Radiographic Methods for the Assessment of Polyethylene Wear After Total Hip Arthroplasty

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J Bone Joint Surg Am. 2005;87:2323-2334. doi:10.2106/JBJS.E.00223

CURRENT CONCEPTS REVIEW

RADIOGRAPHIC METHODS FOR THE ASSESSMENT OF POLYETHYLENE WEAR AFTER TOTAL HIP ARTHROPLASTY

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- All wear-measurement techniques assess femoral head penetration and therefore cannot distinguish between true polyethylene wear and bedding-in. Multiple wear measurements that are made at different time-intervals after bedding-in has occurred are required to determine the true wear rate.
- Computer-assisted edge-detection techniques offer improved accuracy and precision compared with manual techniques and appear to be ideally suited for the retrospective and prospective examination of large groups of patients with intermediate to long-term radiographic follow-up (more than five years).
- While radiostereometric analysis offers improved accuracy and precision compared with computer-assisted edge-detection techniques, widescale clinical application is limited because of its relative expense, the required expertise, and the fact that it can only be used in a prospective fashion.

While total hip arthroplasty remains the single most effective method for the treatment of advanced osteoarthritis of the hip, there is general agreement that wear at the bearing surface remains one of the most important factors limiting long-term survival. The early work of Sir John Charnley involving the use of polytetrafluorethylene (Teflon), for example, yielded disastrous clinical results because of accelerated in vivo wear and the resultant debris-induced foreign-body reaction[1,2]. Over time, it has become even more clear that particulate debris from high and ultra-high molecular weight polyethylene implants plays an important role in the development of periprosthetic osteolysis and total joint replacement failure[3-8]. In an excellent review article, Dumbleton et al. surveyed the literature on wear and osteolysis around prosthetic hip implants[7]. That review indicated that the appearance of osteolysis increases as the rate of wear increases and that osteolysis is rarely observed in association with a wear rate of <0.1 mm/yr. Taken together, this information suggests that new or existing bearing surface materials must demonstrate in vivo wear rates well below this so-called wear threshold for osteolysis.

It is important, therefore, for surgeons to have reliable radiographic methods or tools for measuring polyethylene wear in vivo. The development of such techniques has evolved over the last thirty years from manual methods[9-15] to a variety of computer-assisted techniques that can provide either two-dimensional or three-dimensional wear estimates[16-23]. In addition, radiostereometric analysis has evolved and has been used successfully to measure femoral head penetration in vivo[24-29].

The purpose of the present report is to provide a comprehensive overview of the historical and current radiographic methods for the assessment of polyethylene wear following total hip arthroplasty. This report will outline the strengths and weaknesses of these techniques and will highlight their differences in terms of accuracy and precision. Finally, the present review will explore the need to standardize methods of reporting wear in order to allow for useful comparisons between techniques and to permit proper evaluation of new and existing bearing surface materials.

Relevant Concepts

All in vivo techniques estimate polyethylene wear on the basis of femoral head penetration relative to the acetabulum, with penetration of the head being assumed to represent the true loss of polyethylene material. The measurement of femoral head penetration cannot, however, differentiate so-called bedding-in (consisting of creep of the polyethylene and/or settling of the liner) from the true loss of polyethylene material. In other words, penetration of the femoral head relative to the metal acetabular shell may be due to the settling of the liner within the shell and/or permanent plastic deformation of the polyethylene (creep), both of which will not result in the loss of polyethylene material (wear). As will be discussed later, determination of the true wear rate (after bedding-in) requires examination of femoral head penetration at several time-intervals. While keeping these concepts in mind, the terms wear and femoral head penetration will be used interchangeably in the present review, as is common practice in the literature.

In order for any measurement tool to be useful, it is necessary to know its accuracy and precision (see Appendix). In general, there has been variable reporting of these qualities in the literature[16,18,24,30-35]. In part, this is a reflection of the lack of clearly accepted definitions for both terms. In simplest terms, accuracy is the closeness of agreement between a test result and an accepted reference value or the true value[36]. One of the difficulties in the determination of accuracy is related to the complexity of measuring true polyethylene wear, which requires either the use of a phantom to simulate wear or the direct measurement of wear on retrieved acetabular liners, both of which have limitations. Precision is defined as the closeness of agreement between repeated measurements made under similar conditions[37]. The terms precision and reproducibility often are used interchangeably. More recently, the American Society for Testing and Materials redefined accuracy as a function of both bias (defined as the consistent difference between a set of measurements and an accepted reference value) and precision[37]. The relationship between precision, bias, and accuracy is illustrated in Figure 1. As wear studies have involved the use of a variety of ways to report the accuracy and precision of polyethylene wear measurements, it is very difficult to make direct comparisons between published techniques. When possible, the present review will outline the reported accuracy and precision of the various methods of wear analysis.

Finally, wear-measurement methods can be classified on the basis of technique (manual versus computer-assisted) or the method of analysis (uniradiographic versus duoradiographic, dual-circle versus three-dimensional coordinate system). Wear also can be reported as two-dimensional linear wear (that is, wear in the frontal plane), three-dimensional linear wear (which includes wear out of the frontal plane), or volumetric wear (which is derived from either the two-dimensional or three-dimensional linear wear vectors with use of a variety of formulae). For the purposes of the present report, manual techniques, computer-assisted techniques (both two-dimensional and three-dimensional), and radiostereometric analysis techniques will be examined.

Two-Dimensional Manual Techniques

Charnley and Cupic[10] originally proposed a uniradiographic wear-measurement method that was used to determine the distance from the prosthetic femoral head contour to the contrast wire of the cup on the latest follow-up radiograph. Wear was calculated by subtracting the width of the narrowest mea-

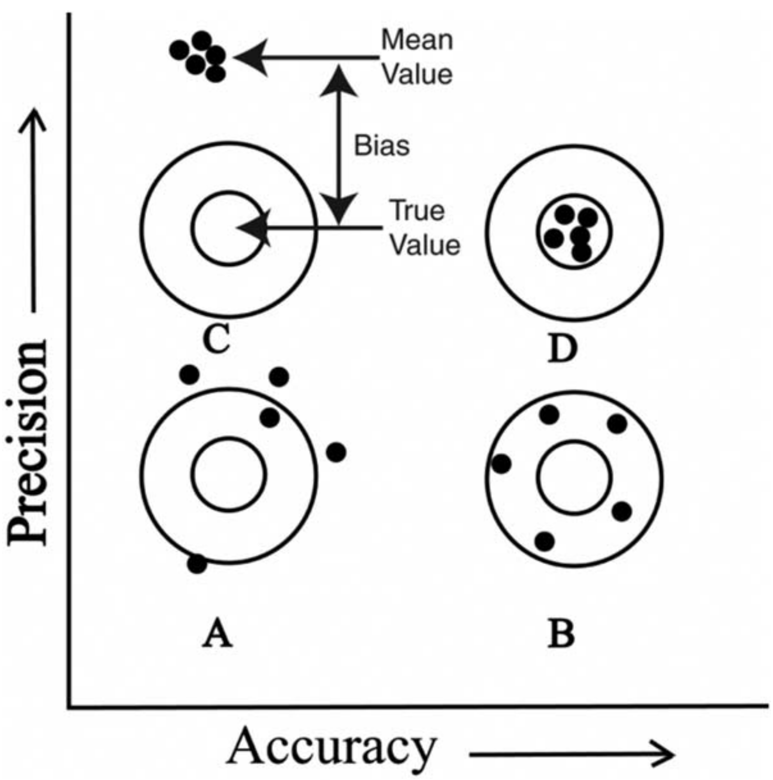

Fig. 1

Diagram illustrating the relationship between precision, bias, and accuracy. Instrument A has low accuracy and low precision, whereas instrument B has high accuracy (the mean value equals the true value) but low precision. Instrument C demonstrates high precision with poor accuracy and large bias, and instrument D is both accurate and precise. Instrument A is unusable, while instrument B can yield useful data if the sample size is adequate and the duration of follow-up is sufficient. Instrument C is precise but inaccurate and contains systematic error (bias). If the bias of the instrument can be corrected through calibration, the instrument may yield acceptable data. (Illustration kindly provided by John M. Martell, MD. Reprinted with permission.)

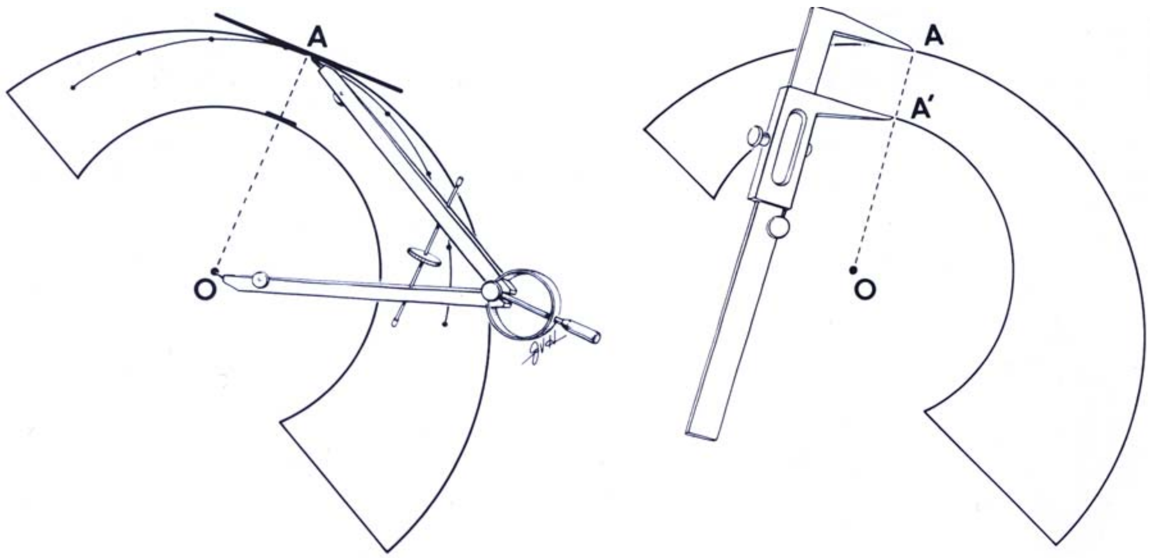

Fig. 2

Illustration depicting the duoradiographic Livermore measurement technique. The direction from the center of the femoral head (O) to the thinnest portion of the polyethylene (O-A) is found at the time of the final follow-up. The distance from the edge of the head to the margin of the cup (A-A´) is measured along this line and is subtracted from the measured polyethylene thickness along the same line on the initial radiograph. (Reprinted from: Livermore J, Ilstrup D, Morrey B. Effect of femoral head size on wear of the polyethylene acetabular component. J Bone Joint Surg Am. 1990;72:518-28.)

surement in the weight-bearing area from the width of the widest measurement in the non-weight-bearing area and dividing the difference by two. However, this technique did not take magnification into consideration and it assumed that wear occurred mainly in the vertical direction.

Charnley and Halley[9] later introduced the duoradiographic technique, which used the same radiographic landmarks as seen on postoperative and follow-up radiographs. Wear was measured by subtracting the distance from the edge of the head to the contrast wire of the cup on the recent radiograph from the measured thickness of the same line on the initial radiograph after correcting for magnification. This method was widely adopted and used in Europe for the evaluation of cemented implants. The accuracy of this technique was reported to be ±0.5 mm[9].

Scheier and Sandel[38] modified the Charnley duoradiographic technique by locating the center of the femoral head with a template. The long axis of the elliptic projection of the contrast wire was drawn, and the distances from the edges of the femoral head to the contrast wire and from the center of the head to the axis of the contrast wire were used to calculate wear. Radiographic enlargement was corrected with this method, but measurement accuracy was affected by the quality of the radiographs and by pelvic tilt.

Livermore et al.[11] improved on these methods by using concentric circles on a template to locate the center of the femoral head and by using a compass to determine the location of the shortest radius from the center of the femoral head to a reference point on the acetabular cup (Fig. 2). Wear was calculated as the difference between caliper measurements on the initial postoperative and follow-up radiographs. All measurements were corrected for magnification with use of the known diameter of the femoral head. The accuracy of this technique was determined by comparing radiographic measurements with direct measurements of the acetabular thickness of retrieved prostheses and initially was reported to be 0.075 mm (range, 0 to 0.4 mm).

Dorr and Wan[14] later described a uniradiographic method of measuring wear that could be used for metal-backed acetabular components. A line was drawn from the superior edge of the metal acetabular component to the inferior edge. Wear was calculated as one-half of the difference between the measured distance from the superior aspect of the femoral head to the superior acetabular rim and the measured distance from the inferior aspect of the femoral head to the inferior acetabular rim. All measurements were corrected for magnification with use of the known diameter of the femoral head, but the authors assumed wear to be horizontal and did not report the accuracy of the technique. However, a modification of this method has since been described; this modified technique takes the direction of wear into account and has been associated with improved accuracy[12].

Recently, Pollock et al.[15] described a uniradiographic technique that follows the dual-circle principle and involves the use of wear templates supplied by the manufacturer. The wear templates, which are created at 20% magnification (to match the magnification of the radiograph), depict a cross-sectional view of the cup and the thickness of the metal shell and show the original position of the femoral head. Wear is calculated by determining the remaining thickness of the polyethylene liner, which is accomplished by measuring the shortest distance between the edge of the femoral head and the inside of the metal shell. The authors who described this technique admitted that the measurements can be inaccurate by as much as 0.5 mm; however, they suggested that this method is more clinically useful than other manual methods, particularly for evaluating thinning polyethylene liners and potential component wear-through in the office setting.

Two-Dimensional Computer-Assisted Techniques

In the 1990s, computer-assisted techniques were developed to reduce measurement variability and to more reliably measure femoral head penetration into the acetabular component. These techniques involved digitizing standard radiographs to create a computer model of the femoral head and the acetabular component. Hardinge et al.[20] introduced the MAXIMA (Manchester X-ray Image Analysis) method of automatic image analysis. This was a duoradiographic method in which radiographs were digitized with a high-resolution camera, a copy stand, and a light box in order to increase the intensity, contrast, and consistency of points and lines. Reference lines were drawn interactively, and software was used to analyze changes in the position of the femoral head. This method was associated with high reproducibility, but no clinical studies were performed and no data on measurement accuracy were provided.

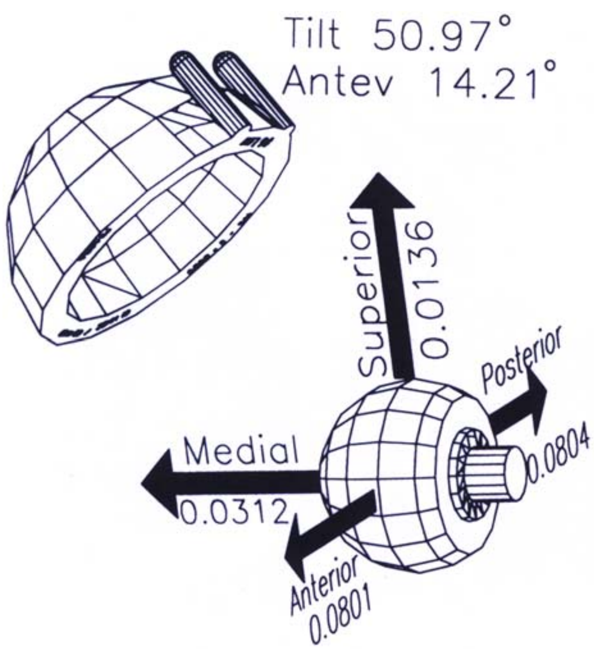

Fig. 3
Illustration depicting the PolyWare technique. This technique creates a three-dimensional solid model of the acetabular component and femoral head on the basis of back-projection of the radiographs (shadow-casting) and CAD/CAM (computer-assisted design/computer-assisted manufacturing) knowledge of the implant. Movement of the head relative to the acetabular shell can then be calculated in three planes. (Reprinted, with permission, from: Devane PA, Bourne RB, Rorabeck CH, MacDonald S, Robinson EJ. Measurement of polyethylene wear in metal-backed acetabular cups. II. Clinical application. Clin Orthop Relat Res. 1995:317-26.)

Ilchmann et al.[39] introduced the EBRA (Ein Bild Roentgen Analyze) method of wear measurement, which originally was designed for migration studies. This was a duoradiographic method that involved the use of a pencil, a ruler, and a digitizing table that was connected to a personal computer equipped with specially developed software. A grid of transverse and longitudinal tangents was drawn to define the position of the pelvis, and a simulated sphere was digitized on the basis of the gridlines. A comparability algorithm was then employed to divide the series of radiographs into comparable subgroups and to analyze the distance between gridlines. Wear-time diagrams were constructed in the horizontal and vertical directions with use of only comparable subgroups of radiographs. Although laborious, the EBRA method has been shown to have the best accuracy when compared with the Scheier-Sandel and Charnley-Duo methods[39] and has been used successfully in Europe for clinical studies[40,41].

Shaver et al.[22] developed an edge-detection technique that involved the use of digitized radiographic images. A software program was used to compute sampling rays emanating outward from the mathematically determined center of the femoral head. The edges of the acetabular and femoral components were identified with use of an edge-detection filter by evaluating the gradients of gray-scale intensity. After correction for magnification, femoral head penetration into the acetabular component was calculated with use of the dual-circle principle. The accuracy of this technique was evaluated in a series of laboratory benchtop studies and was reported to be 0.02 mm without supporting data. This technique was later applied in the clinical setting and was shown to have increased predictive accuracy, particularly for the prediction of long-term wear on the basis of early wear measurements[23].

Three-Dimensional Computer-Assisted Techniques

Devane et al.[16,17] described a three-dimensional measurement technique (PolyWare) for the measurement of polyethylene wear in metal-backed acetabular cups. This technique relied on computer-assisted technology to create a three-dimensional solid model of the acetabular component and femoral head on the basis of back projection of the radiographs (so-called shadovw-casting) and CAD/CAM (computer-assisted design/computer-assisted manufacturing) knowledge of the implant (Fig. 3). With this technique, two-dimensional wear (in the frontal plane) was estimated on the basis of serial radiographs and three-dimensional wear was estimated by incorporating penetration as shown on lateral radiographs. In addition, an algorithm was used to estimate volumetric wear on the basis of three-dimensional head penetration. In their initial article[16], Devane et al. used an acrylic phantom with a simulated head penetration of 8.55 mm and reported a three-dimensional accuracy of approximately 0.15 mm (on the basis of the mean absolute difference between the measured and true displacements) and a volume calculation that was within 8% of the true amount of the polyethylene removed. In addition, on the basis of multiple observations of one good-quality anteroposterior clinical radiograph and one good-quality lateral clinical radiograph, they reported an interobserver and intraobserver reproducibility of ±0.0768 and ±0.0493 mm, respectively (on the basis of the 95% confidence interval of the standard error). In 1999, Devane and Horne[30] reported improved reproducibility and accuracy in association with a more automated imaging protocol involving the use of a phantom setup consisting of two 38-mm-diameter steel balls. Recently, a completely automated version of PolyWare has been developed; this version has been associated with improved accuracy and precision in comparison with previous versions[42].

Martell and Berdia[18] described a semi-automated computer-assisted dual-circle technique (Hip Analysis Suite [HAS]) that was based on edge detection and vector analysis of digital radiographs (so called shadow-comparing) for the determination of polyethylene wear in metal-backed acetabular components (Fig. 4). This novel technique demonstrated approximately ten times better interobserver repeatability (a measure of precision) compared with the Livermore technique performed with either manual calipers or a digitizing tablet. In an analysis of fourteen retrieved acetabular liners, the wear estimates derived with use of the computer-assisted technique differed by an average of 0.08 mm in comparison with the actual wear (as measured with use of an ultrasonic probe), which was substantially better than the estimates made with use of the Livermore technique. In addition, there was good agreement between the computer-assisted wear measurements and 2.0 mm of simulated wear (using a phantom setup in which Lucite was used to simulate soft-tissue absorption and scatter effects). More recently, Martell et al.[19] reported on the use of this technique to provide three-dimensional wear data on penetration as seen on the lateral radiograph. The authors reported that three-dimensional analysis detected approximately 10% more wear than two-dimensional analysis did, but, because of the poor quality of the lateral radiographs, its repeatability was four times worse. They reasoned that the limited improvement in wear detection, coupled with the inferior repeatability, limits the usefulness of three-dimensional edge-detection techniques. Recently, Bragdon[24] demonstrated that the true accuracy and precision of the three-dimensional Martell technique could be maintained with use of two oblique projections, thus avoiding the problems associated with the cross-table lateral projection. Since their introduction, both techniques (Devane's PolyWare and Martell's Hip Analysis Suite) have been used extensively in the literature to assess in vivo polyethylene wear[16-19,30,43-48].

Radiostereometric Analysis

In the early 1970s, Göran Selvik introduced roentgen stereophotogrammetric analysis, now commonly referred to as radiostereometric analysis (RSA)[49]. Radiostereometric analysis is a highly accurate imaging technique that involves implanting tiny radiopaque (tantalum) beads in the human skeleton and around orthopaedic prostheses or hardware, thus allowing for the evaluation of three-dimensional micromotion[50]. Initially, radiostereometric analysis focused on measuring micromotion of prosthetic implants, but it has since been used for many orthopaedic applications, including the measurement of polyethylene wear[25,29,39,50-64].

The measurement of polyethylene wear with use of radiostereometric analysis has been described for both metal-backed and non-metal-backed components. For metal-backed acetabular components, tantalum markers are inserted into the polyethylene liner[29,54] or attached to the end of specially designed towers that are locked into the metal shell[65]. For non-metal-backed components, markers usually are placed in the periacetabular bone or in the periphery of the component. Postoperatively, the patient is positioned over a specialized calibration cage and two simultaneous radiographs are made (Fig. 5). The three-dimensional position of the femoral head with respect to the implanted beads can then be precisely determined over time with use of specialized computer software based on the cage coordinate system. The methodological details of radiostereometric analysis and corresponding software have been fully described[32,49,66,67]. The minimum requirement for three-dimensional wear measurement is visualization of at

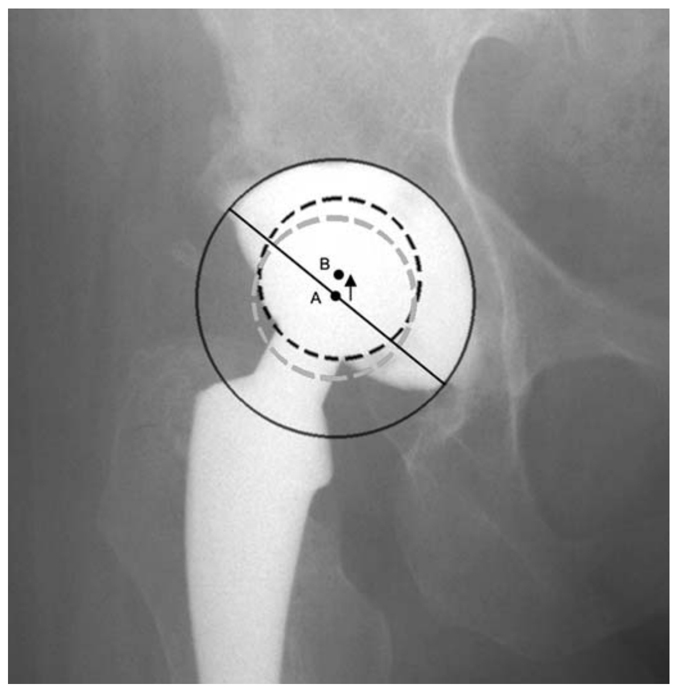

Fig. 4

Radiograph demonstrating the basic principles of the computer-assisted dual-circle technique. The femoral head center and the acetabular center are determined on the basis of edge detection, and motion of the femoral head center (with respect to the acetabular center) is determined with use of vector analysis (A→B), where A is original head center (center of gray dashed line) and B is head center at the time of follow-up (center of black dashed line) on serial radiographs. This technique does not assume that the femoral head center and acetabular centers are identical initially.

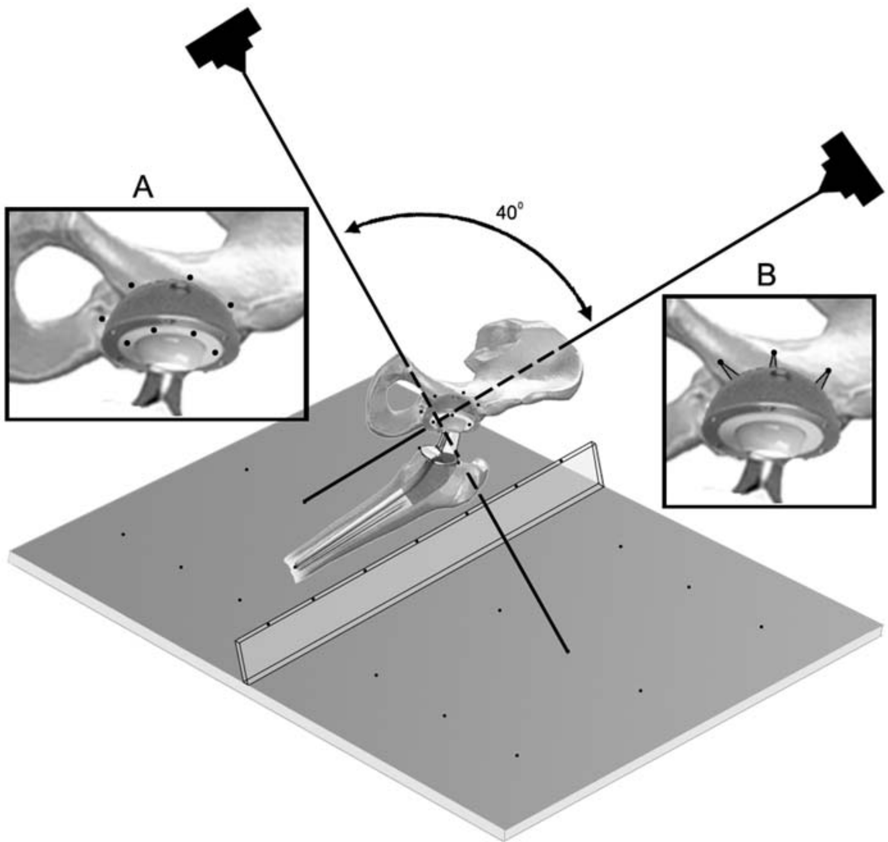

Fig. 5

Illustration depicting the principles of radiostereometric analysis. The space surrounding the implant is calibrated with use of a calibration cage containing tantalum markers. Analysis of wear is based on two simultaneous radiographs, each made at an angle of 40° relative to each other. Motion of the femoral head in three-dimensional space with respect to markers on the acetabular component is reported as three-dimensional wear. Inset A shows characteristic radiostereometric analysis setup with beads in bone around the acetabulum (to measure cup migration) and in the rim of the polyethylene (to measure femoral head penetration). Inset B shows an alternate method, with beads located on towers attached to the metal shell (to measure femoral head penetration).

least three noncollinear markers and accurate visualization of the edge of the femoral head[54]. Wear often is reported as proximal migration (vertical movement) and total migration (three-dimensional wear)[60].

Baldursson et al.[51] were the first investigators to use radiostereometric analysis to evaluate acetabular wear following total hip arthroplasty. Since then, three Swedish groups (from Lund[39,63,64], Malmö[58-62], and Umeå/Göteborg[25,29,54-57]) have reported extensively on the use of radiostereometric analysis as a wear-measurement tool. There has been considerable variability in the reported wear rates as these studies have employed different radiostereometric analysis methods (such as placing beads in the polyethylene as opposed to into the periacetabular bone) and have examined a number of different implant designs and bearing surface materials. One common feature, however, has been the consistent difference between total migration and proximal migration, indicating the presence of so-called "out of plane" wear. Bragdon[24], in a recent study of a cohort of patients with modular metal-backed shells who had been followed prospectively for five years after total hip replacement, reported that the so-called steady-state two-dimensional wear rate (after a bedding-in period) as measured with radiostereometric analysis was substantially (approximately 40%) lower than that measured with Martell's Hip Analysis Suite. One possible explanation for the reported difference in head penetration, and a potential benefit of radiostereometric analysis over edge-detection techniques, may be related to the fact that radiostereometric analysis measurements are made from the rim of the liner and thus any settling of the liner within the metal shell does not affect the measurements.

Recently, Digas et al.[29,57] used radiostereometric analysis to evaluate head-penetration rates associated with conventional and highly cross-linked polyethylene in hips with cemented and uncemented sockets. In the group of hips with all-polyethylene cemented sockets, radiostereometric analysis demonstrated a 50% reduction in proximal wear in association with highly cross-linked polyethylene (as compared with conventional polyethylene) on the basis of radiographs made with the patient standing. In the group of hips with cementless modular sockets, radiostereometric analysis demonstrated a 62% reduction in proximal wear and a 31% reduction in total (three-dimensional) head penetration in association with highly cross-linked polyethylene (as compared with the conventional polyethylene) on the basis of radiographs made with the patient in the supine position.

Assessment of the Accuracy and Precision of Wear Techniques

Several important investigations have been undertaken to explore the accuracy and precision of the various manual, computer-assisted, and radiostereometric analysis techniques[24,31,33-35]. In the study by Barrack et al.[35], wear estimates that were made with use of five different manual techniques and two computer-assisted versions of the Livermore technique were compared with wear measurements that were made with use of shadowgraph technique[13] on twenty-one retrieved liners. The authors found a significant correlation between the radiographic and direct wear measurements with use of linear regression analysis (p = 0.036 to 0.00022); however, there was considerable variability between techniques. They concluded that radiographic wear measurements that are made with use of these techniques should be considered qualitative rather than quantitative. In addition, they thought that the addition of computer digitization to enhance manual methodology did not improve accuracy.

More recently, Hui et al.[31] reported that wear estimates that had been made with use of the Devane and Martell techniques were highly correlated with the actual measurements of two and three-dimensional linear and volumetric wear that were made with use of a coordinate-measuring machine for seventeen retrieved acetabular liners of a single design. The authors found some error or bias in association with both techniques (with PolyWare underestimating wear and the Hip Analysis Suite overestimating wear); the absolute difference between the radiographic estimates and the measured wear was approximately 19% (range, 13% to 24%). Although they thought that the use of these techniques was acceptable in their series of implants with high wear rates (>0.2 mm/yr) and long-term follow-up, the study did not clearly validate the use of these techniques for the evaluation of implants with less wear or shorter follow-up. In addition, the precision of the techniques (as determined with use of standard variance component analysis) ranged from 0.414 mm for PolyWare to 0.242 mm for the Hip Analysis Suite, leading the authors to question the ability of either technique to accurately measure early polyethylene wear when total penetration may be only 0.2 to 0.3 mm.

Using both a phantom apparatus and retrieved acetabular liners, Ebramzadeh et al.[33] demonstrated that computerized wear methods (such as PolyWare and the Hip Analysis Suite) offered greater accuracy (calculated as the absolute error from the true wear) than a variety of manual methods did. However, the greatest improvement in accuracy was seen when the methods were used to evaluate laboratory radiographs (that is, radiographs of the hip phantom apparatus that were made in the laboratory); less improvement was observed when the methods were used to evaluate clinical radiographs. Similarly, Collier et al.[34], with use of an acrylic phantom designed to simulate zero wear, reported acceptable reproducibility but limited accuracy in association with both PolyWare and the Hip Analysis Suite. They thought that the limited accuracy of these computerized methods was due to the difficulty of correctly determining the position of the head relative to the acetabulum when the phantoms were subjected to changes in the radiographic tube position and pelvic position similar to those that would occur in vivo. However, in a recent study involving the use of a phantom hip model and American Society for Testing and Materials definitions, Bragdon[24] reported an accuracy of 0.054 mm and a precision of 0.022 mm in association with the Hip Analysis Suite. In spite of any concerns regarding their accuracy, these techniques have been used to report significant differences between modern low-wear surfaces (such as highly cross-linked polyethylene) and conventional polyethylene at the time of early follow-up[45,68,69].

With respect to accuracy and precision, radiostereometric analysis has been repeatedly and widely validated with use of mathematical analyses[70-74], test-retest investigations[28,54,56,57,75-77], and phantom studies[59,65,78-85]. Recently, radiostereometric analysis was upgraded from an analog system to a digital system[27,66,86] and improved accuracy was demonstrated in association with the digital system[28,79,85]. Bragdon et al.[65] performed a sophisticated phantom study to evaluate the accuracy of radiostereometric analysis as a wear-measurement tool. Under ideal conditions (using beads attached to the femoral component), the accuracy was 0.033 mm for the medial direction, 0.022 mm for the superior direction, 0.086 mm for the posterior direction, and 0.055 mm for the resultant three-dimensional vector with corresponding precisions (at the 95% confidence level) of 0.0084, 0.0055, 0.016, and 0.0135 mm, respectively. Of note, the accuracy was slightly decreased when the femoral head center (as opposed to beads attached to the femoral component) was used to measure penetration, which represents the easiest method to apply in the clinical setting. Using a similar phantom hip setup, Bragdon et al.[79] demonstrated superior accuracy and precision in association with digital as compared with conventional radiography and reported no substantial change in accuracy when the use of beads attached to the acetabular towers was compared with the use of beads inserted in the periphery of the acetabular liner. This was an important finding because beads can be more easily inserted into the acetabular liner in the clinical setting. A recent study by McCalden et al.[87] involving phantoms confirmed the superior accuracy and precision of radiostereometric analysis as compared with both manual and computer-assisted techniques, especially for the measurement of simulated wear of <1 mm.

In the clinical setting, where the absence of a so-called gold standard or true value makes the determination of accuracy impossible, the precision of radiostereometric analysis as a tool for assessing wear has been measured with use of a test-retest protocol. Digas et al.[57] reported a precision of 0.13 mm for the transverse axis, 0.10 mm for the longitudinal axis, 0.20 mm for the sagittal axis, and 0.22 mm for the three-dimen-

TABLE I Summary of Reported Wear-Measurement Techniques

Wear Analysis Technique*	Method†	Technique	Edge Detection
Charnley and Halley[9]	Uniradiographic	Manual	No
Dorr and Wan[14]/Kang et al.[12]	Uniradiographic	Manual	No
Livermore et al.[11]	Duoradiographic	Manual	No
Hardinge et al.[20] (MAXIMA technique)	Duoradiographic	Computer	No
Ilchmann et al.[39] (EBRA technique)	Dual circle	Computer	No
Pollock et al.[15] (templating)	Uniradiographic	Manual	No
Shaver et al.[22]/Pedersen et al.[23]	Dual circle	Computer	Yes
Martell and Berdia[18]	Dual circle	Computer	Yes
Devane et al.[16]	3D coordinate	Computer	Yes
Bragdon et al.[65] (RSA)	3D coordinate	Computer	Yes
Digas et al.[57] (RSA)	3D coordinate	Computer	Yes

*MAXIMA= Manchester X-ray Image Analysis, EBRA = Ein Bild Roentgen Analyze, RSA = radiostereometric analysis. †3D = three-dimensional. ‡2D = two-dimensional, 3D = three-dimensional. §The accuracy and precision as reported in original article are provided, when possible. #Accuracy (based on root mean square error [RMSE]; see Appendix) and precision (based on American Society For Testing and Materials [ASTM] criteria; see Appendix) were calculated on the basis of original published data, when possible. (The calculated accuracy and precision values were kindly provided by John M. Martell, MD. Reprinted with permission.)

sional total on the basis of the absolute mean value (+2.7 standard deviations) of the differences between two subsequent radiostereometric analysis examinations (performed fifteen minutes apart) in forty-five patients. Recently, Röhrl et al.[56] evaluated the precision of wear measurements by repeating 133 radiostereometric analysis examinations after slight repositioning of the patient and found the longitudinal axis precision to be 0.15 mm (95% confidence interval). A summary of the published wear-assessment techniques, including their reported and calculated accuracy and precision, is provided in Table I.

In addition to accuracy and precision, there also is the concept of a detection limit for a given technique. This concept refers to the minimum magnitude of wear that can be reliably detected with use of a given technique. While this concept has not been explored directly in the literature, it is addressed indirectly by all attempts to define accuracy and precision for a given technique. For instance, if a given technique has a measured accuracy of 0.1 mm (100 µm), then it cannot be expected to reliably measure wear at levels below this value. This was confirmed in a recent study by McCalden et al.[87] in which all techniques were unable to reliably measure simulated penetration of <0.15 mm. That study showed that radiostereometric analysis was clearly the most effective method for measuring small amounts of penetration and therefore should be used for measuring low-wear bearings such as highly cross-linked polyethylene. It should be noted that the bedding-in process often results in 0.1 to 0.15 mm of head penetration in the first twelve to twenty-four months, thus placing head penetration in the range of measurable wear for both radiostereometric analysis and computer-assisted edge-detection techniques.

Controversies in Wear Analysis

Two-Dimensional, Three-Dimensional, and Multiple-Vector Wear Analysis

Controversy remains with regard to the benefit of or need for the measurement of three-dimensional wear, that is to say, wear occurring outside of the frontal plane. Many authors have questioned the need for three-dimensional analysis because the majority of wear can be measured on anteroposterior radiographs alone and because decreased precision has been associated with the analysis of lateral radiographs[19,31,47,48,88]. In contrast, other authors have maintained that three-dimensional analysis is required for accurate wear assessment[16,17,30,43,44,89-92]. In addition, the evidence of multiple wear vectors on retrieved polyethylene liners[13,89-92] suggests that the accuracy and precision of wear measurement techniques, which assume a single wear vector, will be limited and may underestimate true wear. However, Hui et al.[31] demonstrated that the polyethylene wear of retrieved liners was not substantially underestimated with use of the Hip Analysis Suite and PolyWare, which assume a single wear vector. Furthermore, the vast amount of evidence linking osteolysis with head penetration has been performed with use of two-dimensional wear techniques[7,8]. Moreover, the calculation of volumetric wear (derived from complex formulae on various assumptions, with use of either the two or three-dimensional vector data[13,16,18,90,93]) may have little benefit compared with the reporting of two or three-dimensional penetration rates alone.

The Bedding-in Phenomenon

There is substantial evidence and general agreement that a considerable amount of the head penetration that occurs within the first years following the index procedure repre-

TABLE I ***(continued)***

Type of Wear Reported†	Reported Accuracy§ *(mm)*	Reported Precision§ *(mm)*	Calculated Accuracy (RMSE)# *(mm)*	Calculated Precision (ASTM)# *(mm)*
2D	0.35-0.5			
2D	0.17	3.05	1.96	1.31
2D	0.075	2.18	1.64	0.62
2D				
2D	0.11			
2D	0.52-0.60		0.25	0.06
2D	0.2		0.047	0.01
2D, 3D, volumetric	0.08	0.004-0.060	0.033	0.072
2D, 3D, volumetric	0.15	0.0493-0.0768	0.025	0.006-1.07
2D, 3D	0.022-0.086	0.0084-0.0135	0.065	0.067
2D, 3D		0.10-0.22		

sents the bedding-in phenomenon, a combination of settling of the modular liner and creep of the polyethylene[23,47,48,88,94] (Fig. 6). In general, the steady-state (true) wear rate can be determined either retrospectively by plotting wear against time[48] or prospectively by determining when the wear rate stabilizes (that is, when interval wear rates are not significantly different[19]). To date, there is no clear standard for reporting wear with regard to defining a starting point or differentiating between steady-state wear and wear that includes bedding-in. Standardizing methods of reporting in vivo wear becomes even more difficult as bedding-in and creep may be unique to the acetabular design, the population of patients studied, and the type of polyethylene used. Accurate and meaningful determination of the true rate of polyethylene wear may require starting wear analysis at twelve to twenty-four months postoperatively, after the majority of bedding-in has occurred. With regard to the reporting of wear, there may be little value to including head penetration that occurs during the first year other than to identify the amount and completion of the bedding-in process.

Image Quality and Positioning Issues

The performance (accuracy and precision) of all radiographic wear-analysis techniques is dependent on image quality and reproducible patient positioning. Efforts to standardize the radiographic technique and patient positioning (for example, by ensuring that proper anteroposterior pelvic radiographs are made with the acetabular position being comparable between intervals and by ensuring that good-quality lateral radiographs are made with the plate perpendicular to the beam) should improve image quality and allow for the best possible analysis. In addition, the evolution from analog to digital films should improve image quality (by eliminating the need to convert analog films to digital images with use of a scanner), thus improving both the precision and the accuracy of these techniques, as already demonstrated with radiostereometric analysis techniques[28,79,85].

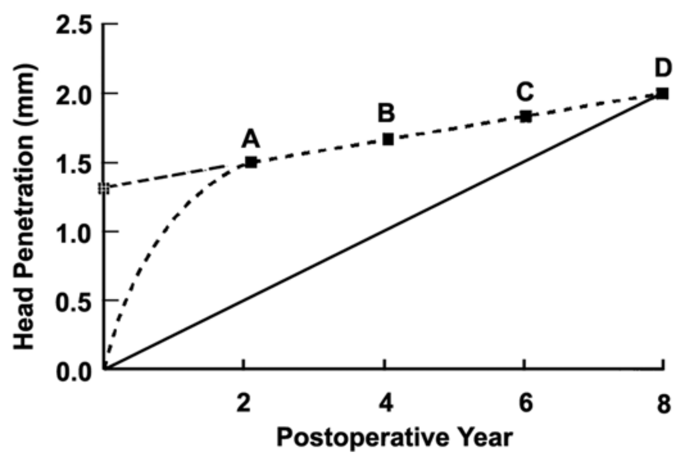

Fig. 6

The apparent wear rate from time 0 to point D includes bedding-in (polyethylene creep and liner settling) and is higher (as indicated by a greater slope) than the true steady state wear rate (line A-D). The magnitude of the bedding-in effect can be estimated by the Y intercept of line A-D (1.4 mm). In this example, the true wear rate can be estimated by the slope of the line fitting the data from two to eight years. (Reprinted from: Sychterz CJ, Engh CA Jr, Yang A, Engh CA. Analysis of temporal wear patterns of porous-coated acetabular components: distinguishing between true wear and so-called bedding-in. J Bone Joint Surg Am. 1999;81:821-30.)

It remains controversial, however, whether supine or standing radiographs are required to accurately determine femoral head penetration. While some authors have demonstrated differences between weight-bearing and non-weight-bearing radiographs[57,95], most authors have reported no difference between the wear measured on supine radiographs and that measured on standing radiographs[24,29,96,97]. Although weight-bearing radiographs may ensure that the femoral head is in contact with the polyethylene, this is perhaps most relevant in the early postoperative period, when muscle tone may not have returned; thus, such radiographs probably are not necessary for subsequent examinations.

Along these same lines, problems with image quality, lack of standardized patient positioning, and poor muscle tone in the early postoperative period may lead to the calculation of outlier data or negative wear. With a properly powered study, however, these potentially spurious results should have little impact on the calculation of mean head penetration rates. Outlier data and instances of negative wear should nonetheless be reported in all studies of wear.

Overview

All in vivo wear-assessment methods are used to measure femoral head penetration and therefore cannot distinguish between true polyethylene wear and bedding-in of the liner. Nevertheless, these tools provide clinically relevant information because there is a clear association between measured femoral head penetration and the development of periprosthetic osteolysis, suggesting a so-called wear threshold. Computer-assisted edge-detection techniques offer improved accuracy and precision compared with manual techniques and appear to be ideally suited for the retrospective and prospective examination of large groups of patients with intermediate to long-term radiographic follow-up (more than five years). Radiostereometric analysis offers improved accuracy and precision compared with edge-detection computer-assisted techniques and therefore is best suited for the examination of modern low-wear bearing surfaces such as highly cross-linked polyethylene, particularly at the time of early follow-up at two to three years. However, the widescale clinical application of radiostereometric analysis may be limited because of its relative expense (requiring a well-trained dedicated technician, a specific calibration cage and radiographic suite, and computer software), the required expertise, and the fact that it can only be used in a prospective fashion (with the implantation of tantalum beads and specialized postoperative radiographic examinations).

There remains a need for agreement on the definitions and techniques used for the determination of accuracy and precision of new and existing wear-measurement tools. Recent work has provided a standard to facilitate future clinical and experimental studies of radiographic wear measurements following total hip arthroplasty[98]. This standard provides suggestions with respect to the type of radiographic projections, the criteria for the inclusion and exclusion of images to be studied, and the conversion of analog to digital images for both radiostereometric analysis and computer-assisted edge-detection techniques.

While the accuracy and precision of the wear-measurement technique are undoubtedly important, the real issue is whether a given technique is sensitive enough to detect wear-rate differences that are biologically important, that is, above or below the threshold of osteolysis. In this way, computer-assisted edge-detection techniques have met this standard as they have been used almost exclusively to define the so-called wear threshold with conventional polyethylene. In the case of highly cross-linked polyethylene, for which the potential for osteolysis has not been established, radiostereometric analysis may be required to define any possible wear threshold because of the low rate of head penetration. Standardized methods of reporting in vivo wear, such as reporting the true wear rate following bedding-in, will allow for useful comparisons between wear techniques and will help to identify any true differences in wear between different implants or materials.

Appendix

eA An appendix showing the mathematical formulae used for the calculation of precision and accuracy is available with the electronic versions of this article, on our web site at jbjs.org (go to the article citation and click on "Supplementary Material") and on our quarterly CD-ROM (call our subscription department, at 781-449-9780, to order the CD-ROM).

NOTE: The authors thank Dr. John Martell for his help and support in creating this review and for providing access to his work, which appears in this manuscript. In addition, the authors acknowledge the PhD work of Dr. Charles Bragdon, which has been invaluable to the creation of this review.

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The authors did not receive grants or outside funding in support of their research or preparation of this manuscript. They did not receive payments or other benefits or a commitment or agreement to provide such benefits from a commercial entity. No commercial entity paid or directed, or agreed to pay or direct, any benefits to any research fund, foundation, educational institution, or other charitable or nonprofit organization with which the authors are affiliated or associated.

doi:10.2106/JBJS.E.00223

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