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REVIEW **OPEN ACCESS**

Comparison of the Mechanical and Osseointegrative Performance of Porous Tantalum and Titanium for Acetabular Implantation in Total Hip Arthroplasty: A Literature Review

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Abstract
Introduction: Stability of the acetabular component is a critical factor in the success of primary and revision total hip arthroplasty (THA) procedures. As such, the identification of implant surface characteristics that maximize stability of the acetabular cup is an important research objective. While titanium has historically been the most commonly used implant material, the proportion of THA procedures utilizing porous tantalum (PTa) implants has increased in recent years. The objective of this review is to examine the comparative mechanical and osseointegrative performance of PTa and porous titanium (PTi) and interpret these results in the context of primary and secondary stability of acetabular implants in THA, as characterized by strength of initial mechanical attachment and successful interlocking at the bone-implant interface, respectively.
Methods: A literature search using a predetermined protocol and inclusion criteria yielded 7 articles presenting results of comparative testing of mechanical performance or osseointegration of PTa and PTi in the context of THA.
Results: Neither PTa nor PTi presented consistently superior results in mechanical tests designed to correlate to primary stability at the metallo-biological surface nor in measures of osseointegration intended to represent secondary stability in THA.
Discussion: In comparing PTa and PTi, it appears that the characteristics of the implant coating's pores may have a more significant impact on factors affecting the stability of an acetabular cup implant than the metal selected. However, determining the ideal pore morphology for this application is complex; pore characteristics that would suggest mechanical compatibility may conflict with those that would encourage more effective osseointegration.
Conclusion: When extrapolated to be indicators of hypothetical clinical success, the results of this review are consistent with those of recently released macro-analyses of clinical outcomes: PTa and PTi acetabular cups, as they are currently manufactured, produce clinically equivalent outcomes. In the development and comparison of coating options, pore morphology and its complex effects on stability must be adequately accounted for; only then can we reach a faithful conclusion regarding the ideal porous adhesion surface for acetabular implant in THA.

Keywords: total hip arthroplasty; acetabular implant; porous tantalum; porous titanium; trabecular metal; osseointegration; acetabulum

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Introduction

Over the past 50 years, there has been considerable evolution in the acetabular components used in total hip arthroplasty ("THA") procedures. In the early 1980s, the usage of cementless acetabular implants began to surpass that of traditional cemented components [1]. The transition to increased reliance on biological fixation through bone remodeling for stable long-term attachment of implant components generated significant experimentation in terms of the bone-facing implantation surface, especially in terms of morphological structure [2]. Given that aseptic loosening is the most common reason for THA revision, and that the number of both THA and revision THA procedures performed each year continues to increase [3], the identification of implant surfaces that maximize functional connection between bone and implant and consequently improve stability of the acetabular component is an important research objective.

The ability of an uncemented acetabular implant to achieve adequate stability can be interpreted through two lenses: primary stability, which describes the initial mechanical attachment at the bone-implant interface, and secondary stability, which can be assessed over time as interactive bone remodeling (osseointegration) occurs [4].

Secondary stability relies on primary stability; osseointegration occurs optimally when relative motion at the implant-bone interface is less than 40μm [3], as excessive micromotion will stimulate the formation of a fibrous membrane around the implant, inhibiting successful bone remodeling [5].

Widely recognized as a biologically inert and reliable material for surgical applications, titanium has historically been used as an implant material in THA, and the early aforementioned experimentation related to surface treatments for cementless fixation used titanium and titanium alloys. While various surface treatments to facilitate osseointegration were explored during this experimentation period, including fibermesh, sintered beads, and plasma spray coatings, porous morphologies emerged as a clinically well-performing option [1]. While used in a solid form in medical applications since the 1940s, tantalum, another transition metal, was not used in a porous morphology for human implantation until the 1990s [6]. It was at this point that tantalum began to be considered as an alternative and potential competitor to titanium for usage as an implant material. Following United States Food and Drug Administration clearance of a porous tantalum ("PTa") monoblock acetabular cup in 1997, the common clinical usage of PTa in THA was established [6], and presently, the proportion primary and revision THA procedures utilizing PTa cups continues to increase [7].

As the number of PTa acetabular components implanted into human recipients has grown, increasing the population size available to study, and as time has passed to allow for longer-term evaluation of outcomes, the body of research comparing the clinical results of porous titanium ("PTi") and PTa acetabular cups has experienced significant development. Given the observed trend in the usage of newer tantalum-coated cups in contrast to more established titanium-coated models, despite unremarkable clinical outcomes in comparison to traditional PTi cups [8,9], forming a better understanding of the differences in THA-relevant performance between the two compared materials from a non-clinical viewpoint may illuminate why the superior long-term clinical outcomes excitedly anticipated by many have not been observed. This paper aims to consolidate and interpret the results of research on the mechanical and osseointegrative performance of PTi and PTa in order to comment upon which material, through ostensible differences in resulting primary and secondary stability, would be expected to achieve superior clinical performance in THA.

Methods

A literature search was conducted using two academic databases: Ovid MEDLINE (1946 to January 27 2023) and EMBASE (1947 to January 27 2023). Search terms were ("trabecular metal" OR "tantalum" OR "PTi cups" OR "porous acetabular cup" OR "porous cup") AND ("acetabul*" OR "pelvic*" or "cotyloid cavit*" OR "femur" or "femoral" OR "hip"). After removing duplicates, this literature search yielded 1152 initial results. After filtering of results with titles containing "knee" OR "ankle" OR "osteonecrosis" OR "necrosis" OR "tibia" OR "shoulder", 881 results remained. After manual review of the titles of these results by a single reviewer, 205 results remained. Manual review of the abstracts of these results by the same reviewer resulted in the selection of 7 articles which presented outcomes of comparative testing that were reported as results in this review. Articles that were included were published in peer-reviewed journals, were applicable in the context of THA, and discussed both PTi and PTa, focusing on comparative mechanical testing or measures of osseointegration. Articles that did not provide comparative results of both PTi and PTa, as well as those which focused on comparative clinical outcomes, were excluded. From the 205 results remaining after abstract review, an additional 10 articles were used for the purpose of meaningful synthesis within the existing body of knowledge on the topic.

Results

The findings of the articles included in this review were sorted into two categories, in accordance with the outlined research question: comparative mechanical testing and osseointegration measurement, framed as exemplifying primary and secondary stability in THA. The relevant findings are described below.

Mechanical Testing

Five of the seven included articles presented comparative mechanical testing. Using composite hemipelvises, Beckmann et al. [3] compared relative motion at the bone-cup interface at three load levels and found that the PTi implant showed significantly less motion at the lowest load, but the PTa implant showed significantly less motion at the highest load. Several studies took measurements of the force required to separate implants from bone at varying points in time, all using loading devices to apply precise levels of force, but varying experimental set-ups. Wang et al., who performed a push-out test between porous implants with the same pore size, found that PTa and PTi showed similar peak values of push-out force at 2, 4, and 8 weeks post-implantation [10]. Contrastingly, Wu et al. performed a pull-out test, with five PTi alloy structures with varying porosity levels, and found that the PTi cages with the two highest porosity levels demonstrated statistically significantly higher pull-out strengths than the PTa cage [11]. Bondarenko et al. performed a test of implant break-out force, comparing the force required to detach an implant from both normal and osteoporotic bone tissue 8 weeks after implantation in four available PTi alloy implants against the PTa implant [2]. They found that in both normal and simulated osteoporotic bone, the breakout force of the tantalum was not significantly different than two of the three titanium alloy

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products, but one of the titanium alloy products withstood much lower break-out force than the other three [2]. In a unique test that sought to compare the compression deformation resistance and stress-strain parameters of both scaffold types with that of pig bone, Fan et al. performed uniaxial compression tests on the scaffolds and found that the deformation behaviour and stress-strain parameters of the tantalum scaffolds were closer to that of pig bone scaffolds than the titanium scaffolds [12].

Bone Growth Measurement

Four of the seven included articles presented comparative measurements of bone growth associated with PTa and PTi implants, often taking measurements at several points in time post-implementation. For example, Wu et al. compared bone formation 6 months post surgery post-surgery through a histomorphometric analysis and found that the PTi cage showed significantly higher average daily bone growth than the PTa cage in terms of bone graft inside the cage's gross structure, but bone growth into the pores and bone growth surrounding the implant was comparable [11]. In terms of bone volume inside the cage pores, measured as percentage of available volume utilized, as well as bone volume on the outside of the cage, measured as percentage of available area utilized, the PTi cage showed significantly higher growth of bone volume than the PTa cage. In terms of bone volume on the outside of the cage, measured as percentage of available area, the PTi cage showed higher bone growth than the PTa cage. In a bone healing score, in which the portion of fibrous tissue, cartilage tissue, immature (woven) bone, and mature (lamellar) bone was assessed and a score between 1-10 was assigned using an evaluation matrix, there was not a statistically significant difference between PTi and PTa. While a statistically significant quantified result was not achieved, the reviewers noted that the PTi cage exhibited more mature bone relative to the PTa cage, with a higher proportion of trabecular bone formation, whereas the PTa cage exhibited more cartilage formation, indicating a lower bone maturity relative to the PTi cage. In looking at cell migration into pores, cluster formation, and cell linkage, the PTi cages with larger pore size showed more favourable results than the PTa cage, whose cells displayed a flatter morphology and less interconnection with its surface [11]. Assessing the progression of bone remodeling in a different way and serving as an example of the importance of taking the same measurements at successive points in time, Bandyopadhyay et al. looked at osteoid formation at 5 and 12 weeks post-implantation, and found osteoid formation to be higher for PTa than the PTi at 5 weeks post-implantation. Superior bone interlocking was also observed for than PTa in comparison to the PTi. At 12 weeks, the osteoid formation of PTa continued to outperform that of PTi, but the differences in bone interlocking ceased to be statistically significant [13]. Taking a comparatively gross approach, Bondarenko et al. measured osseointegration in terms of direct bone-to-implant contact as measured in μm found that PTa and PTi did not have significant differences in bone-implant contact at 3 months [14]. Finally, taking steps to minimize uncontrolled variables, Wang et al. used PTa and PTi implants with the same porosity, pore shape, pore size, and pore distribution, and found that the depth and area of new bone in the porous of the implants were comparable at 2, 4, and 8 weeks post-implantation [10].

Discussion

This paper strives to amalgamate the currently disjointed research on the THA-relevant mechanical and osseointegrative performance of PTi and PTa as potential surface coatings for an acetabular implant as part of THA. In assessing the collected results of testing performed, it was found that neither material consistently performed better in either category of testing: those meant to represent biomechanical attachment in THA, nor those measuring bone growth at the metallo-biological interface.

Comparative Mechanical Testing

In comparing the performance of PTa and titanium structures in the included mechanical testing, it was not the inherent properties of the materials themselves (e.g., the modulus of elasticity, or resistance to corrosion) that were compared; rather, it was the results or manifested impacts of the physical properties of the two possible acetabular cup coatings that were consolidated and interpreted. This differentiation is important to establish the novelty and usefulness of this review.

In the mechanical tests performed in the five selected studies, performance of an implant material that would be considered superior or favoured in the context of THA would be that which displayed less bone-implant relative motion at varying load levels and greater force required for separation of bone and implant. Results indicated that there was often no statistically significant difference between the performance of PTi and PTa, or results that were statistically significant but not consistent; for example, one material exhibited superior performance at one tested load level, but the other performed better at another tested load level. Given that neither PTa nor PTi displayed consistently superior results in these mechanical tests designed to correlate to primary stability at the bone-implant interface based on strength of initial mechanical attachment, it would not be expected that significant short-term differences in stability would be seen in clinical outcomes.

Comparative Measurements of Bone Remodeling

Results from comparative testing of osseointegration with PTa and titanium scaffolds provided information regarding which porous material scaffolds experienced superior bone growth at the metallo-biological interface when tested under controlled conditions. This approach, which focused only on the actual observed osseointegrative outcomes can be differentiated from other research which, often by focusing on osteogenic effects of the material (e.g., ability to influence osteocalcin mRNA expression), aims to determine which material would be expected to display better osseointegration from a theoretical standpoint.

In the measures of bone growth measurement obtained from the four selected studies, performance of an implant material that would be considered superior or favoured in the context of THA would be that which displayed more extensive bone remodeling at the bone-implant interface. This would be observed as more extensive growth into and on the surface of the tested scaffold, greater depth and volume of bone growth into pores, and the presence of more mature bone tissue (i.e., more lamellar bone, and less fibrous and cartilaginous tissue and woven bone) [5]. Results indicated that there was often no statistically significant difference between the osseointegration observed with the PTa and PTi surfaces, or results that were statistically significant but not consistent; for example, in some tests, PTa scaffolds experienced quicker and more advanced bone growth, while in others, PTi scaffolds did. Given that neither PTa nor PTi displayed consistently superior results in these measures of osseointegration intended to represent secondary stability in THA based on successful bone interlocking at the bone-implant surface, it would not be expected that significant long-term differences in stability would be seen in clinical outcomes.

Relationship of Findings to Observed Comparative Clinical Outcomes

As described above, when interpretating comparative mechanical and osseointegrative performance as being analogous to primary and secondary stability of acetabular cups in THA, neither PTa nor PTi demonstrated consistent superiority as an adhesion surface. When extrapolated to be indicators of hypothetical clinical success, these findings are consistent with recently released results of clinical performance. In 2022, systematic review and meta-analysis of clinical outcomes concluded that, in applications of primary THA, tantalum and titanium acetabular cups demonstrate clinical equivalence [8] and, additionally, when used in acetabular revision surgery, there was no significant difference in cup survival, no significant difference in the overall incidence of adverse events, and mixed results in terms of incidence of dislocation and infection rate [9].

Other Considerations in Comparative Material Selection

In considering the usage of PTa in replacement of PTi, it is important to be aware that tantalum is more expensive, heavier, and more difficult to process because of its higher melting point [10]. A question thus emerges: why does the proportion of acetabular implants that are PTa continue to increase? Early studies that examined the suitability of PTa for usage in arthroplasty implants used canine models, and the promising results of these studies fueled optimism and excitement in the first decade of the 2000s regarding this new material, described at the time as having a "limitless horizon of possibilities for use" [6]. However, it should be noted that the bone ingrowth seen in more recent human retrieval studies does not match that seen in earlier animal models. For example, Bobyn et al. found 17-25% bone ingrowth into the pores of a tantalum coated acetabular component in a canine model, as published in 1999 [15]. Then, however, upon being able to access acetabular components from human patients undergoing revision surgery, Hanzlik et al. found only ~4% bone ingrowth, as published in 2015 [16]. While it is a ubiquitous fact that medical research performed on animal models may not translate into identical results in human patients, it seems that early studies using animal models that showed exceptional results have fueled the escalating usage of the tantalum material, despite insignificant differences in clinical results that have been published more recently.

Validity of Proxy Application and Interaction of Scaffold Characteristics

Using the two discussed types of testing as explicit proxies for primary and secondary stability, respectively, in order to make direct and unequivocal commentary on the achievement of these states in THA would represent an overly simplified interpretation. Baral et al. demonstrated that the amount of bone ingrowth within a porous component was not necessarily the determining factor of successful implant fixation, finding similar clinical outcomes and long-term fixation amongst implant surfaces that were observed to display a 3-fold difference in bone ingrowth [17]. This suggests that long-term stable fixation relies on factors besides the amount of bone ingrowth. As such, osseointegration measures cannot be used directly as a proxy for secondary stability. In fact, characteristics of an implant that encourage deeper bone ingrowth may create undesirable effects in the quality of the bone that is remodeled. For example, they may encourage stress shielding due to a mismatch between the stiffness of the implant and surrounding bone tissue [10].

Wu et al. described another potential conflict amongst interacting implant characteristics; implant material characteristics that contribute to primary stability may be inconsistent with those that encourage secondary stability, as an increase in porosity that may enable better nutrient transportation characteristics and cell transportation ability may considerably reduce the stiffness of a cage, a factor that must be carefully controlled to optimize bone remodeling [11]. That is, pore characteristics that would suggest mechanical compatibility and thus effective primary attachment may conflict with those that would encourage more effective osseointegration and resulting secondary stability.

The importance of pore morphology has not been widely acknowledged in comparisons of PTa and PTi acetabular implant surfaces to date. Tested materials are simply categorized as being "porous", and exclusive focus is subsequently placed on the metal that is utilized, with indifference to the variability in tested scaffolds' pore characteristics. Studies included in this review act as evidence of the potential significant contribution of pore morphology to observed results. For example, Bondarenko et al. found that when testing several available titanium implants (of varying pore characteristics) with the PTa product, the titanium implant options with a porosity more similar to that of the tantalum implant tested displayed comparable results, while the other titanium implants with different porosity displayed varying results [2]. This demonstrated that it was the pore characteristics that affected the performance more drastically than the material itself. Wu et al. found parallel effects: PTi alloy structures with similar pore morphology displayed results that were similar to each other but significantly different from those of PTi alloy structures with less similar pore morphologies [11]. It should be noted that some authors have acknowledged the potentially overriding impact of pore characteristics in their testing. Wang et al., for example, performed their testing using PTa and PTi implants with the same porosity, pore shape, pore size, and pore distribution; they found no statistically significance difference in any of their results [10]. This commentary can be comprehended within the framework laid by a foundational principle of scientific research: to obtain accurate and meaningful results in studying a causal relationship, an experiment must be designed to control for extraneous variables.

Conclusion

The results of this study suggest that the selection of titanium versus tantalum as the material for a porous adhesion surface does not unilaterally produce a superior outcome in primary nor secondary stability of an acetabular implant in THA. Characteristics of a component coating other than the metal from which it is manufactured are equal, if not greater, contributors to its comparative performance. As such, the results of this study, especially in conjunction with interpretations from other articles referenced in the above discussion, suggest a concrete avenue for future research. In comparisons to this point, pore morphology has not been adequately accounted for; comparing pore morphologies that are potentially non-ideal among materials cannot produce a conclusion as to the ideal porous material. The pore characteristics that result in the best outcome of the complex interplay between mechanical perfection for this particular application and maximal encouragement of osseointegration need to be identified for each material separately. Given their inherent characteristics, this will be different for each material; that is, the porosity that is ideal for acetabular implant usage for titanium is not likely to be identical to that for tantalum. Only after these determinations will comparison of the two options result in a faithful conclusion regarding the ideal porous adhesion surface for acetabular implant in THA. If PTa emerges as superior to PTi for coating of acetabular implants in THA, discussion can then ensue regarding another complex interplay: that of increased cost of raw material and processing requirements against improved clinical outcomes.

List of Abbreviations Used

THA: total hip arthroplasty
PTa: porous tantalum
PTi: porous titanium

Conflicts of Interest

The author declares that they have no conflict of interests.

Ethics Approval and/or Participant Consent

Due to the study reported in this manuscript taking the form of a literature review, ethics approval and participant consent was not required.

Authors' Contributions

MSJ: conceptualized and designed the study, acquired and interpreted the data, drafted and revised the manuscript, and provided final approval of the version to be published.

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