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Press-fit stability of uncemented hemispheric acetabular components: a comparison of three porous coating systems

Accepted: 10 October 2001 / Published online: 22 January 2002
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Abstract Cementless acetabular components require good initial fixation to allow bony in-growth. The initial press-fit stability, important for designs that do not rely on supplemental fixation, was examined for three designs with different porous coating systems: beads, fiber mesh, and plasma spray. The ability to withstand tangential loads was determined (maximum rim loads: 122–1730 N). The plasma-sprayed acetabular cups withstood the greatest tangential load within the specified range of motion of 150 μm ($P < 0.01$). Differences in surface preparation of titanium acetabular cups may significantly affect the initial stability of the implants in rim loading.

Résumé Les composants acétabulaires non-cimentés exigent une bonne fixation initiale pour permettre une repousse osseuse. La stabilité initiale après impaction, qui est importante pour les cupules qui n'ont pas de fixation complémentaire, a été examinée pour trois types de cupules avec un revêtement poreux différent : billes, filet et plasma vaporisé. La capacité à supporter des charges tangentielles a été déterminée (charges maximales du

bord: 122–1730 N). Les cupules plasma – vaporisées ont supporté la plus grande charge tangentielle dans l'amplitude de mobilité de 150 μm ($P < 0.01$). Les différences dans la préparation de la surface en titane peuvent affecter considérablement la stabilité initiale des implants soumis à des contraintes de bord.

Introduction

Throughout the 1970s and early 1980s, cement fixation of acetabular components was standard practice in total hip arthroplasty. However, cemented acetabular components were observed to have a high incidence of late loosening [2, 16, 27]. In the last decade surgical methods and technology have evolved to the point where uncemented acetabular designs are used in an attempt to achieve longer-lasting fixation, and numerous cementless acetabular components of varying designs are available. The fundamental principle of metallic, uncemented designs is that a close, conforming, and stable metal–bone interface is required to allow successful osseointegration and longevity of the implant. Frequently, augmentation with screws, pegs, or threads is used to reinforce the initial press-fit of hemispheric cups to facilitate stable apposition at the bone-metal interface. While screw and peg fixation provides initial stability, two fundamental problems have been noted with these systems. First, screw fixation is not innocuous; reports of vascular and neural injury have led to an awareness that there are safe zones in the acetabulum. The literature outlines a limited area suitable for screw or peg placement [9, 10, 24]. Second, screws and the commensurate screw holes have been linked to fretting/wear debris, to the egress of wear particles from the joint, and to osteolytic changes in the pelvis [6, 17].

In the interest of operative time and to eliminate additional risks of screw/peg fixation, many surgeons began using hemispheric, holed components with a simple interference fit. Underreaming the acetabulum by approximately 2 mm has been observed as optimal for a stable

Statement on conflict of interest: No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

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press fit [1, 5]. Though there are clear biomechanical differences between the use of cement, screws, pegs, and interference fit, clinical experience has not appeared to exhibit the dramatic differences [7, 28]. It has been inferred that there is enough initial component stability in each design to prevent micromotion incompatible with osseointegration.

Recently, manufacturers have begun producing acetabular shells without screw holes, thereby addressing the problems of fretting wear, debris egress, and anatomic danger. This development is somewhat limiting since it eliminates the option of adding screws if additional stability is desired. Stability in these implants is achieved only through the initial interference or scratch-fit of the porous surface of the metal shell and the underreamed bony acetabulum. Assuming appropriate pore size of the component, the primary influence on bone ingrowth is the ability to prevent micromotion through the frictional stability between the acetabular component and the bone.

Unlike the overwhelming amount of survival data on cemented acetabular components, studies of the biological success of cementless components without screw or peg augmentation have been relatively few and short-term [4, 23, 25, 28]. At the same time, little consideration has been given to the influence of surface preparation on the stability of these implants. Therefore, the tangential ("levering-out") load-bearing capacities of hemispheric uncemented acetabular components with three different surface treatments were examined.

Material and methods

Uncemented acetabular components from three manufacturers were tested. Each component had a different porous treatment on its outer surface: Richards (Memphis, Tenn.) beaded, Zimmer (Warsaw, Ind.) fiber mesh, and Biomet (Warsaw, Ind.) plasma spray (Fig. 1). All cups were hemispheric with an outer diameter of 56 mm, were titanium, and were equipped with a single insertion pilot hole.

The cups were tested in a synthetic trabecular bone surrogate (Darofoam, Daro, Butler, Wis.). The elastic modulus and apparent density of this foam was assessed and found to be similar to the range found in trabecular bone ($E=147 - 565$ MPa, $\rho_a=0.30-0.54$ g/cm³). The foam was prepared according to manufacturer's directions and cast in 4-in. sections of 4-in. diameter polyvinylchloride (PVC) tubing. With a surgical reamer attached to a drill press, the foam was reamed to 54 mm.

Eleven cups (three beaded, four fiber mesh, and four plasma sprayed) were tested in rim (tangential) loading on an Instron servohydraulic testing machine. To ensure proper seating a uniform compressive load of 980 N was applied to each cup prior to testing. Each cup was loaded through a 3.175 mm-wide platen on one side of the rim, at a stroke rate of 0.0254 mm/s, to a maximum rim rotation of 150 μ m – a displacement inconsistent with bony ingrowth [19]. Linear and rotational motion of the cups was monitored with a Keyence LB301 laser (Keyence, Woodcliff Lake, N.J.) from the opposite side of the rim. A schematic diagram of the test setup is shown in Fig. 2. It was observed that, upon initial rim loading, the acetabular cups uniformly underwent additional linear motion before experiencing rotational motion. Therefore, the maximum load during linear motion was subtracted from the final load at 150 μ m of rotational motion to define the "failure" load. This load was thus indicative of the force required to cause

Fig. 1 Various coating systems tested in this study. From right to left: fiber mesh, beaded, and plasma-sprayed

Fig. 2 Schematic diagrams of test setup in rim loading. The acetabular cup and darofoam specimen are shown in cross-section

Table 1 Mean failure loads. Means values for maximum load at 150 μ m of tangential (rim) rotation for three designs of uncemented hemispheric acetabular cups. Standard deviations are provided in parentheses

Component surface preparation	Mean rim failure load (N)
Beaded	504 (142)
Fiber mesh	455 (351)
Plasma sprayed	1157 (645)

150 μ m of tangential motion, independent of any settling that occurred in the implant. The adjusted maximum loads were used to perform a Kruskal-Wallis rank sum test [13]. A power analysis was performed to assess whether an adequate sample size was used.

Results

Mean "failure" loads for rim loading are given in Table 1. A Kruskal-Wallis test shows a statistically significant difference ($P<0.01$) in maximum load at 150 μ m between the three surface preparations for tangential loading. The plasma-sprayed cups failed at a mean load that was more than twice the maximum load of either the beaded or fiber-mesh cups (Fig. 3).

Fig. 3 Maximum load at 150 μ m of tangential rotation for interference fit acetabular cups

Discussion

During the development of cementless acetabular components, several different ingrowth systems and methods of fixation have been utilized. All of the systems attempted to achieve close, conforming, and stable apposition between the metallic shell and bone. When achieved, this strategy would protect against micromotion and allow bony ingrowth or ongrowth. Micromotion is not conducive to bony incorporation. Even small amounts of motion greater than 150 μ m have been shown to be incompatible with ingrowth [19]. The uncemented system designs must resist the high loads generated about the hip during normal activities in order to resist micromotion and achieve stability. The tangential loads on the specimen may cause rotation of the cup both perpendicular and parallel to the hemispherical plane of the implant. This study investigated the perpendicular fixation, with loads applied through the rim of the acetabular cup.

To resist micromotion, most early uncemented acetabular designs incorporated some form of augmentation device for fixation. These included macrointerlocks such as threads, screws, and pegs. Although threaded cups were commonly used in Europe, this fixation method did not prove superior to the microtextured components commonly used in the United States [15, 28]. Fixation by pegs and screws may present several problems. Despite the popularity and apparent effectiveness of pegs, they can be difficult to apply in cases of anatomic variance. Furthermore, they may prevent full seating of the component [20], penetrate undesirable anatomic areas, fail to seat deeply enough into hard bone or overpenetrate soft bone, or may not obtain purchase in the face of bone loss. Screws can be selectively placed and provide a desirable mechanical advantage. However, they may prove anatomically disastrous if malpositioned [9, 10, 24]. Further, screws may shift or loosen the cup during tightening [18, 26], cause stress shielding [26], or induce fretting [11, 24]. Additionally, empty holes may provide a path for egress of debris from the joint to the acetabular bone, resulting in osteolytic changes [17]. These

problems, compounded with the lack of apparent difference in failure rates [15], have led to the acceptance of hemispheric press-fit acetabular components without holes, pegs, or threads.

In comparative studies the literature is unclear with regard to the most stable acetabular construct. While supplemental fixation appears to provide better resistance to micromotion than the pure press-fit components [11, 14, 21], the position, shape, and implantation technique of the supplemental fixation, as well as the number of fixation points, have critical effects on the ultimate construct strength and stability [1, 3, 11, 12, 22].

To date, there are relatively few data on the success of cementless acetabular components implanted without supplemental fixation [4, 23, 25, 28]. Besides osteolysis, unstable or improper initial fit may be the most common factor in unsuccessful cementless implants [1, 11]. In fact, a stable initial fit and bony apposition are required to allow osseointegration and are correlated with clinical success [8]. Initial stability must be achieved and is provided by interference fit alone in the systems studied in this series. It has been reported that a true hemispheric design with an underreaming of 1-to-2 mm provides excellent stability while avoiding complications such as nonseating or fracture, which may occur with underreaming in the 3-to-4 mm range [1, 5]. Underreaming takes advantage of the viscoelastic properties of the pelvis and allows the acetabular bone to "grab" the cup.

Motion of an implanted acetabular cup can occur in one of two modes. The first is settling within the acetabular bone, which will be highly dependent on the quality of the underlying bone as well cup design and surgical technique. While settling has enormous implications on clinical outcomes, it does not result in significant, relative motion between the bone and the surface of the implant. For that reason it was not examined in this study. In all of the specimens tested, however, initial settling was noted under the applied rim load. The second mode of motion is rotational in nature, caused by the tangential loads posed by the femoral component articulating against the acetabular component. Rotation can occur within the plane of the cup's edge or out of this plane.

In this study, the stability against loads that cause out-of-plane rotations was investigated by providing an applied load to the rim of the acetabular cup. This stability was assessed as a function of surface treatment (fiber-mesh/beaded/plasma spray). The biomechanical comparison required implantation into a standard bone surrogate due to the variability in anatomy and bone properties of human pelvi. While the method of application of the force is different than what would be seen in vivo, the resultant tangential forces between the porous surface of the cup and the bone would be similar in nature. A statistically significant difference was noted in this mode of loading, with the plasma-sprayed acetabular components withstanding the greatest load before undergoing 150 μ m of motion. Stability to in-plane rotations may be different – even though they are also due to tangential loading – due to the continued contact of the full porous surface with the underlying bone. This mode of motion also deserves to be investigated to fully characterize uncemented cup stability.

Overall, the results of this work indicate that the type of surface coating available on a cementless acetabular cup is likely to play a role in the establishment of initial stability, especially in tangential loads causing rotation out of the plane of the cup's edge. For clinical applications this must be considered in conjunction with each surface's proclivity to induce bony ingrowth for long-term fixation.

Acknowledgements The authors would like to thank Mari Milosic and Kevin Ventura for their initial work on this project. Acetabular components were provided by Smith-Nephew Richards, Zimmer, and Biomet. Funding was provided through the Providence Hospital Research and Education Fund.

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