UNDESIRABLE PHASE TRANSFORMATIONS IN ZIRCONIA HIP BALLS - MECHANICAL AND HYDROTHERMAL TRIGGER MECHANISMS

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INTRODUCTION

The feature that makes yttria-stabilized, tetragonal zirconia polycrystalline (Y-TZP) ceramic both strong and fatigue resistant is its ability to partially transform under stress from tetragonal phase to its monoclinic phase, i.e. an inherent metastability [1]. However if this transformation triggers in zirconia (Zr) involuntarily, under combinations of mechanical or hydrothermal stress, it would have a detrimental roughening effect on the articulating ceramic surface of zirconia balls and polyethylene cups (PE). The risk would be increased wear with Zr/PE hip joints [2, 4]. With over half a million zirconia balls implanted in patients [1], there is the additional risk with high-activity lifestyles and implant-impingement trauma increasing frictional heating and creating mechanical shock in the aseous hip environment. Thus our aim was to subject Y-TZP zirconia balls to selected hydrothermal and mechanical shocks as possible triggers for monoclinic phase transformation.

METHODS

Due to the zirconia balls being removed from the US market by 2001, we relied on samples already archived in our laboratory whereas our retrieved zirconia balls came directly from an international group of collaborators. Overall our study materials represented four zirconia vendors and included HIPped, non-HIPped, alumina-doped and non-alumina-doped zirconia balls.

Zirconia balls were aged in an autoclave (121°C, 1 bar, 5-30 hrs) to determine the effect of heat and moisture. The effect of mechanical trauma was examined by four methods; a) to simulate severe impingement, a titanium cup rim was loaded against Zr ball and rotated under load (1-12KN), b) to simulate severe abrasive wear, Zr ball was run against a diamond rasp in a hip simulator and c) to simulate severe 3rd-body wear, a Zr ball was run in a slurry of alumina powder (1 μm size) using bovine serum in a hip simulator. Pressure, shear and temperature effects created by PE-cups were studied in a hip simulator model. Zirconia balls were run in a wear study to five million cycles duration and then analyzed. Effects of PE-cup wear on balls pre-transformed by autoclave were also studied by wear simulator. Lubrication and PE-cup studies were then run with implant combinations Zr/Zr in water, Zr/Al in serum, and Zr/PE in water.

RESULTS

The simulated mechanical trauma triggered local surface destruction on zirconia balls but did not trigger significant monoclinic transformation. This may rule out mechanical impingement as a sensitive trigger for the transformation seen in retrievals. In contrast the hydrothermal study revealed major transformation from tetragonal to monoclinic phase for all balls. For example by 10-12 hours autoclaving the 26mm Al-doped balls revealed 5-13 % monoclinic content, this doubling by 15-30 hours autoclaving (Fig. 1). The 26mm diameter balls had greater transformation than 22mm balls, with monoclinic transformation averaging 0.81%/hour versus 0.56%/hour of autoclaving, respectively. A most dramatic finding was the high transformation to monoclinic on articulating surfaces of retrieved balls (30%-85%) at < 10 years). Prior in-vitro, aging studies had predicted only 5% monoclinic in a "20-year" simulation model. Clearly there was an accelerated transformation happening in-vivo in some zirconia. The fact that the maximum monoclinic transformations corresponded to the contact regions with the PE cup indicated that tribological conditions were acting as the trigger. Otherwise, the whole ball surface would have likely have transformed. Our laboratory wear simulation to 5 million cycles duration did not increase monoclinic content. We found also that the sensitivity of Y-TZP ceramic to the lubrication mode was only evident with all-zirconia bearings, resulting in a catastrophic disintegration of balls and cups with water lubrication. However in studies of Zr/Zr run in serum, the bearings held up for over 20 million cycles with no measurable wear. Thus it was likely that the serum proteins offered a major protecting role in vitro and in vivo. In contrast the zirconia/UHMWPE couples run in water did not trigger any adverse effects. Thus there was a contrary lubrication effect depending on choice of Zr/Zr or Zr/PE combinations.

DISCUSSION

Our in-vitro studies of mechanical and thermal shock to zirconia balls showed that the hydrothermal process was the dominant mechanism of transformation. The severe mechanical shock treatment damaged the Zr bearing surfaces but did not result in transformation. The extent of monoclinic transformation on some retrieved zirconia balls was dramatic. The sites of monoclinic transformation originated in the wear zone indicating that in-vivo tribological conditions operating under the PE-cups were the likely trigger. This did not happen during our hip simulator studies and may indicate that we know virtually nothing about the hydrothermal conditions operating inside the ‘hot zone’ of a patient’s Zr/PE hip joint. It is still unknown why some zirconia balls transformed aggressively in vivo and some did not not [3, 4]. The answer may lie in variations in manufacturing processes that resulted in some balls being more metastable than others [2]. Our in-vitro data with the 22mm balls being more metastable than 26mm balls would support this hypothesis. The additional processes of hipping and Al-doping are reputed to stabilize the Y-TZP balls [1]. However there is retrieval evidence that some of these will also transform in vivo.

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REFERENCES


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Figure 1: Relationship between the hydrothermal aging and % monoclinic phase.