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WEAR MEASUREMENT OF RETRIEVED POLYETHYLENE ABG 1 CUPS BY UNIVERSAL-TYPE MEASURING MICROSCOPE AND X-RAY METHODS

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Background: Polyethylene wear is considered a most important part of periprosthetic osteolysis development. Thus, its measurement is central to contemporary orthopaedics.

Aims: The aim of this paper was to compare the accuracy of three radiographic techniques for wear measurement. Secondly, the influence of the abduction angle of the cup on measurement accuracy was investigated.

Methods: Wear was measured manually in 80 patients by a single observer according to the Livermore, Charnley, and Dorr description. A multi-component statistical analysis was used to test the hypothesis that the Livermore technique was superior. *In vitro* data obtained from a Universal-type measuring microscope served as a gold standard.

Results: *In vitro* measurements showed an average linear wear of 0.363 mm per year (0.000–0.939, SD 0.241) with a corresponding volumetric wear rate of 161 mm^3 per year (0–467, SD 118.2). The Livermore technique showed the least deviation from the optical reference standard and a superior position from the viewpoint of error analysis but the correlation coefficient was slightly less (r = 0.761) than for the Dorr and Charnley techniques (r = 0.795 and r = 0.778, respectively). In addition, the mean error of the Dorr method differed significantly from zero (p = 0.036). Overall, the Livermore technique was the most accurate method for polyethylene wear measurement regardless of the abduction angle of the cup.

Conclusions: The Livermore technique performed manually was more accurate than the Charnley and Dorr methods. Nevertheless, we consider the Dorr technique an adequate tool for day-to-day wear measurements, mainly due to its simplicity.

INTRODUCTION

Of serious concern to prosthetic wear is the generation of submicron-sized particles that provoke a foreign-body inflammatory response which can lead to osteolysis and ultimately prosthetic failure[1]. There are numerous studies supporting this concept, clearly demonstrating an association between high wear rates of acetabular polyethylene (PE) liners and osteolysis[2]. In order to measure the amount and rate of prosthetic wear, various *in vivo* and *in vitro* methods have been developed offering clinicians the ability to identify, monitor, and study prosthetic cup liner wear[3]. *In vivo* wear measurement methods rely on the assumption that a definite relationship exists between quantifiable X-ray penetration of the prosthetic head in the cup and the true amount of wear[3]. *In vitro* techniques are typically based on changes observed in comparison to manufactured trademark prostheses measured directly using floatation or fill-in material (liquid, oil, plaster, wax, etc.)[4], or indirectly with various optical or technical instruments combined with mathematical calculations[5]. A gravimetric analysis is another approach, but it is mainly applicable for experimental purposes.

The Anatomique Benoist Girard 1 total hip prosthesis (ABG 1; Howmedica, Staines, England) has recently been referred to as problematic due to accelerated PE wear[6–10]. Actually, our Department of Orthopaedics was among the first to witness a problem with this prosthesis[11, 12]. Other authors, including the international ABG study group, eventually recognized this disadvantage as well[13]. The main objectives of this study were to accurately report and compare the wear data from retrieved ABG 1 prostheses measured by means of three established radiological techniques, and a novel *in vitro* optical measurement standard. Additionally, the effect of cup abduction angle on *in vivo* wear measurement accuracy was examined to see if this parameter influences X-ray dependent wear measurements.

MATERIAL AND METHODS

Between March 2003 and June 2004, eighty retrieved ABG 1 total hip prostheses were investigated using both *in vivo* radiological and *in vitro* optical wear measurement methods. All the hips were revised due to wear-related complications (osteolysis, synovitis, aseptic loosening). Included were 22 men (27.5 %) and 58 women (72.5 %) with a mean age of 52 years (range 34–65, SD 7.16) at the time of revision. The mean time from the latest X-ray image to the date of revision was 3.2 months (range 0–32, SD 4.32), the mean length of X-ray follow-up was 5.3 years (range 1.9–8.8, SD 1.54), and the mean time from index surgery to the prosthetic removal was 67 months (range 26–106, SD 18.9).

A description of the ABG 1 ("Anatomique Benoist Girard", Howmedica, Staines, England) prosthesis has been published elsewhere[14]. The ABG 1 PE liners (GUR 4150) were ram-extruded and sterilized in air by gamma irradiation. Immediately after retrieval, the liners were visually inspected for signs of surface damage[15] including evidence of ridges between prosthetic head impressions. Then, the polyethylene liners were immersed in Sekusept aktiv (Ecolab GmbH, Düsseldorf, Germany) for 24 hours, and sterilized in formaldehyde for 2 hours. After drying they were photographed, and sealed in plastic film prior to optical measurement.

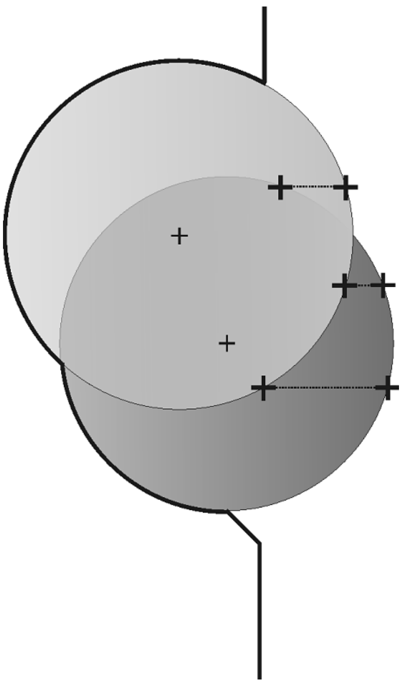

Fig. 1. Principle of wear measurement using a Universal-type measuring microscope. This method is based on the determination of the maximum distance between the manufactured and post-use center of the prosthetic ball in the retrieved cup. These centers are defined by nine space coordinates determined on the surface of the ball using a stylus.

Non-weight bearing radiographs were taken in patients routinely scanned in the lying position using a standardized X-ray beam centring and tube distance from the body. Wear measurements were performed manually by one of us (JG) using the original guidelines of Charnley and Halley[16], Livermore et al.[17], and Dorr and Wan[18]. With the Charnley and Halley method, the wear was obtained after subtracting the narrowest thickness of the cup (measured between the outlines of the femoral head and the cup) from the corresponding thickness in early postoperative X-ray. The Livermore technique required a template of concentric circles and a compass for identification of the shortest distance from the centre of the femoral head to the outer outline of the cup on the prerevision X-ray. Measurement of corresponding femoral head penetration on the postoperative X-ray was then performed. The wear was defined as the difference between postoperative and prerevision figures. With the Dorr method only a prerevision X-ray was examined. A line was drawn from the inferior to the superior edge of the cup followed by measurement of the distances from the inferior edge of the cup to the femoral head and from the femoral head to the superior edge of the cup, respectively. The wear was defined as a half of the difference between these measurements. The measured distances were corrected for magnification and final results were entered into an Excel database (Microsoft) where the relevant calculation was done. The abduction angle of the cup was measured using a horizontal line joining the bottom of Kohler's figures, the contours of the ischial tuberosities, or the obturator foramina.

The *in vitro* wear measurement was performed by one of us (VH) using his original methodology[19] and a Universal-type measuring microscope (VEB, Carl Zeiss Jena, Germany). Briefly, the largest shift from the centre of the original (pre-surgery) prosthetic head position to the centre of the post-use head position was determined

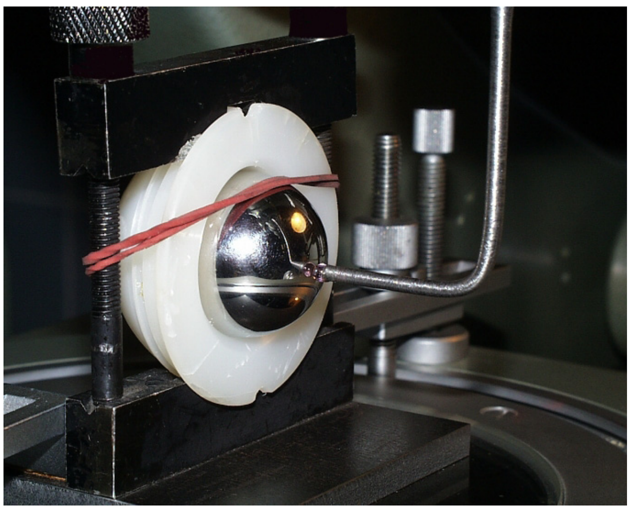

Fig. 2. Universal-type measuring microscope with prosthetic ball fixed in one of the two positions and stylus localized on the surface of the ball.

using a simplified two-sphere model (Fig. 1). This was performed by inserting a prosthetic femoral head into the retrieved cup followed by its fixation in both head positions. For each position nine space coordinates in contact with the ball outside the measured cup were recorded with a touch stylus (Fig. 2). The obtained data were converted into linear values using a computational algorithm[20]. In our study, linear wear rates (i.e. mm per year) had to be compared because the date of the latest X-ray examination could not necessarily concur with the cup retrieval data. If a corresponding ball size was unavailable, then the largest size (27.99 mm) was used. The diameter of the retrieved prosthetic balls ranged between 27.93 mm and 27.99 mm (median 27.98 mm). All of the wear measurements were carried out in a double blind experimental design.

Statistical analysis included parametric and nonparametric tests: correlation coefficients, Mann-Whitney U-test, Friedman test, Wilcoxon test and Sign test for matched data, as applicable. Nonparametric tests were necessary due to the skewed distribution of the data. The Mann-Whitney U-test test was used to compare the accuracy of X-ray measurements in two patient subgroups of different abduction angles. The Friedman, Wilcoxon and Sign tests were used to compare the accuracy of the three X-ray techniques under study. All the analyses were performed using the SPSS version 10.1 statistical package (SPSS Inc., Chicago, USA) with $p < 0.05$ considered significant.

RESULTS

In vitro measurements ($n = 80$) showed an average linear wear of 1.958 mm (0–8.735, SD 1.37) and an average volumetric wear of 869 mm^3 (0–2824, SD 658.2). Two extreme values were excluded from the data by remote value specific analysis (stem-and-leaf plots, normal Q-Q plots). The resulting average linear wear rate of the reduced group was 0.363 mm per year (0.000–0.939, SD 0.241) with a corresponding average volumetric wear rate of 161 mm^3 per year (0–467, SD 118.2).

The average linear wear rates measured using Livermore, Charnley, and Dorr techniques equalled 0.363 mm per year (0.018–1.221, SD 0.2567), 0.397 mm per year (0.034–1.085, SD 0.2761), and 0.408 mm per year (0.074–1.162, SD 0.2761), respectively. Figures 3 a–c show how well these methods correlated to the determined *in vitro* values. The data obtained by Dorr and Charnley technique had less variance around the straight line and slightly higher correlation coefficients compared to the Livermore method. However, no analysis showed any strong correlation between manually performed radiological and direct wear measurement. Moreover, none of the straight lines passed through the intersection point of the figure (Fig. 3 a–c). Statistical differences were assessed, based on both the absolute (radiological value minus the optical standard) and relative (wear rate differences as a percentage of the optical reference value) figures. Overall, the Livermore method had the least error rate in relation to the *in vitro* measurements resulting in a mean devia-

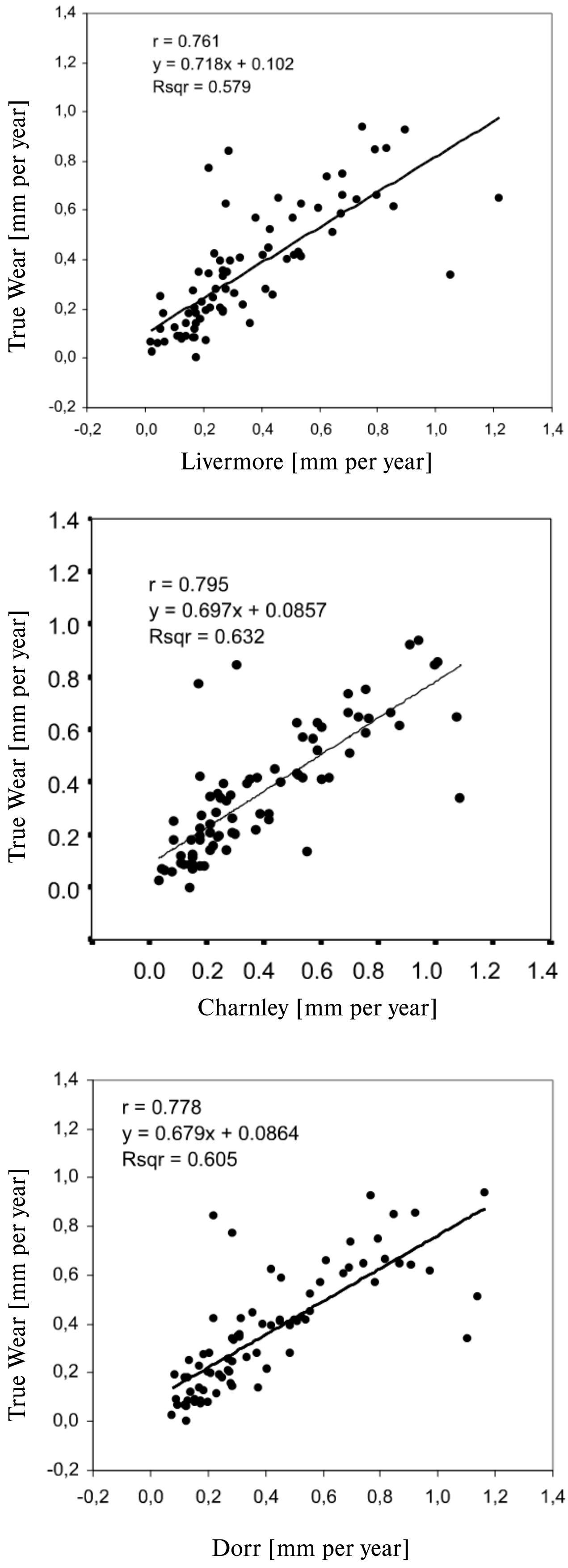

Fig. 3. a-c Regression analysis data showing the correlation between Livermore (a), Charnley (b) and Dorr wear rate data (c), and those based on optical technique.

tion of 0.0012 ± 0.1731 mm (Tab. 1). Furthermore, it was found that the mean error of the Dorr technique differed significantly from zero (Sign test, $p = 0.036$) alerting us to bias in the radiological measurement to significantly overestimate the true wear. Similar findings were achieved for both the Dorr and Charnley method having analyzed relative figures (Sign test, $p = 0.0001$, $p = 0.003$, respectively). The accuracy of each radiological technique was also evaluated non-parametrically (Wilcoxon test) and showed the Livermore method to be the most accurate (Charnley-Livermore, $p = 0.0001$; Dorr-Livermore, $p = 0.0003$). On the other hand, the difference between the Charnley and Dorr techniques was not significant ($p = 0.120$).

The effect of cup abduction angle was analyzed using the Mann-Whitney U-test, Friedman test, and Wilcoxon test. The average abduction angle for the whole group was 44.5° (30°–72°, SD 8.02). The hips were divided into two subgroups according to the measured abduction angle: abduction angles below or equal to 40° ($n = 30$) and abduction angles above 40° ($n = 49$). According to the Mann-Whitney analysis, all three radiological wear measurement techniques were more accurate in cups with abduction angles below or equal to 40°. The Livermore method had the smallest difference in accuracy of wear measurement with respect to the abduction angle of the cup (Mann-Whitney U-test, $p = 0.844$) while the Dorr method showed the largest difference (Mann-Whitney U-test, $p = 0.055$). Interestingly, the Wilcoxon test for matched pairs revealed a significant difference in the accuracy of wear measurements only between the Charnley and Livermore technique ($p = 0.013$) but not for the other pairs. As a result, measurements with the cup abduction angle of 40° or less were the most accurate using the Livermore method, and the least accurate using the Dorr method.

Even though the abduction angle was greater than 40° the Livermore technique showed better accuracy than Charnley and Dorr methods. Moreover, the differences found between single radiological measurements were significant for each pair under investigation (Wilcoxon test, $p = 0.003$ for Charnley- Livermore; $p = 0.001$ for Dorr-Livermore; $p = 0.017$ for Dorr- Charnley).

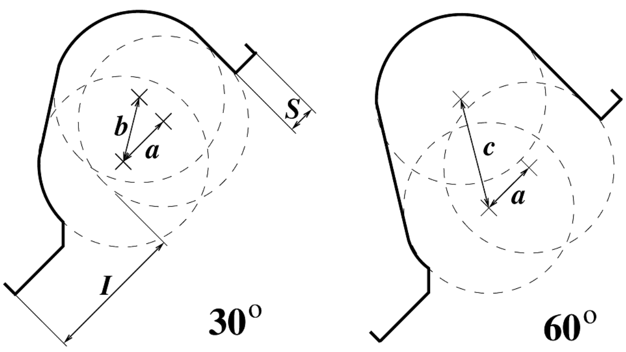

Fig. 4. The accuracy of Dorr and Wan figures to calculate linear wear depends on the angle between the cup inlet and main wear vector. With the increasing angle the difference between inferior (*I*) and superior (*S*) abscissas is diminishing regardless of the femoral ball shift magnitude.

DISCUSSION

This study was focused on measuring the true wear values for ABG 1 prostheses that had been identified before as problematic due to accelerated wear[6-10,12,21]. Based on our *in vitro* measurements[19], the linear wear ranged from 0 to 4.6 mm, and the volumetric wear from 0 to 2824 mm^3 which corresponded to the mean linear and volumetric wear rates of 0.363 mm and 161 mm^3 per year, respectively.

Duffy et al. measured PE wear using computer assistance (Imagica, Viewtec, Saint-Maurice, France) and found mean ABG 1 prosthesis wear rates to be 0.32 mm per year (0–0.95) and 0.45 mm per year (0.12–0.95) for all hips and those waiting to be revised or revised, respectively[7]. Giannikas et al.[21] used the Rokkum and Reigstad measurement technique and reported wear ranging from 0.4 to 4.0 mm (mean 1.02 mm) in hips with accelerated wear. This corresponded to wear rates ranging from 0.063 to 0.76 mm per year (mean 0.25 mm per year). These data fully agree with the findings of the present study. Moreover, they can explain our experience that almost 50 % of the hips with ABG 1 prostheses had to be revised due to wear-related problems up to ten years of follow-up. On the other hand, a 10-year survival of the ABG 1 stem and cup of 100 % and 97 %, respectively, was published by other authors[13]. In fact, they did recognize the problem of accelerated wear with this prosthesis, finding 20 % to have high-wear rates after ten years of follow-up (13 of 65 living patients). Surprisingly, a recent report from the Finnish Arthroplasty Register revealed a 79 % ten-year survival rate when the endpoint was defined as cup revision for any reason[22].

The aim of our study was to compare the accuracy of three manual radiological measurement methods described by Livermore[17], Charnley[16] and Dorr[18] to *in vitro* optical wear measurements[19]. A multi-component statistical analysis demonstrated the superiority of the Livermore technique over Charnley duo-radiographic and Dorr single-radiographic methods. Pollock et al.[23] compared the accuracy of manufacturer-developed wear templates for PE wear measurements to manual radiographic methods (Dorr and Livermore) in 17 retrieved liners after a mean of 12 years. The mean error in the Dorr method (i.e. 1.54 ± 1.21 mm) was much greater than the Livermore method (0.07 ± 0.62 mm) and wear-template method (-0.04 ± 0.28 mm). Similarly, Ebramzadeh et al.[24] confirmed the advantage of the Livermore method under laboratory conditions having compared the median errors of the Livermore, Charnley, and Dorr techniques (i.e. 0.1 mm, 0.23 mm and above 1.7 mm, respectively) but the accuracy decreased when the same methods were used in clinical situations. Surprisingly, the mean error of the Dorr technique was much less in our study than in the above-mentioned studies (Table 1). Interestingly, a modification of the Dorr method taking into account the wear direction has been published recently[25]. Unfortunately,

Table 1. Differences between data obtained from manually performed radiological measurements and those obtained by optical technique.

Technique	Absolute Deviations (mm per year)	Relative Deviations (% of microscopic value)
Livermore[17]	0.0012 (SD 0.1731)	8.54 (SD 52.75)
Charnley[16]	0.0345 (SD 0.1691)	19.51 (SD 56.82)
Dorr[18]	0.0448 (SD 0.1754)	27.06 (SD 56.64)

we are unable to comment on its accuracy, because we have not used it yet.

The correlation between radiological and direct wear measurement found for each method under investigation was rather weak in our study, but still higher than that reported by Barrack et al. who investigated 21 retrieved polyethylene cups by a shadowgraph technique as a gold standard[26]. This group obtained the best correlation for the Dorr technique ($r = 0.72$, $p = 0.00085$) followed by the Charnley and Livermore techniques ($r = 0.53$, $p = 0.014$ and $r = 0.36$, $p = 0.1$, respectively). On the other hand, similar results to our study were published by Ohlin and Selvik[27] for Charnley duo-radiographic method and *in vitro* wear measurements ($r = 0.69$). These discrepancies may stem from dissimilarities between the cups under study because the ABG 1 cup may be more suitable to the Livermore technique than the LSF cup[26] probably due to a difference in the number of holes in the metallic shell. Furthermore, the role of inter-observer variability should not be underestimated suggesting better familiarity with the more complicated Livermore methodology. Finally, the differences in the number of cases included in the separate studies may have influenced the results of the statistical analysis.

As to the effects of abduction angle on accuracy of *in vivo* measurements, we found that the manually performed Livermore method was the most accurate technique for *in vivo* polyethylene wear measurements regardless of the position of the cup (i.e. wear direction). Moreover, in our study the Dorr method had better accuracy when used with the abduction angle of the cup below 40° compared to a greater angle. This seems to be in conflict with Pollock et al.[23] who concluded that the Dorr method was becoming very inaccurate with central wear of the polyethylene cup (i.e. with a lower abduction angle of the cup). Based on the geometrical analysis it is evident that the original Dorr and Wan figure functions well, providing the wear vector is directed up to 30° against the plane of the polyethylene cup. Actually, the higher the angle between the cup and the wear vector, the higher the error of the measurements according to Dorr and Wan (Fig. 4). In fact, the majority of our hips were those with asymmetrical wear mode with the main wear vector directed superiorly which might have been related to both the abduction angle of the cup in our study (mean 44.5°) and the neck-stem angle of the ABG 1 (132°).

We concede a number of weaknesses in this study, e.g. the retrospective origin of the radiographic images obtained from routine practice without strict control over the body position, the fact that none of the radiographic examinations was weight-bearing and intrinsic uncertainties of the *in vitro* optical measurements performed by a single observer.

CONCLUSION

Our study demonstrated (1) an unacceptably high wear rate in retrieved ABG 1 prostheses, indicating the necessity for meticulous follow-up and special attention to all patients carrying these implants, (2) higher accuracy of the manually performed Livermore radiological measurements of polyethylene wear than the Charnley and Dorr techniques with only insignificant deviations from the direct measurement. However, we believe that the Dorr method is adequate for routine wear measurements because of its simplicity and rapidity despite having the poorest accuracy.

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