Validation of acetabular cup wear volume based on direct and two-dimensional measurements: hip simulator analysis

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Abstract The volumetric wear in retrieved cups can be assessed by mathematical conversion based on linear measurements and by a fluid-displacement method. We used a hip simulator model to produce wear in 22-, 28-, and 32-mm hip implants and then assessed the volumetric wear using a gravimetric wear method. We then compared the findings with those obtained with the linear and fluid-displacement methods. For the linear method, we translated the linear wear to the volumetric wear using the equations developed by Charnley et al., Kabo et al., and Hashimoto et al. The fluid-displacement method showed the strongest correlation with the gravimetric wear method, and it was found to overestimate the volume slightly (by 3%–9%). According to the linear wear conversion, however, the equation by Kabo widely underestimated the volume by 33%–40%. The equation used by Charnley tended to overestimate the volume (by 4%–17%), whereas Hashimoto’s equation tended to slightly underestimate the volume (by 2%–12%). The fluid-displacement method demonstrated an average error of 0.34% ± 13.40% when the wear exceeded 400 mm³. The linear wear was thus converted to the volumetric wear most accurately using Hashimoto’s equation, with the average error being −3.8% ± 14.0%. Of the four measurement modalities, the fluid-displacement method showed the most accurate results. We therefore confirmed that the fluid-displacement method is the most accurate way to determine volumetric wear in retrieved cups.

Key words Volumetric wear · Fluid-displacement method · Hip simulator · Total hip arthroplasty

Introduction

It is generally accepted that late implant loosening in hip-joint replacements is most likely caused by the body’s phagocytic reaction to liberated wear debris. Such cases frequently leads to loss of fixation followed by pain due to the excessive implant micromotion. An analysis of the ultrahigh molecular weight polyethylene (UHMWPE) wear rates in such patients is thus important to identify the clinical, material, and design factors that may be associated with problems of osteolysis and implant loosening.1,8,13–17,20,27 A wear analysis of retrieved implants is of particular relevance to validate not only the proposed role of polyethylene (UHMWPE) wear debris in osteolysis4,23,26 but also the wear-rate predictions reported in hip-simulator studies.4,11,12

Radiographic methods have provided many estimates regarding migration of the femoral head into the cup.5,9,21,28 Although there were only a small number of implants, the direct measurement of wear in cups obtained at revised surgery and autopsy cases has provided additional confirmation (Table 1). One observed limitation was the accuracy of the mathematical expression used to relate the linear wear rates to the volumetric wear rates. Of the four pathways used to obtain volumetric wear rates, three relied on a mathematical conversion to obtain the desired result (Fig. 1). Only the three-dimensional contour-measurement method (CMM) and the fluid-displacement method (FDM) directly demonstrated volumetric wear rates. In addition, all such “dimensional” wear measurements included both creep and plastic-deformation effects. We herein use the term “gross wear” to denote wear measurements, including creep or plastic deformation effects.

The late Sir John Charnley measured the gross wear evident in revised polytetrafluorethylene (PTFE) cups and was the first to make the observation that the femoral heads migrated along a cylindrical track (Fig. 2a). Because he found “no exceptions” to this cylindrical wear phenomenon, he reasoned that a simple tunneling equation would suffice to calculate the volumetric wear from direct measurements of the remaining cup thickness. This simple equation...
Wear volume = $\pi r^2 h$  

(1)

allowed conversion of linear wear to volumetric wear.\textsuperscript{4}

Charnley also made an important observation that the PTFE volumetric wear rate increased as the head size increased.

Assessment of the volumetric wear is now understood to be complex depending on the implant geometry and the direction taken by the migrating femoral head. Several studies have pointed out that Eq. (1) was accurate only if the ball migrated directly along the Y-axis (Fig. 2a) of the cup and also noted that this wear direction seldom occurred in practice.\textsuperscript{13-17,20,27} When the migration was not on the Y-axis, an assessment of the wear volume became much more complex.\textsuperscript{8}

For example, there was clearly no cylindrical pathway at wear path “D” (Fig. 2b). In addition, the cup geometry, regarding such factors as a rim bevels or posterior lips (Fig. 2a), clearly introduced additional complexity. Some cup designs may be completely hemispherical (Fig. 2c); and some, such as the Charnley type, may have a cylindrical extension to provide additional stability (Fig. 2d). In addition, with only two exceptions,\textsuperscript{10,16} most of the studies assumed that the radius of the wear pathway ($r$) was the same as the radius of the cup ($R$). In most hip implants the radial clearance tends to be $R - r = 100-200\mu m$ with UHMWPE cups.\textsuperscript{8} This indicates that the wear pathway may have a much smaller contact area until the ball has fully worn in

\begin{table}[h]
\centering
\caption{Comparison of wear methods and the results measured in cups retrieved at surgery or autopsy}
\begin{tabular}{|l|c|c|c|c|c|}
\hline
Study & Year & Head size (mm) & No. & Cup type & Volumetric wear rate (mm/year) & Note \\
\hline
Charnley\textsuperscript{4} & 1969 & 22 & 39 (REV) & PTFE & 835 (DIR) & Eq-1 \\
 & & 25.25 & 11 (REV) & PTFE & 1006 (DIR) & \\
 & & 28.5 & 6 (REV) & PTFE & 1134 (DIR) & \\
 & & 41.5 & 2 (REV) & PTFE & 1905 (DIR) & \\
Kabo\textsuperscript{20} & 1993 & 22 & 5 (REV) & PE & 26 (REP) & Eq-2, 47% < Eq-1 \\
 & & 28 & 23 (REV) & PE & 76 (REP) & \\
 & & 32 & 9 (REV) & PE & 89 (REP) & \\
Hashimoto\textsuperscript{17} & 1995 & 32 & 57 (REV) & NS & 543.9 (REP) & Eq-3: FDM better than REP \\
 & & & & & 1161.7 (FDM) & \\
Syechterz\textsuperscript{27} & 1996 & 32 & 26 (AUT) & 18MB, 8PE & 40 (REP) & Eq-3 \\
Hall\textsuperscript{14} & 1996 & 22.25 & 129 (REV) & PE & 55 (REP) & Eq-1 \\
 & & & & & 82 (FDM) & \\
Hashimoto\textsuperscript{17} & 1995 & 32 & 57 (REV) & NS & 543.9 (REP) & Eq-3: FDM better than REP \\
 & & & & & 1161.7 (FDM) & \\
Sychterz\textsuperscript{27} & 1996 & 32 & 26 (AUT) & 18MB, 8PE & 40 (REP) & Eq-3 \\
Hall\textsuperscript{14} & 1996 & 22.25 & 129 (REV) & PE & 55 (REP) & Eq-1 \\
 & & & & & 82 (FDM) & \\
Sychterz\textsuperscript{27} & 1996 & 32 & 26 (AUT) & 18MB, 8PE & 40 (REP) & Eq-3 \\
Hall\textsuperscript{14} & 1996 & 22.25 & 129 (REV) & PE & 55 (REP) & Eq-1 \\
 & & & & & 82 (FDM) & \\
Berzins\textsuperscript{1} & 1997 & 32 & 15 (AUT) & MB & 94 (FDM) & \\
 & & & & & NS (US) & US: \\
Sychterz\textsuperscript{27} & 1996 & 32 & 26 (AUT) & 18MB, 8PE & 40 (REP) & Eq-3 \\
Hall\textsuperscript{14} & 1996 & 22.25 & 129 (REV) & PE & 55 (REP) & Eq-1 \\
 & & & & & 82 (FDM) & \\
Jasty\textsuperscript{19} & 1997 & Varied & 22 (AUT) & PE & 35 (FDM) & \\
 & & & & & 62 (FDM) & \\
 & & & & & 39 (FDM) & \\
Hall\textsuperscript{15} & 1998 & 22.2 & 112 (REV) & PE & 52 (REP) & Eq-2 \\
 & & 28.6 & 29 (REV) & PE & 62 (REP) & Eq-1 \\
 & & 32 & 23 (REV) & PE & 89 (REP) & \\
Hall\textsuperscript{16} & 1998 & 22.25 & 84 (REV) & PE & 56 (REP) & Eq-2 \\
\hline
\end{tabular}
\end{table}

AUT, autopsy; DIR, direct measurement of cup wall-thickness (linear wear); Eq-1, equation 1: Charnley tunneling equation; Eq-2, equation 2: Kabo modification of Charnley tunneling equation; Eq-3, equation 3: Hashimoto modification of Charnley tunneling equation; FDM, fluid-displacement method (volumetric wear); FEM, finite element analysis method; MB, metal-backed UHMWPE liner; PE, retrieved UHMWPE cup; PTFE, polytetrafluoroethylene; REP, replica method involving assessment of circularity (linear wear); REV, revision surgery; NS, not specified; UHMWPE, ultrahigh molecular weight polyethylene; US, ultrasonography

Fig. 1. Four pathways for volumetric wear measurements. CMM, contour measurement method; FDM, fluid displacement method