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Simulation of acetabular coverage of femoral head using anteroposterior pelvic radiographs

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Abstract We developed a computer program to perform three-dimensional analysis of the acetabular coverage of the femoral head using two anteroposterior (supine and erect) radiographs of the hip. The center of radiation was marked, and an additional vertical line was placed on radiographs in the neutral standing position, permitting estimation of change in pelvic tilt and its effect on acetabular coverage. We studied 64 normal hip joints, 82 acetabular dysplastic hip joints, and 15 hip joints that had undergone rotational acetabular osteotomy (RAO). In normal hips, the pelvis tilted posteriorly on standing, and the anterior acetabular coverage decreased, but the extent of reduction was not significant. However, in dysplastic hip joints, the pelvic tilt changed from the posterior to anterior direction and from the painful side to the nonpainful side with progression of osteoarthritis. While RAO provided sufficient correction of anterior coverage for acetabular dysplasia, lack of posterior coverage was sometimes observed.

Introduction

Many three-dimensional (3D) systems have been developed to increase the accuracy of determination of acetabular coverage [1, 4, 5, 10, 13]. Computed tomographic (CT) 3D reconstruction techniques utilize images obtained with the patient supine. Compared with CT, obtaining two orthogonal anteroposterior (AP) radiographs is significantly less expensive and results in greatly diminished exposure to ionizing radiation.

The purpose of this study was to develop a computer program to perform 3D analysis using two AP radiographs of the hip taken in the supine and erect positions.

We analyzed the more accurate coverage with correction of the pelvic tilt in the standing position, and investigated the effect of direction and degree of tilting on acetabular coverage.

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Patients and methods

We used AP radiographs of 64 normal hip joints of 32 subjects, including 10 men and 22 women aged between 14 and 68 years (mean age 43 years). They had slight low back pain, and hip radiography was performed to rule out hip disease. They had no abnormalities in their hips, lower extremities, or gait, no abnormalities on radiographs, and no specific spinal lesions.

We also examined AP radiographs of 82 dysplastic hip joints of 47 subjects, including 7 men and 40 women aged between 18 and 63 years (mean age 39 years).

An additional 15 subjects who underwent rotational acetabular osteotomy (RAO) [11] more than 5 years before the study were also examined. They included 3 men and 12 women aged between 19 and 49 years (mean age 28 years), and each had normal gait and activities of daily living with sufficient lower extremity muscle power.

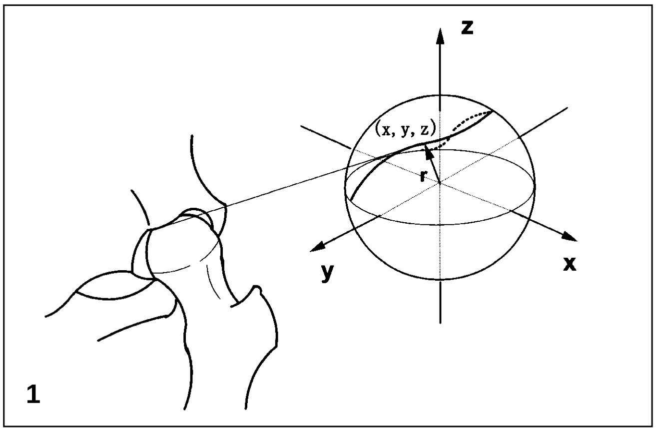
3D method of analysis

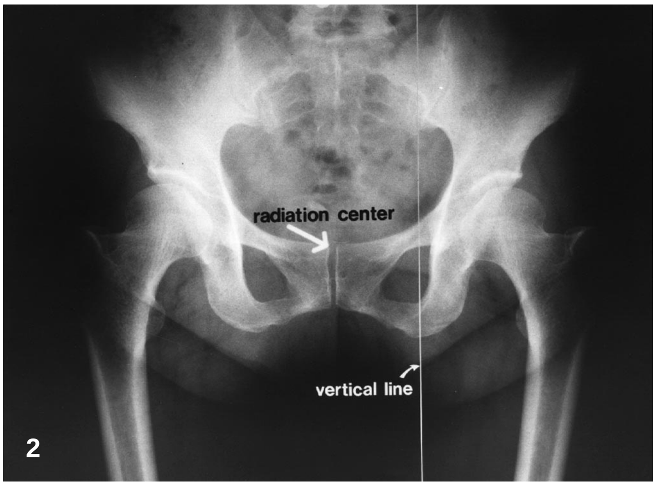
Our technique was based on the method of Konishi (ACX method) [7], i.e., determination of the *y* and *z* coordinates using a plain AP radiograph and of the *x* coordinate using the equation of spheres (Fig. 1). Assuming that the femoral head was spherical and the contour of the projected shadow of the head was ellipsoid, the center of the sphere and its radius from the contour could be determined using the least-squares method.

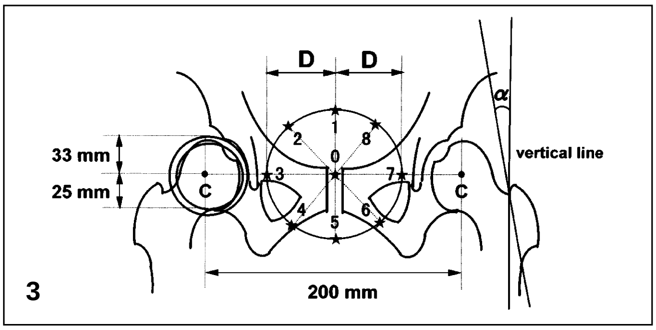
The computer program (HIP.EXE Ver4.3Xen) was designed using an N88 BASIC (NEC, Tokyo) and requires a personal computer (PC 9800BX, NEC, Tokyo) and a digitizer (KC5500, Graphtec, Kobe).

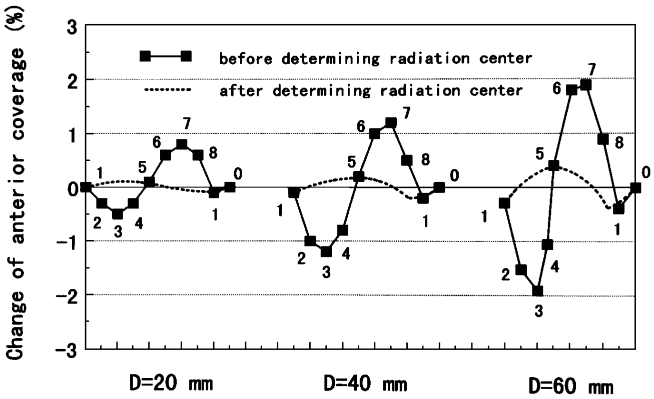
With the conventional procedure using only supine AP radiographs, values different from the true coverage are sometimes obtained because the effect of pelvic tilt is not considered. We therefore marked the center of radiation and placed an additional vertical line on the AP radiograph in the neutral erect position (Fig. 2).

We traced all contours of the femoral head and acetabulum, and determined the radiation center, vertical line, center of symphysis pubis, and teardrops using the digitizer. The vertical line was









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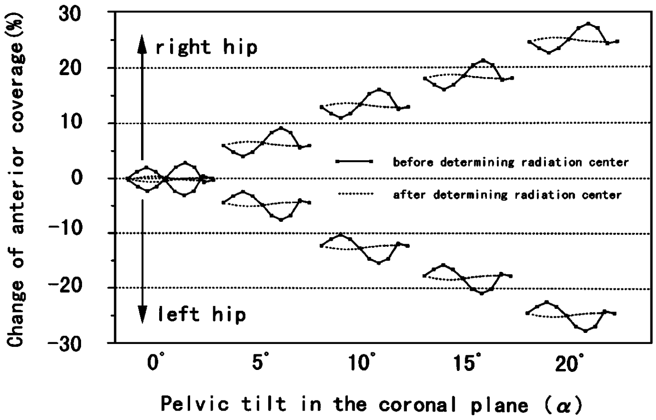

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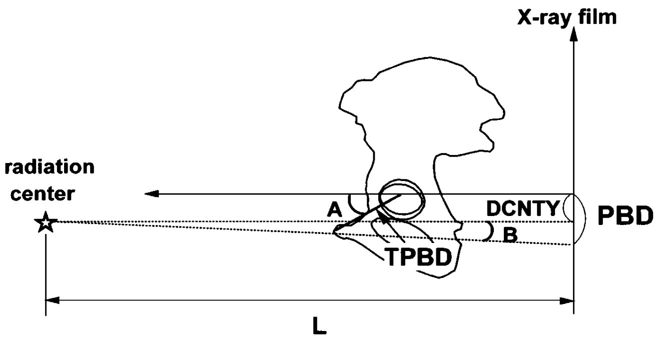

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Fig. 1 Schema used to determine the *y* and *z* coordinates using a plain anteroposterior (AP) radiograph and the *x* coordinate using the equation of spheres ($x^2 + y^2 + z^2 = r^2$)

Fig. 2 The center of radiation was indicated during radiography with a radiopaque marker. The *vertical line* was determined by placing a radiopaque wire perpendicular to the floor on which the patient stood

Fig. 3 Simulation model of the hip joint: the radius of the femoral head was 25 mm, the radius of the acetabulum 33 mm, the acetabular coverage 50%, the length between the bilateral centers of the femoral head (C) 200 mm, and the CE angle 0°. The *central circle* with numbered points 0–8 represents the deviation of the radiation center, α represents the gradient of the vertical line, and *D* represents the distance from the radiation center to the center of the symphysis pubis

Fig. 4 With the radiation center undetermined, the anterior coverage varied by less than 4% with D = 20–60 mm and α = 0°. Varying the position of the center mark did not significantly affect the anterior coverage

Fig. 5 Placement of the vertical line significantly affected the anterior coverage. Increasing the pelvic tilt in the coronal plane from 0° to 20° changed the anterior coverage by more than 20% (*D* = 60 mm)

Fig. 6 Procedure for estimating the angle of pelvic tilt: If the center of radiation is determined on a radiograph, the angle of tilt *(A)* and the true PBD (TPBD) can be estimated by equations (1) and (2):

$$PBD = TPBD\,[\sin(A) + \cos(A)\tan(B)] \quad (1)$$

$$\tan(B) = [TPBD\sin(A) - DCNTY]/[L - TPBD\cos(A)] \quad (2)$$

PBD: The distance between symphysis pubis and BCF; BCF: The line connecting the bilateral centers of the femoral heads; DCTNY: The distance between the radiation center and BCF on the X-ray film; L: The distance between the radiation center and the X-ray film

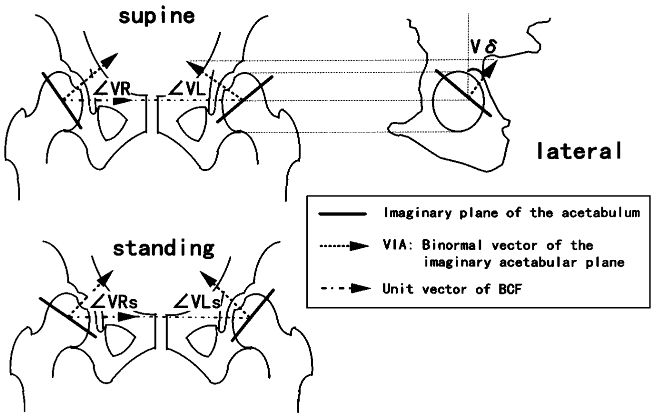


Fig. 7 To calculate the angle of tilt, we determined the bilateral unit vector of BCF under conditions (1), (2), and (3):

$\angle$ VRs – $\angle$ VR ≒ 0 (1)

$\angle$ VLs – $\angle$ VL ≒ 0 (2)

⊿ V δ (R) ≒ ⊿ V δ (L) (3)

⊿ V δ (R): Change of V δ in the right hip; ⊿ V δ (L): Change of V δ in the left hip

determined by placing a radiopaque wire perpendicular to the floor on which the patient stood. We then made a 3D contour of the acetabulum, and calculated the coverage rates (total, anterior, posterior) and all indices (additional "d" indices were also estimated after correcting for the pelvic tilt, e.g. center-edge angle: CEd, and acetabular-head-index: AHId).

The accuracy of our system and the usefulness of these marks were investigated in the simulation model. In fact, the position of the radiation center on the 64 normal real radiographs varied within 70 mm horizontally and 120 mm vertically. We therefore analyzed the change in values with displacement of the radiation center (numbered points 0–8 in Fig. 3), i.e. with change in distance from the center of the symphysis pubis (D = 20 ~ 60 mm) and the gradient of the vertical line ($\alpha = 0 \sim 20°$) in this model (Fig. 3). The gradient indicates the tilt of the vertical line that was intentionally induced to determine the significance of this line.

While varying the position of the center mark did not significantly affect anterior coverage, placement of the vertical line did (Figs. 4, 5). The vertical line thus made possible more accurate analysis of coverage.

Moreover, the center mark was very important to analysis of the pelvic tilt in the sagittal plane. We recently devised our own index following the method of Katada and Ando [6] using the height of the obturator foramen and the distance between the teardrops. Our index (PBD) is the distance between the symphysis pubis and the line connecting the bilateral centers of the femoral head (BCF) on AP radiographs. By determining the center of radiation on the radiographs, we could estimate the angle of tilt (A) and the true PBD (TPBD) (Fig. 6).

We calculated the binormal vector of the imaginary plane of the acetabulum, i.e. the average open plane of the acetabulum (VIA). The posterior angle (V δ) between VIA and the coronal plane was the most important variable in determining the angle of tilt. If V δ was decreased in the standing position, this indicated that the pelvis rotated posteriorly. We estimated the change in pelvic tilt due to positional changes by determining the unit vector of BCF as well as the angle of tilt, both of which were calculated by the method demonstrated in Fig. 7.

Statistical analysis

Student's *t*-test was used for statistical evaluation, and P values less than 0.05 were considered statistically significant. In order to determine the dispersion of obtained values and thereby eliminate the digitizing errors, digitization was performed three times for each normal hip. The calculated value was then approximated to the first decimal figure, and the angle of tilt to the second decimal.

Results

In normal hips, each calculated value was less in the standing than in the supine position, but the difference was not statistically significant. V δ decreased on standing, indicating that the pelvis was tilted posteriorly and the plane of the acetabulum faced anteriorly. The reduction of anterior coverage was otherwise insignificant. The acetabular coverage in women was less than that in men, and the posterior tilt in women was significantly greater than that in men (Table 1).

The same tendency was observed for dysplastic hips (Table 1). However, each value in the standing position was significantly less than that in the supine position. Yet each value varied in accordance with the condition of the

Table 1 Calculated values for each group (*RAO* rotational acetabular osteotomy)

		Normal men (n = 20)	Normal women (n = 44)	Dysplastic hip (n = 82)	RAO (n = 15)
Total coverage (%)	Supine	87 ± 6	86 ± 5	63 ± 11 ⎤ **	94 ± 6
	Standing	86 ± 6	84 ± 6	61 ± 11 ⎦	93 ± 5
Anterior coverage (%)	Supine	85 ± 6	83 ± 6	59 ± 12 ⎤ **	91 ± 7
	Standing	83 ± 7	80 ± 6	56 ± 12 ⎦	91 ± 7
A/P ratio[a] (%)	Supine	95 ± 3	94 ± 4	88 ± 10 ⎤ **	95 ± 7
	Standing	93 ± 4	91 ± 5	84 ± 11 ⎦	95 ± 6
CEd angle[b] (°)	Supine	31 ± 6	29 ± 5	9 ± 9 ⎤ **	37 ± 8
	Standing	29 ± 7	27 ± 5	8 ± 10 ⎦	37 ± 11
V δ (°)[c]	Supine	–21 ± 4 ⎤ *	–21 ± 5 ⎤ *	–28 ± 8 ⎤ *	–14 ± 5 ⎤ **
	Standing	–25 ± 4 ⎦	–28 ± 7 ⎦	–33 ± 9 ⎦	–16 ± 6 ⎦
Pelvic tilt (°) sagittal	Posterior	4.2 ± 2.3 —*—	6.4 ± 4.3	5.6 ± 3.9	3.5 ± 2.1

* $P < 0.01$, ** $P < 0.05$

[a] A/P ratio = Anterior coverage/posterior coverage × 100

[b] CEd angle: Center-edge angle with correction for pelvic tilt

[c] V δ: Angle between the binormal vector of the imaginary acetabular plane and the coronal plane (minus indicates backward)

Table 2 Comparison of various dysplastic hip groups and normal hip group

			Coverage (%)		A/P ratio (%)	CEd angle (°)	V δ (°)	Pelvic Tilt (°)	
			Total	Anterior				Coronal[c]	Sagittal[c]
Group 1		Supine	68 ± 11 *	64 ± 11 *	91 ± 7	13 ± 9 **	−25 ± 6 *	1.2 ± 8 *	6.8 ± 3.4
(n = 12)		Standing	63 ± 12	58 ± 13	85 ± 9	10 ± 10	−31 ± 7	(Ps)	(posterior)
Group 2	Ps	Supine	63 ± 10 *	58 ± 11 *	87 ± 11	9 ± 9 *	−30 ± 8 *	0.9 ± 0.4 (n = 11)	
(n = 18)		Standing	61 ± 10	55 ± 10	84 ± 11	7 ± 9	−37 ± 7	(Ps) **	7.0 ± 3.2
	OPs	Supine	68 ± 8 *	64 ± 8 *	90 ± 8 *	13 ± 7 *	−30 ± 6 *	1.7 ± 1.1 (n = 7)	(posterior)
		Standing	65 ± 8	58 ± 8	83 ± 7	11 ± 7	−37 ± 8	(OPs) **	
Group 3	Ps	Supine	59 ± 12 *	55 ± 14 *	88 ± 11	4 ± 10	−28 ± 8 *		
(n = 8)		Standing	54 ± 13	51 ± 16	87 ± 14	2 ± 12	−32 ± 10	2.0 ± 1.3[a] *	3.6 ± 2.3 **
	OPs	Supine	65 ± 9	61 ± 9	91 ± 10	8 ± 9	−27 ± 9		(posterior)
		Standing	67 ± 7	62 ± 8	89 ± 11	11 ± 8	−30 ± 9		
Group 4	Ps	Supine	56 ± 12	50 ± 12	80 ± 12	5 ± 8	−25 ± 5		7.9 ± 3.5 (n = 5)
(n = 9)		Standing	60 ± 13	54 ± 15	82 ± 10	6 ± 10	−31 ± 10	3.1 ± 2.7[b] **	(posterior)**
	OPs	Supine	58 ± 13	53 ± 14	85 ± 10	4 ± 8	−24 ± 5		1.4 ± 2.1 (n = 4)
		Standing	55 ± 13	50 ± 15	81 ± 11	3 ± 10	−28 ± 9		(anterior)**
Normal hips		Supine	86 ± 6	84 ± 6	94 ± 3	29 ± 6	−21 ± 4 *	0.2 ± 1.4	5.7 ± 3.9
(n = 64)		Standing	84 ± 6	81 ± 8	91 ± 4	28 ± 6	−27 ± 6		(posterior)

*$P < 0.01$, **$P < 0.05$
[a] All hips tilted toward the side with less advanced disease
[b] All hips tilted toward the shorter lower extremity
[c] Statistically significant difference compared with normal hips

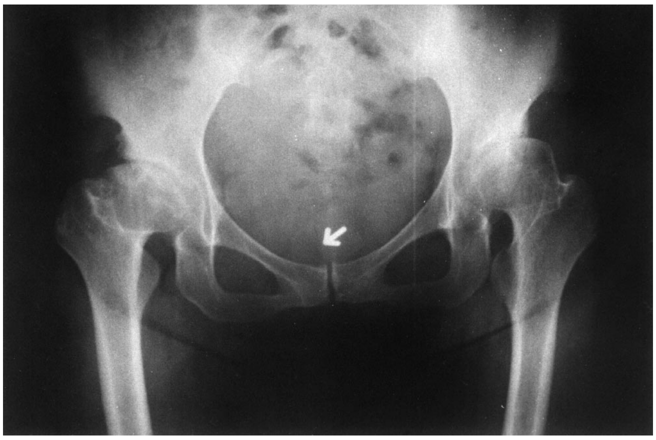
contralateral hip and the pelvic tilt. Therefore, we classified dysplastic hips into four groups as follows.

Group 1: One hip was normal and the other was prearthrotic, i.e., exhibiting dysplastic features without observable narrowing of the joint space or sclerosis.
Group 2: Hips were prearthrotic bilaterally.
Group 3: The two hips exhibited different stages of arthrosis, e.g., one hip had an early arthrosis (sclerotic changes with slight narrowing of the joint space), while the other was prearthrotic.
Group 4: One or both sides had advanced arthrosis (marked narrowing of the joint space), and the lower extremities differed in length.

We examined the pelvic tilt in the coronal plane by classifying the two hips into a painful or more painful side (Ps) and a nonpainful or less painful side (OPs).

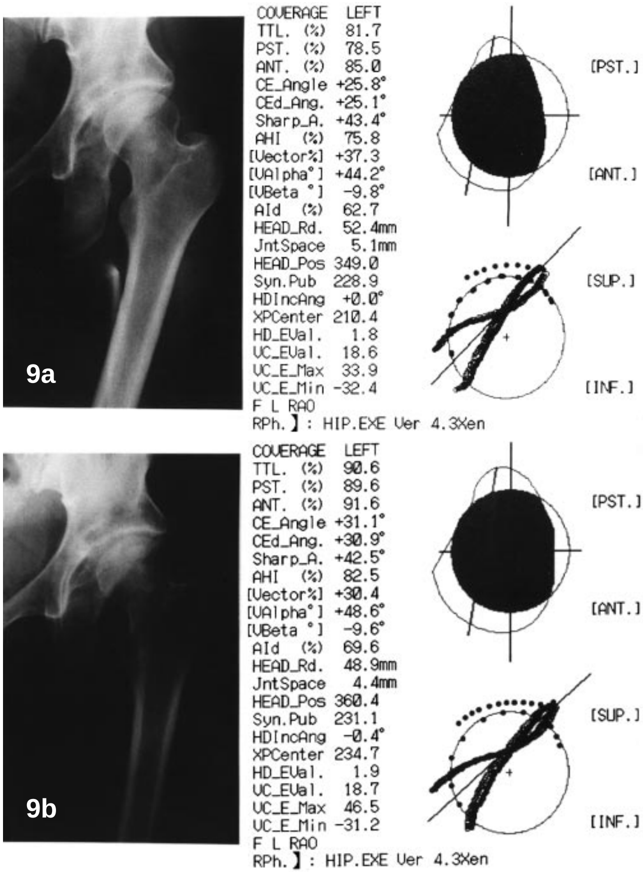
Group 1. In all cases, the pelvic tilt was toward Ps in the coronal plane, and posterior in the sagittal plane. The angle in the coronal plane, but not that in the sagittal plane, was significantly larger than in normal hips. Total coverage, anterior coverage, CEd, and V δ were significantly decreased in the standing position. The anterior-posterior coverage ratio (A/P ratio) was decreased in the standing position, but the degree of decrease was not significant (Table 2).

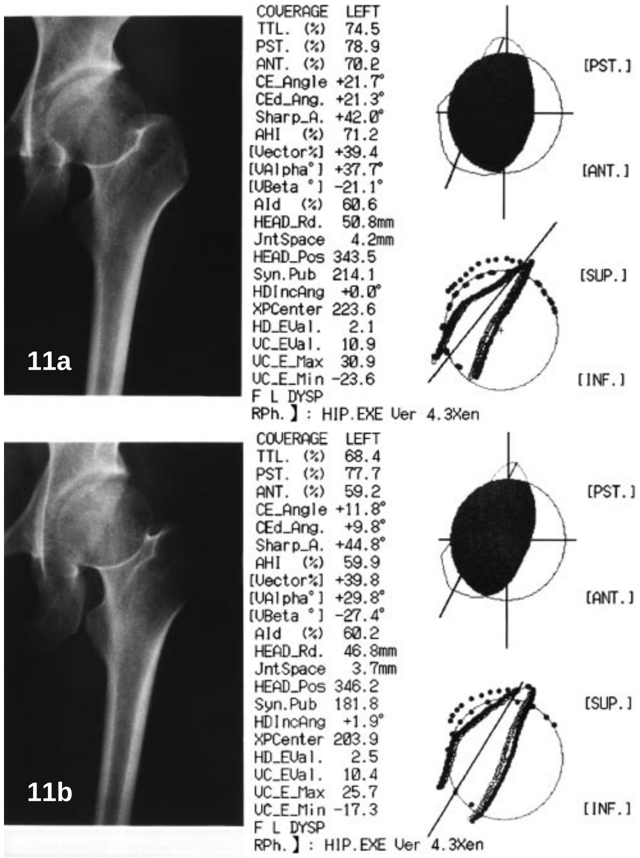
Group 2. The tilt in the coronal plane was toward Ps in 11 cases and OPs in 7 cases. The angle of tilt in the coronal plane was significantly larger than in normal hips. In all cases, the pelvic tilt in the sagittal plane was posterior, and the angle was not significantly larger than that in



		supine right	supine left	standing right	standing left
Total coverage	(%)	42	56	55	50
Anterior coverage	(%)	37	48	48	41
A／P ratio	(%)	80	74	76	69
CEd angle	(°)	−6	5	2	2
V δ	(°)	-36	-40	-25	-34
Tilt of BCF	(°)	0		4.2	
Pelvic tilt	(°)	4.6 anteriorly			

Fig. 8 Calculated values for a 37-year-old woman with bilateral advanced arthrosis. Her right leg was 2 cm shorter than the left one. Each value for the right side (Ps) increased on standing. The increase in V δ on standing indicated an anterior pelvic tilt, and the tilt of BCF (4.2°) indicated that the pelvis inclined to the right by 4.2°. Our procedure also revealed that her angle of pelvic tilt in the sagittal plane was 4.6° anteriorly





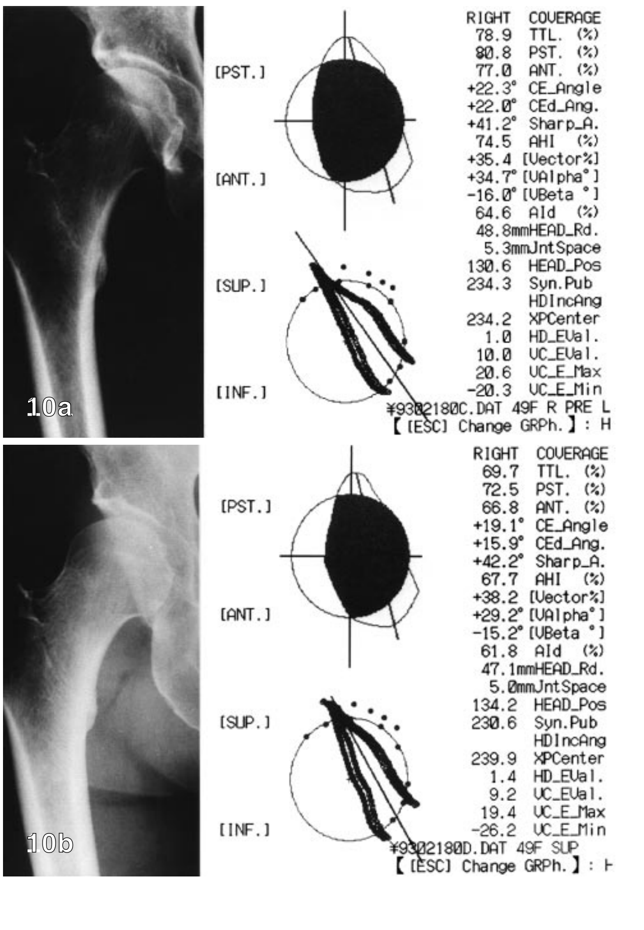


Fig. 9 a, b A 28-year-old woman underwent rotational acetabular osteotomy (RAO) 13 years previously, and had a normal gait and no clinical problems with the operated hip. Her posterior coverage in the supine position was 79%, and the A/P ratio was 108%, indicating insufficient posterior coverage (**a**). On standing, the ratio improved to 102% with the pelvis tilted 5.4° posteriorly (**b**)

Fig. 10 a, b Calculated values for a 49-year-old woman who complained of right hip pain. Each calculated value for acetabular coverage in the supine position was within normal limits (**a**). However, on standing, it decreased to more than 2 SD below the normal with the pelvis tilted 6.2° posteriorly from the neutral position (**b**)

Fig. 11 a, b Calculated values for a 35-year-old woman who developed left coxalgia after a long walk. Each calculated value for the acetabular coverage in the supine position was almost normal (**a**). However, on standing, it decreased remarkably to more than 2 SD below the normal with the pelvis tilted 11.3° posteriorly and 1.9° to the right (**b**) normal hips. All indices of Ps were smaller than those of OPs, and all indices were significantly decreased in the standing position with the exception of the A/P ratio of Ps (Table 2).

Group 3. In all cases, the tilt in the coronal plane was toward the less osteoarthritic side, and the angle was significantly larger than that in normal hips. Moreover, the tilt in the sagittal plane was posterior, and the angle was significantly smaller than that in normal hips. All indices of Ps were smaller than those of OPs, and were significantly decreased in the standing position with the exception of the A/P ratio and CEd. Although each index of OPs tended to be increased, the degree of increase was not significant (Table 2).

Group 4. The tilt in the coronal plane was toward the shorter lower extremity, and the angle was significantly larger than that in normal hips. The tilt in the sagittal plane was anterior in 4 cases (e.g., Fig. 8) and posterior in 5 cases. None of the indices in the supine position differed significantly between Ps and OPs, but each index of Ps tended to increase on standing, while those of OPs tended to decrease (Table 2).

In all patients who had undergone RAO, the pelvic tilt in the sagittal plane was posterior, and the angle was less than that in the other groups. Coverage was sufficiently improved by RAO, and the anterior coverage was satisfactory as judged by the A/P ratio (Table 1). However, some cases lacking posterior coverage due to the anterolateral transfer of the acetabulum by RAO were detected (Fig. 9).

Discussion

Conventional two-dimensional (2D) indices such as the center-edge angle [14], angle of Sharp [12], and acetabular-head-index [3] reflect only to a limited extent the true acetabular coverage of the femoral head. Klaue et al. [8] discussed the importance of congruency, which is measured by the difference between the acetabular radius and the femoral head radius, as it related to the mechanism of the acetabular rim syndrome. Genda et al. [2] calculated the contact pressure of the acetabulum and reported the importance of the relationship between the A/P ratio and the biomechanical factors involved in osteoarthritis. They considered cases of primary osteoarthritis as 3D dysplastic hips, since 2D indices for such cases are sometimes within normal limits. We often encounter such dysplastic hips and other hips that appear to be normal in the supine position but whose anterior coverage decreases with posterior pelvic tilt on standing (Figs. 10, 11).

In dysplastic hips, such as those with early arthrosis with slight pain but without difference in lower extremity lengths, there was a tendency to make up for the insufficient coverage due to pelvic inclination toward the painful side. With the progress of arthrosis, the pelvis inclines to the less painful side, and the angle of posterior tilt decreases. We considered these changes to be physiological compensatory phenomena. We observed an anterior pelvic tilt in those patients with highly advanced arthrosis and difference in lower extremity lengths. The coverage in such cases improved on standing.

Our simulation permitted estimation of acetabular coverage under nearly physiological conditions using a simple system. Notably, 3D reconstruction using CT is not usually performed because of its radiation hazard and high cost. The dose of radiation at the skin is 0.15–0.27 rad for the AP pelvic radiograph and 0.4–1.8 rad for each CT scan slice. 3D reconstruction requires at least 20 slices (slice/1 cm each for 20 cm), and thus the total dose required is more than 8 rad. The cost of CT imaging for a patient in Japan is about ten times that of a plain radiograph. In addition, CT scanning requires a high performance system provided with a reconstruction facility, and therefore we cannot obtain the 3D information in all clinics. On the other hand, our method requires only two radiographs and an ordinary personal computer.

However, our method has several disadvantages. It is based on the assumption that the acetabular surface and the femoral head are spherical. Therefore, many errors in calculated values occur in cases of highly disruptive and incongruent hips. If the contour of the anterior and posterior acetabular rims are unclear on a radiograph, we cannot trace them with the digitizer; this sometimes occurs in patients with RAO. We believe that radiographs must be taken under appropriate conditions to achieve clear visualization of the acetabular rims. Experimental quantitative analysis of pelvic tilt appears to be a roughly presumptive method. Konishi [9] calculated the angle of tilt by other method (normal men: 4.9° normal women: 5.4°) and obtained results almost the same as ours. Also, our concept of the binormal vector in the imaginary plane of the acetabulum appears not to be applicable to highly deformed femoral heads.

Nevertheless, we believe that our method is very useful for the screening of dysplastic hips. Moreover, if RAO is unsuccessful, it will be difficult to fix the acetabular component of total hip arthroplasty under conditions of insufficient posterior coverage. However, the appropriate acetabular covering in RAO can be estimated individually with our method.

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