We have previously described a simple and reproducible three-dimensional technique of CT for the measurement of the cover of the femoral head in acetabular dysplasia in adults. We now describe the application of this technique in ten patients with symptomatic dysplasia to assess the degree and direction of dysplasia and to measure the cover obtained at acetabular osteotomy.

The indices obtained gave a useful indication of the degree and direction of the dysplasia and confirmed which components had been used most efficiently to achieve cover. The information is easily presented in graphical form and gives a clearer indication of the cover obtained than the indices derived from plain radiographs.

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Accurate assessment of indices of dysplasia and of cover of the femoral head is difficult,1-4 but is essential when planning and evaluating osteotomies around the hip.1,5-7 Some information concerning lateral cover of the femoral head can be obtained from plain radiographs by measuring the centre-edge angle of Wiberg, and about anterolateral cover from the ‘false-profile’ view of Lequesne and de Seze.1,8-13

Complicated mathematical estimations of acetabular cover have also been made from plain radiographs but the methods are complex and include many assumptions regarding the geometry of the hip.8,14

More information may be obtained from CT7,11,15-19 and three-dimensional (3D) CT studies20,21 but these involve high exposures to radiation and are difficult to interpret. No MRI techniques have been described for assessing acetabular dysplasia.

We have devised a simple and reproducible 3DCT technique to measure cover of the acetabulum in adults.22 We now describe its use in planning the correction required for periacetabular osteotomy and in assessing the amount obtained.

Patients and Methods

We studied ten women with a mean age of 26 years (16 to 41) who had symptomatic acetabular dysplasia. We measured the centre-edge angles (CEA) on the anteroposterior (AP) and false-profile views (VCA), the acetabular index of the weight-bearing zone (TA), the femoral head extrusion index (FHEI) and the lateral subluxation index (LSI)1,8-10,13,23,24 (Table I) before and after operation. All measurements were made on standing AP pelvic and false-profile views by two independent observers. We also carried out 3DCT on all the patients before and after operation to identify the degree and direction of the dysplasia, to plan the correction required at the time of periacetabular osteotomy, to assess the correction obtained subsequently and to compare it with the preoperative plan, the contralateral side and a normal control group (Figs 1 to 6).

For CT we used a GE HiLight Scanner (GE Medical Systems, Milwaukee, Wisconsin). The subject was positioned supine with the midline of the body aligned with the central axis of the scanning table. The hips were extended and the feet stabilised with the hips in 15° of external rotation. Care was taken to ensure that there was no pelvic tilt or flexion of the hip or knee. Helical 3 mm CT sections were obtained at a pitch of 1:1 (120 kV, 300 mA, field-of-view 38 to 42 cm, standard algorithm) through both acetabula and femoral heads. The helical CT data were reconstructed at 1 mm intervals, then transferred to a 3D workstation (Advantage Windows Workstation; GE Medical Systems) and a 3D model of the pelvis obtained using the automated reconstruction program. This discards all...
soft-tissue signals and produces a surface-shaded image of the bony structures. The filter criteria used were those preset in the reconstruction algorithm in the software. Since all the patients were to undergo periacetabular osteotomy, their femoral heads were either spherical or nearly so. It was therefore possible to view simultaneously the axial, coronal and sagittal images, and to place a cursor manually at the centre of the femoral head. Vertical planar images were obtained through the centre of the femoral head at various rotations from 0° (anterior acetabular margin) through 90° (lateral margin) to 180° (posterior margin). The acetabular margin was defined as the edge of the smooth subchondral bony surface. The CEA was measured at rotational increments of 10° around the acetabular rim. That at 90° thus corresponds to the classical CEA of Wiberg on an AP radiograph of the pelvis. The data were then presented graphically, with the CEA on the y-axis and the rotational position on the x-axis (Figs 7 and 8).

We had previously obtained control data from 15 normal hips in 12 subjects with a mean age of 34.2 years (19 to 49) who had CT for the evaluation of contralateral acetabular fractures (9 patients) or for the assessment of soft-tissue abnormalities (3 patients, 6 hips). These findings and their reliability, validity and reproducibility have already been published.22

The intraobserver variability for this technique was assessed using six randomly selected patients with dysplastic hips. The mean error of measurement was 2.4° (0 to 4.3), and was greatest in the posterior aspect of the acetabulum.

Indices of dysplasia based on the area under the curve on a graph of the CEA versus position along the acetabular rim were calculated and presented as a ratio of the dysplastic to the normal hip. Global coverage was thus defined as the area under the curve from the 0° to 180° positions, anterolateral cover from the 0° to 40° rotational positions, lateral cover from the 50° to 120° positions, and posterolateral cover from the 130° to 180° positions.

CT covers a smaller area than plain radiographs of the pelvis and the effective dose of radiation using this technique is 1.46 mSv, which compares favourably with a plain AP radiograph of the pelvis (1.6 mSv) or a false-profile view (1.0 mSv).

Results

The 3DCT technique was simple to learn and rapid to perform.

Even in this small series the degree and direction of the acetabular dysplasia were seen to be very variable. Table I gives the measurements from the plain radiographs and Table II the indices of dysplasia.

The data are easily presented both as images (Figs 3 to 6) and in graphical form (Figs 7 and 8) and give a clearer indication of the cover obtained than the plain radiographs. Figures 3 to 6 illustrate pre- and postoperative coronal images at 25° and 90° for a typical patient. These correspond to the CEAs on the corresponding AP and false-profile radiographs. The correction obtained is easily quantified by these angles on the postoperative images. For each patient, the preoperative graphical record was compared with that of the control group (Fig. 7) and used to plan the correction required at surgery. Thus, in the case illustrated, anterior correction of 10° and lateral correction of 15° were deemed necessary. The postoperative graph confirms that these were achieved. We found that the indices for both lateral and anterior dysplasia improved to a mean of approximately 1 in line with a similar improvement in global coverage (Table II).

Posterior cover was less well addressed but was improved in all but one patient (Fig. 8). Preoperative knowledge of the posterior cover is necessary in order to prevent further uncovering at this site.

The indices for dysplasia confirmed which components had been most efficiently addressed by osteotomy. Thus, the mean overall global index was 0.625 suggesting an average deficiency in cover of 37.5%. This was most marked laterally (55%) but also anteriorly (40%) and posteriorly (31%). The indices are most useful in allowing comparison between patients, and between pre- and postoperative cover. The ranges and means obtained suggest that we achieved the desired correction in these cases.

Discussion

Encouraging early results were reported for the Bernese periacetabular rotational osteotomy, the aim of which was to recreate relatively normal anatomy.6,25,26 The advantages of this procedure are that it can be performed through a single incision, either iliofemoral or ilio-inguinal, the posterior column remains intact rendering the osteotomy stable and allowing early mobilisation, the blood supply of the acetabulum is not threatened and rapid union occurs.27

Table I. Mean (range) pre- and postoperative measurements from plain radiographs (see text)

<table>
<thead>
<tr>
<th></th>
<th>Preop</th>
<th>Postop</th>
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</thead>
<tbody>
<tr>
<td>CEA (degrees)</td>
<td>2.4 (-3 to +11)</td>
<td>33.8 (24 to 45)</td>
</tr>
<tr>
<td>VCA (degrees)</td>
<td>13.8 (-2 to +35)</td>
<td>27 (15 to 42)</td>
</tr>
<tr>
<td>TA (degrees)</td>
<td>20.2 (12 to 30)</td>
<td>4.1 (0 to 10)</td>
</tr>
<tr>
<td>FHEI (%)</td>
<td>37.5 (29.4 to 50.0)</td>
<td>14.3 (8 to 19)</td>
</tr>
<tr>
<td>LSI</td>
<td>1.30 (0.7 to 2.1)</td>
<td>1.08 (0.80 to 1.7)</td>
</tr>
</tbody>
</table>

Table II. Mean (range) pre- and postoperative indices for dysplasia

<table>
<thead>
<tr>
<th></th>
<th>Preop</th>
<th>Postop</th>
</tr>
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<tbody>
<tr>
<td>Anterior</td>
<td>0.60 (0.29 to 0.85)</td>
<td>1.05 (0.87 to 1.23)</td>
</tr>
<tr>
<td>Lateral</td>
<td>0.55 (0.33 to 0.77)</td>
<td>1.00 (0.64 to 1.33)</td>
</tr>
<tr>
<td>Posterior</td>
<td>0.69 (0.48 to 0.99)</td>
<td>0.88 (0.59 to 1.21)</td>
</tr>
<tr>
<td>Global</td>
<td>0.63 (0.46 to 0.87)</td>
<td>0.96 (0.78 to 1.11)</td>
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</table>
Intra-articular pathology may also be addressed at the time of surgery. Careful 3D planning is required and over-correction with posterior uncovering must be avoided.\textsuperscript{11,18,28}

Two recent studies after acetabular osteotomy\textsuperscript{29,30} have relied solely on indices obtained from AP radiographs, such as the CE angle, acetabular angle and cover of the femoral head. These may allow some qualitative assessment of the acetabular cover to be made but are limited by potential errors,\textsuperscript{2-4} the overlap of bony structures and by the lack of 3D information.\textsuperscript{28}

Konishi and Mieno\textsuperscript{14} and Mieno et al\textsuperscript{28} described the estimation of 3D acetabular cover using only an AP radiograph of the hip. This technique assumes that the acet-

\textsuperscript{528} F. S. HADDAD, D. S. GARBUZ, C. P. DUNCAN
Coronal planar image through the centre of the femoral head. The CEA is measured as the angle between the vertical axis and the line connecting the centre of the femoral head to the lateral acetabular margin. The 90° position corresponds to the classical CEA of Wiberg on the anteroposterior radiograph of the pelvis. The preoperative angle in this patient was 12.6°.

Measurement of the CEA at the 25° position of the right hip. The preoperative angle was 17.2°. This is an example of how the pelvic model is rotated around a vertical axis to obtain CEAs in 100 increments from the anterior (0° position) to the posterior rim (180° position) of the acetabulum.

Corresponding postoperative CT scan slices illustrating the improved coverage with an angle of a) 38.7° in the 90° position and b) 50.4° in the 25° position.
Abulum and femoral head are spherical and congruent, and is susceptible to errors produced by alterations in positioning and divergence of the x-ray beam. It is also complex and time-consuming. Chosa et al.

8 have used the CEA on the AP and false-profile views to define a mathematical formula for acetabular cover. This is based on the same assumptions as Konishi’s technique and has similar drawbacks, although it may be useful for large screening studies.

Acetabular cover may be ideally assessed by CT which provides 3D information with high spatial resolution. 5,11,19-21,31,32 The method of Klaue et al. 11 involves tracing the acetabular cartilage and femoral head on to multiple axial images. The overlapping contours are analysed by a 3D graphics program which gives a reconstruction of the cartilage of the hip. The technique of Murphy et al. 5 involves the construction of surface contour maps of the acetabular surface and femoral head derived from axial images, from which the acetabular orientation can be determined. Containment of the femoral head is defined in terms of anterior, lateral and posterior (centre-edge) angles. The anterior and posterior angles are, however, measured in a transverse plane and are not analogous to the CEA which is measured in a vertical plane. Anda 33 suggested that the terms anterior and posterior acetabular sector angles should be used, rather than anterior and posterior CEAs. The limitations of these techniques include the need for specialised computer and graphics equipment, and the time-consuming nature of the analysis. Abel et al. 16 have indicated the significant advantages of 3D reformatted images over plain CT.

Our method of CT analysis has distinct advantages. The technique is not time-consuming: a single hip can be analysed in approximately 20 minutes. It is reproducible with small inter- and intraobserver variability for normal hips, 22 and small variability for dysplastic hips. The CT results are directly comparable with the findings on plain radiographs. The CEA of Wiberg, as defined on an AP radiograph, is equivalent to our CEA at the 90° (lateral) position, and that as measured from a false-profile view (VCA) is equivalent to our CEA at the 25° position.

Our technique has proved to be invaluable when planning surgery. There is much individual variation among patients with dysplasia of the hip. 1,7,11 We are able to define the degree of correction, in terms of angular cover of the femoral head, required in any single plane at the time of surgery. The cover of a dysplastic acetabulum can be compared with mean normal values, and the amount of rotation required to correct the dysplasia can be measured from the graph as the difference between the dysplastic hip and the normal control hips at various points along the curve. The use of angular measurements also allows for variations in the size of the patient.

The data obtained are easily presented in graphical form, can be used when counselling patients, and give a clearer indication of the cover obtained than any of the indices on plain radiographs. Ultimately, they may help to define subpopulations of patients with dysplasia who may benefit from other interventions. 27

The technique has other potential applications. CT reformating is gaining popularity in the management of neuromuscular disease of the hip, 36,38 and has been used to plan computer-assisted periacetabular osteotomy. 25 In future it may be used in the assessment of subluxation of the hip, 35 and for measuring the thickness of cartilage. 36

There are, however, some important limitations. It is not ideally suited to patients with non-spherical femoral heads since the centre of the femoral head cannot be defined precisely. Patients who need periacetabular osteotomy require spherical or nearly spherical femoral heads for the procedure to succeed, and previously described techniques have assumed sphericity of the femoral head. 1,14 Malalign-

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Graph of postoperative cover compared with ‘normal’ controls. This curve was used to determine the degree of correction required and to assess whether this had been achieved postoperatively.

Graph showing pre- and postoperative cover in a patient who was effectively overcorrected anteriorly and laterally but slightly undercorrected posteriorly.
ment of the pelvis on the CT scanner will affect the measurements. While lateral pelvic tilt can be controlled by assessing the anteroposterior scout image, the vertical tilt (i.e., lumbosacral lordosis or kyphosis) is difficult to control and may lead to inaccurate measurements. Abel et al have shown, however, that some of these errors are overcome by 3D reformatting. There is also concern about the dose of radiation to the reproductive organs, especially since most patients with adult acetabular dysplasia are women of child-bearing age. MRI may ultimately be used, and would have the potential for dynamic weight-bearing studies.

The surgical correction of acetabular dysplasia requires clear visualisation of the underlying anatomical abnormalities so that reconstruction can be planned appropriately. The desired degree of correction and the effect of under- or overcorrection on the outcome have not, to date, been clearly determined. The 3DCT imaging technique which we describe is simple and reliable and can play a clinical role in the diagnosis and quantification of acetabular dysplasia, in the planning of rotational acetabular osteotomies and the evaluation of the radiological correction obtained.

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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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