c – Diagrams of the sections through each acetabular bone.

Fig. 4a

Fig. 4b

Photomicrographs showing the computer determination of the lengths and areas of the zones of the growth plate. The mean area of each zone was divided by the mean length to obtain the mean height, and the ratio between the heights was considered an index of the rate of growth. Figure 4a – The growth plates as detected at histological examination ($\times 75$). Figure 4b – The areas of the proliferative (P) and hypertrophic (H) zones are highlighted ($\times 75$).

lyser Computer), using a light microscope. The lower limit of the hypertrophic zone included all cells with a preserved shape and a nucleus. The transition from the proliferative to the hypertrophic zone was determined from the ratio between the transverse and the longitudinal diameter of the cells. In the hypertrophic layer this ratio is nearly one, while in the proliferative layer the transverse diameter is larger than the longitudinal.¹⁷ The upper limit of the proliferative zone included the lower cluster of cells present in each column.¹⁸ The length and area of each zone were measured three times in each microscope field. This was repeated at three different points on each growth plate. The mean height of each zone was determined by dividing the area by the length. The rate of growth of the bones of the acetabulum was then compared.

Statistical analysis was undertaken using Student's *t*-test and ANOVA.

Validation of the method. In order to determine the reliability of the method of assessing the rate of growth, the upper part of the femur was divided along the longitudinal axis of the femoral shaft by an oblique cut. The ratio of the rate of growth of the femoral head to the greater trochanter was determined; this should be 3:2.¹⁹

Results

Radial and anatomical dissection (acetabular micro-anatomy). Four different growth plates were identified on all specimens from both groups when stained with both haematoxylin and eosin and Alcian Blue (Fig. 5). One was

Fig. 5a

Fig. 5b

Fig. 5c

Figure 5a – Microphotographs of sections from 0° (I) and 30° (II) radial cuts. Figure 5b – Microphotographs of sections from the two planes (I and II) of the anatomical cuts. Similar growth plates were detected (haematoxylin and eosin $\times 75$). Figure 5c – Diagram of the anatomical sections.

directed towards the articular surface (GP1), one towards the centre of the triradiate cartilage (GP2), and the other two (GP3 and 4) towards the adjacent flanges of the triradiate cartilage (Fig. 6).

Evaluation of the growth rate (histological and computer analysis). There was a significant difference in the rate of growth between the different growth plates (ANOVA, $p = 0.002$). That for each (GP1, 2, 3 and 4) was

determined on the radial and anatomical dissections. There was no significant difference between these two measurements ($p = 0.096$). The mean rate of growth of each plate was determined.

The rate of growth of the growth plates directed towards the articular surface (GP1), the centre (GP2) and on each side of the same flange (GP3 and 4) was compared. That of the iliac growth plate was significantly lower than that of the ischium and pubis ($p = 0.021$ and $p = 0.024$, respectively). The rate of growth of the pubic and ischial growth plates was similar ($p = 0.922$). The rate of growth of the pubic growth plate was significantly lower than that of the ischium ($p = 0.031$). Those of the iliac and pubic growth

plates ($p = 0.514$) and iliac and ischial growth plates ($p = 0.052$) were similar. For each flange the rate of growth on both sides was similar (anterior (iliopubic) $p = 0.392$; posterior (ilio-ischial) $p = 0.089$; and inferior (ischial-pubic) $p = 0.268$).

The rate of growth of each flange of the triradiate cartilage considered as a single growing unit was compared. That at the anterior iliopubic flange was significantly higher than that at the posterior ilio-ischial flange ($p = 0.0008$). They were similar at the posterior ilioischial and inferior ischiopubic flanges ($p = 0.136$) and at the inferior ischial-pubic and the anterior iliopubic flanges ($p = 0.253$).

Fig. 6

Diagram showing the acetabular microanatomy. A and B demonstrate the radial and anatomical sections. A1 and B1 show how the sections intersected the growth plates at different inclinations. Despite this, the detected growth rates were almost identical ($p = 0.096$) with each technique.

Validation of the method. The rate of growth of the growth plate of the femoral head was greater than that of the greater trochanter ($p = 0.001$); the ratio was 3:2.

Discussion

We have described the detailed anatomy of the growing acetabulum, dividing each component (ilium, ischium and pubis) into subunits. The direction of their growth was recorded and the relative rates of growth in these areas measured.

In our specimens, we demonstrated four distinct growth plates for each acetabular bone. Previously, the orientation of the cell column has been used to detect different growth plates.¹⁸ Both radial and anatomical dissections showed similar growth plates and rates of growth for each acetabular bone ($p = 0.096$). The anatomical dissection makes evaluation of growth easier since the cuts are more closely orthogonal to the surface of the growth plate than those in the radial dissection. The multidirectional growth around each acetabular bone contributes to its complex tridimensional development. The anatomy and growth of the three acetabular bones have previously been debated. Ponseti⁵ described growth plates at the acetabular surface and at the triradiate cartilage. Gepstein et al¹⁴ considered the triradiate cartilage as a single growing unit. O'Hara¹⁶ gave a detailed description of the cartilage which surrounded the acetabulum and stressed the importance of the ring apophysis, noting that in dysplastic hips if the labrum was excised and peripheral cartilage lost, the acetabular rim failed to develop satisfactorily. Dissecting the acetabulum both anatomically and radially as we have described has allowed us to compare the techniques and confirm reproducibility.

The acetabulum does not grow in isolation. Its orientation is affected by growth at the pubic symphysis and at the sacroiliac joints. The pelvis itself enlarges by appositional growth subperiosteally at the surface and by the apophyses, notably the iliac apophysis, extending around its periphery.

Ideally, the rate of growth should be estimated from the height of the proliferative layer on a section perpendicular to the growth plate in which the cell columns were vertical. Since it is impossible to obtain sections perpendicular to all growth plates we estimated the rate of growth from the ratio of the heights of the proliferative to the hypertrophic zones. Even with oblique sections, both zones of the growth plate were sectioned at the same angle, and thus the ratio of the heights of the two zones did not change with the angle of section.²⁰ Our study comparing the rate of growth of the head of the femur and greater trochanter confirmed the reliability of the technique. Nonetheless, it is often difficult to determine the height of the proliferative and hypertrophic zones.^{18,21} The height of the cell columns may vary and not all columns extend from the resting zone to the hypertrophic layer; some are aborted and others divide. Incomplete columns may therefore reflect the morphology

of the growth plate and not the plane of section.¹⁸ The cell columns and collagen fibres tend to become orientated so that they are orthogonal to the direction of loads acting upon them.²² Since the acetabulum is hemispherical, cell columns fan away from the joint surface. It was necessary therefore to use the mean height in assessing the thickness of different layers. Specific stains for different areas of the growth plate, such as Alcian Blue with different molarities of $MgCl_2$, proved to be of little value in separating the zones of the growth plate. The reproducibility of our technique has been demonstrated by sectioning each acetabulum differently and finding no difference in the rates of growth measured by the two techniques.

We consider that during growth under physiological circumstances the height of the hypertrophic zone remains constant. By contrast, the height of the proliferative zone varies and is related to the rate of growth.²³⁻²⁷ Growth depends on the formation of new chondrocytes and this occurs only in the proliferative cell zone.²⁸ The longitudinal rate of growth of any growth plate is therefore a function of the number of cells in the proliferative zone²⁹ since no cellular reproduction occurs in the hypertrophic zone.³⁰

The observation that the bones of the acetabulum and their growth plates grow at different rates helps to explain some of the changes in the acetabulum which occur after birth. Bone growth is, in part, genetically determined, but also reflects mechanical stimuli.²³ Growth at the centre of the acetabulum and in the triradiate cartilage tends to enlarge it, and make it relatively shallow. Growth at the growth plates directed towards the articular cartilage tends to shrink it and make it relatively deep. The combined growth at all growth plates tends to enlarge it and maintain its spherical shape. The compressive forces applied by the femoral head are likely to stimulate its spherical growth.

Fig. 7

Diagram of the different growth rates (arrows) at the growth plates of the ilium, ischium and pubis. The number and size of the arrows reflect the magnitude of growth. GP1 growth is directed towards the articular surface.

Although the effect of these forces on the adult acetabulum has been investigated,³¹ few studies have considered those which pass through the hips of the infant. At birth, the infant lies with the pelvis and the lower limbs in a flexed position. Forces transmitted along the line of the flexed femur are likely therefore to be predominantly posterior. This may explain why in our study growth appeared to be maximal in the posterior ischial part of the acetabulum (Fig. 7). This will allow a neutral or retroverted socket at birth to become progressively anteverted, with an increase in the posterior wall by growth at the anterior growth plate of the ischium. As the pelvis 'unwinds' from flexion and the hips extend, the forces are likely to be distributed through the superior part of the acetabulum, which would tend to increase in the iliac part of the acetabulum. This probably accounts for the steady decrease in the acetabular index seen on radiographs.

Our study has shown that acetabular development is a result of growth at four distinct growth plates and the three acetabular bones. This growth has to be precisely controlled for the formation of a normal acetabulum. Any anomaly or lesion of the growth plates will interfere with this complex interaction and may lead to acetabular maldevelopment and dysplasia.

The authors wish to thank Mr Martin Gargan for providing the specimens that allowed this study to be carried out and Mrs Barbara Marks for her assistance in the preparation of the manuscript.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

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