Is it safe to use ceramic on polyethylene bearings in revision hip arthroplasty for ceramic fracture?

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Aims
Ceramic bearing fracture is a rare complication following implantation using modern ceramic bearing materials. The ideal revision bearing option in such cases is debated. We aimed to investigate the safety of a hard on soft bearing following ceramic fracture in total hip arthroplasty.

Methods
Data on all patients undergoing revision following ceramic fracture between January 2016 and January 2019 were collected retrospectively. Templating software was used to determine linear wear between the first post-revision radiograph and latest available follow-up. Univariate analysis was used to examine patient demographics and the wear rates of the polyethylene components. The intra- and inter-rater reliability of wear measurements was calculated. Additionally, in vitro testing was undertaken to assess the effects on bearing surfaces of residual ceramic particles.

Results
A total of 12 patients underwent revision for ceramic fracture in the study period. The mean age at revision was 62 years (54 to 72). There were six liner and six head fractures revised to delta ceramic heads and cross-linked polyethylene acetabular components. At mean follow-up of 3.8 years (0.5 to 6.1), median 4.4 years (IQR 2.0 to 5.1), linear wear rate was calculated at 0.08 mm/year (SD 0.06). Both intra- and inter-rater reliability was excellent with intraclass correlation coefficient (ICC) scores of 0.99 at all timepoints. In vitro testing showed an increase in head roughness in metal on polyethylene bearings after ceramic particles were embedded, but no increase in ceramic on polyethylene (CoP) or ceramic on ceramic bearings.

Conclusion
Revision to CoP bearings following ceramic fracture does not cause early catastrophic wear at early follow-up, aligning with the in vitro study observations. It appears safe to use this hard on soft bearing combination, given that wear rates are comparable to what is expected in a primary hip arthroplasty setting. Longer follow-up is required to establish if this trend persists.

Take home message
- Revision to ceramic on polyethylene bearings following ceramic fracture does not cause early catastrophic wear at early follow-up.
- It appears safe to use this hard on soft bearing combination, given that wear rates are comparable to what is expected in a primary hip arthroplasty setting.
- Longer follow-up is required to establish if this trend persists.

Introduction
Bearing fracture is a rare but devastating complication, even with modern fourth-generation ceramic bearing materials. The manufacturer-reported rates of fracture are 0.001% and 0.021% for Biolox delta

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ceramic femoral heads and acetabular cups, respectively (CeramTec, Germany).[1]

Current guidance from the literature supports revising the components to ceramic on ceramic (CoC) or ceramic on polyethylene (CoP) bearing, with traditional thinking towards CoC.[2] A CoC bearing is expensive compared to other bearings, and there is the concern about using an articulation that has already failed, in a revision procedure. CoC articulations are also prone to problems with minor malorientation such as noise generation, which can be exacerbated when optimum component positioning is harder to achieve in a revision setting. CoC also offers limited acetabular reconstructive options.

Revision to a hard on soft bearing (delta ceramic head and cross-linked polyethylene) is controversial, with concerns about catastrophic third body wear caused by the fractured ceramic particles, even after radical synovectomy. Conversion to a construct with a metal on polyethylene bearing surface has been shown to lead to catastrophic wear.[3] The wear of the head can be due to hard ceramic particles embedded into the polyethylene, causing abrasive wear to the softer metal head or third body wear from residual ceramic particles.

In our institution, the concerns about reimplanting a CoC bearing have led to using a ceramic on polyethylene construct, with the belief that any third body particles will embed in the polyethylene and prevent significant additional wear, as the ceramic head is the same material and will be resistant to wear from the fractured particles, in comparison to a metal head.

Currently, there are no published reports on the radiological wear of CoP bearings following revision for a ceramic fracture in total hip arthroplasty (THA). The aim of this study was to assess wear radiologically of CoP bearings following revision for ceramic fracture; and also to examine in vitro the effects of fractured ceramic particles on THA bearings.

Methods

Retrospective radiological review

We undertook a retrospective review of the revisions in our tertiary referral service for ceramic fracture between January 2016 and January 2019; this allowed a mean follow-up time of 3.8 years (0.5 to 6.1). Information was collected from the National Joint Registry (NJR), revision database, electronic notes, and Picture Archiving Communications System. Templating software (TraumaCad; Brainlab, Germany) was used to measure the liner wear on calibrated repeat anteroposterior (AP) radiographs immediately postoperatively and on the latest radiographs available. Femoral head penetration was measured as the difference in distance from the liner margin in the weightbearing area and the edge of the femoral head on both initial and follow-up radiographs, similar to that described by Charnley and Halley.[4] This was done on two separate occasions by two independent observers (CG, VT). Repeat measures were done four weeks apart at both timepoints to allow assessment of intrarater reliability as well as inter-rater reliability. This was done using the intraclass correlation coefficient (ICC) on measurement data. Furthermore, a one-way analysis of variance (ANOVA) was performed on both observers' wear rates to examine for significant differences.

This project was reviewed by our institution's ethics board and formal ethical approval was deemed not to be required.

In vitro study

An in vitro study assessed the effects of residual ceramic fragments on THA bearings. THA bearing combinations studied included: CoC, CoP, and metal on polyethylene (MoP). To mimic residual debris following ceramic fracture, a universal testing machine was used to apply an increasing load to a misaligned cobalt-chromium (CoCr) head and delta ceramic liner. This resulted in stress concentrations at the rim and fracture. Resultant ceramic particles were passed through stainless steel filtration meshes, and 48 mg of ceramic debris, < 1 mm in size, was used in subsequent testing.

The ceramic debris was then embedded into the surfaces by mixing with 0.1 ml of lubricant and introduced between the articulating surfaces of CoC, CoP, and MoP bearings (n = 3), using a universal testing machine. A load was applied (3 kN) for 30 seconds to mimic peak load in a gait cycle. THA bearings were then mounted in an anatomical single station hip simulator (Prosim, UK) in a clinically relevant position surrounded in 25% (v/v) bovine serum and a standard gait cycle applied for 7,200 cycles at 1 Hz (described previously).[5] Surface roughness of femoral heads was measured pre- and post- hip simulator testing using a contacting profilometer (Talysurf PGI800 profilometer; Taylor Hobson, UK).

Statistical analysis

Using univariate analysis, we examined patient demographics and wear rates for all patients. Intra- and inter-rater reliability was assessed using the intraclass correlation coefficient (ICC) and a one-way ANOVA. All statistical analysis was performed using SPSS v. 28.0 (IBM, USA). A value of $p < 0.05$ was deemed statistically significant.

Results

Retrospective radiological review

Included in the radiological analysis were 12 patients (nine male, three female) with a ceramic fracture who underwent revision to a CoP bearing. At the time of revision surgery, the mean age of the patient was 62 years (54 to 72) and the mean BMI was 31 kg/m^2 (18 to 37). Of the 12 patients, 11 were American Society of Anesthesiologists (ASA)[6] grade II at the time or revision with one patient ASA grade III. The revision surgeries were undertaken between March 2016 and March 2019, and the mean time from the patient's previous procedure to the time of their revision surgery was 8.2 years (1.2 to 14.9). The follow-up ranged from six months to 6.1 years, with a mean of 3.8 years and median of 4.4 years (IQR 2.0 to 5.1).

Two patients presented with ceramic fracture of a revision THA and ten were fractures of primary THA. There were six liner and six ceramic head fractures seen in our series. Six patients underwent revision of both components, five underwent revision of the acetabulum with a head exchange, and one had change of the head and liner only. There were seven uncemented acetabular components and five cemented. All fractures occurred in CoC bearings and they were revised to delta ceramic heads and Marathon crosslinked polyethylene (XLPE) liners (crosslinked with 5mRad (50kGy)

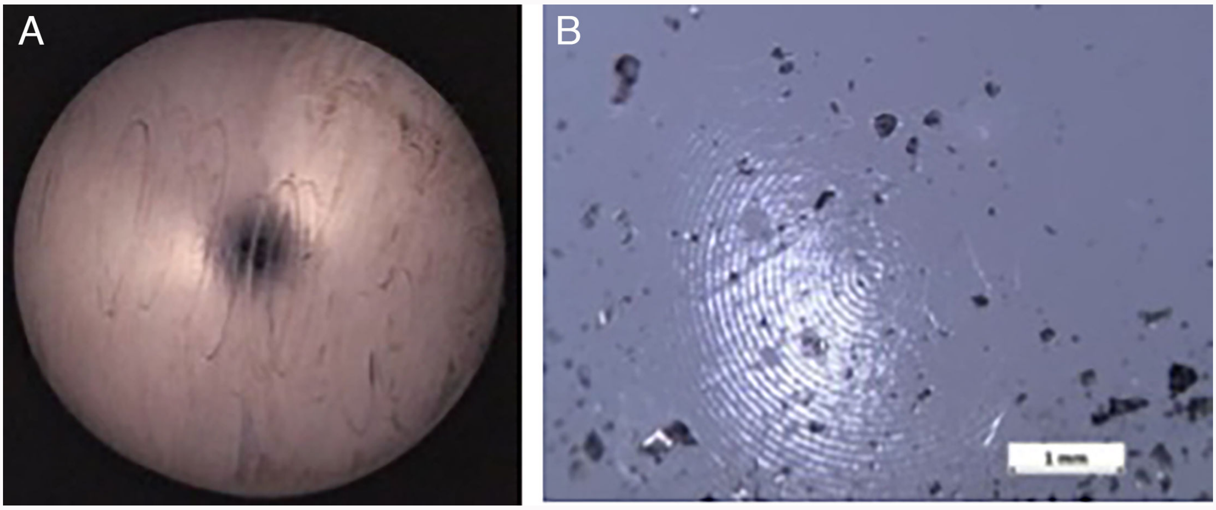

Fig. 1
Metal on polyethylene bearing following short-term hip simulator testing with embedded ceramic particles. a) Ceramic on ceramic head showing extensive scratching, and b) polyethylene liner with embedded particulate. Scale: 1 mm.

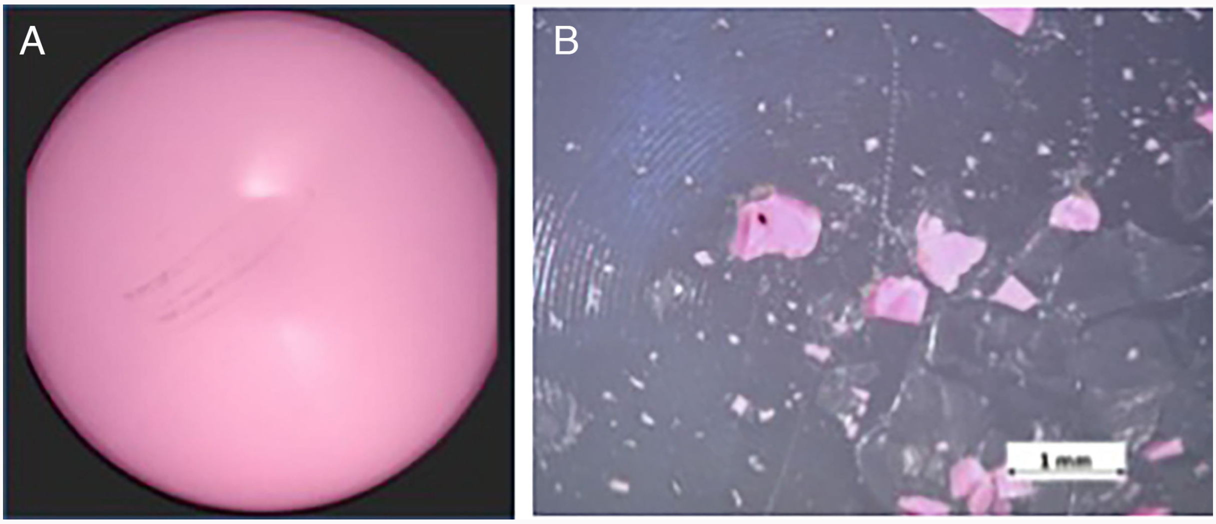

Fig. 2
Ceramic on polyethylene bearing following short-term hip simulator testing with embedded ceramic particles. a) ceramic head (minor scratching highlighted with graphite pencil rubbing), and b) polyethylene liner. Scale: 1 mm.

γ radiation) with a combination of uncemented Pinnacle and cemented Marathon acetabular cups (DePuy Synthes, USA). The most common head size used was 32 mm (46%, n = 6) followed by 36mm (31%, n = 4), and 28mm (23%, n = 3). At a mean follow-up of 3.8 years (0.5 to 6.1), the overall wear rate was calculated to be 0.08 mm/year (SD 0.06; 0.00 to 0.18). There was no evidence of radiological loosening or osteolysis in the series. Both inter- and intrarater reliability was excellent at both timepoints at 0.99 and 0.99 throughout. One-way ANOVA performed on each observer's calculated wear rates showed no significant differences in wear rates between and within observers (p = 0.497). There were no instances of catastrophic failure, although one hip was subsequently revised for infection, nine months after the revision for ceramic fracture.

In vitro study
The in vitro study was conducted to embed clinically relevant ceramic wear particles in different THA bearings (CoC, CoP, and MoP), followed by short-term hip simulator wear testing to assess changes in surface roughness. The short-term nature of this testing (7,200 cycles) meant that the damage to articulating surfaces was recorded, rather than wear measurements. Damage was observed on the MoP (Figure 1) and CoP (Figure 2) bearings following testing. No damage was visible on CoC bearings following testing.

Surface roughness measurements of the femoral heads pre- and post-testing are shown in Figure 3. A significant increase in surface roughness (Ra) was observed in the CoCr head in the MoP articulation, which reflects the extensive damage that was observed (Figure 1a). There was less damage (surface roughening) caused by ceramic particles embedded in the polyethylene liner (Figure 2b) to the ceramic head

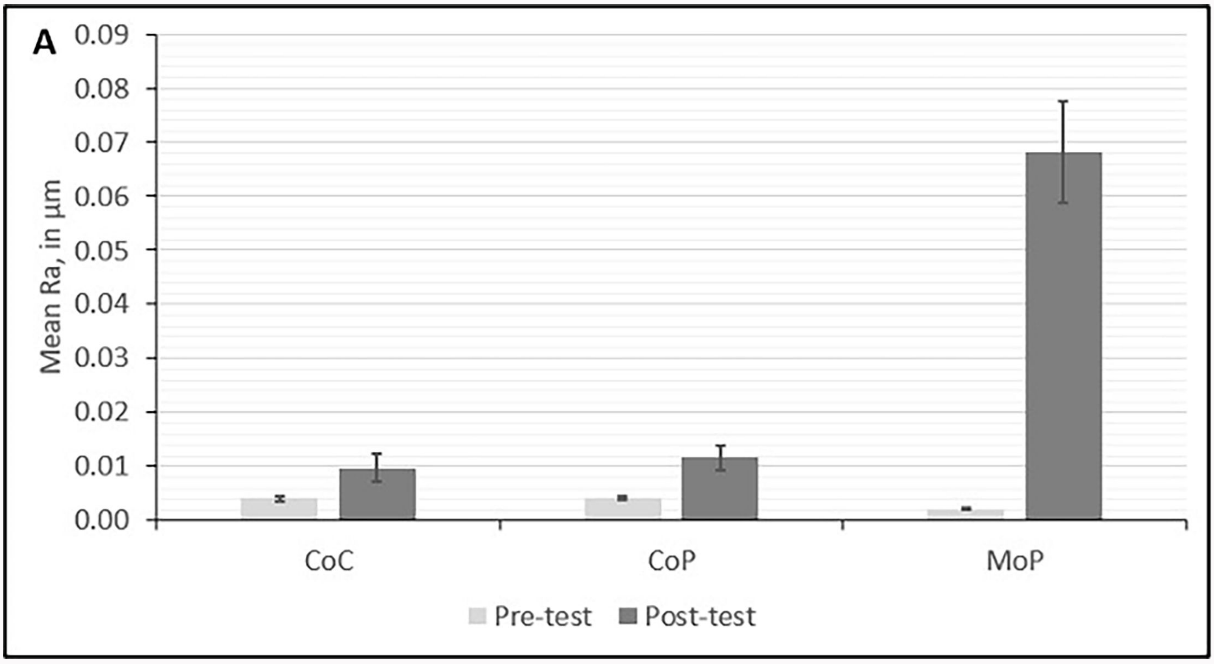

Fig. 3
Surface roughness (Ra) of the femoral heads pre- and post-test articulation with residual ceramic particles. Data are shown as mean (95% CI) (n = 3). CoC, ceramic on ceramic; CoP, ceramic on polyethylene; MoP, metal on polyethylene.

(Figure 2a), and only a negligible increase in surface roughness of the head was observed. This increase in surface roughness was similar to the one observed on ceramic heads in the CoC bearing.

Discussion

Our short-term follow-up series has shown no catastrophic wear after ceramic fracture in THA when revised to a CoP bearing. This is the first paper to report on the 2D radiological wear of CoP bearings following ceramic fracture in THA, and has demonstrated a rate of 0.08 mm/year (SD 0.06) over a mean timeframe of 3.8 years (0.5 to 6.1). This is not dissimilar from the rates recently described in the literature, where numerous studies, examining > 1,500 hips, have shown primary wear rates for CoP THAs to be between 0.015 and 0.086 mm/year.[6–11] Numerous methods are used in the literature to measure wear, with 2D, 3D, and multiple-vector wear analysis available; however, controversy exists over the ideal method, and the utility of more complex methods require specific radiographic preparation.[12] Our study utilized single retrospective radiographs, obtained as part of clinic follow-up. This scenario guided our methodology as it did not allow for more complex analysis, such as radiostereometry. TraumaCAD was used to allow manual uniradiogaphic analysis of follow up radiographs, similar to that published by Rajpura et al,[11] and reassuringly showed excellent intra- and interrater reliability in this study. Furthermore, although software such as PolyWare (Draftware, USA) and Hip Analysis Suite (University of Chicago, USA) are available, studies have reported limited accuracy over manual techniques when using clinical versus laboratory radiographs in the shorter term.[13,14]

Ceramic offers excellent properties as a bearing surface, with a good scratch profile, hardness, wettability, and wear. However, it is a brittle material, and ceramic fracture, although rare with fourth-generation ceramics, presents a complex challenge. CoC is an expensive combination, and concerns for noise generation with patient dissatisfaction, as well as favourable results for MoP and CoP bearings, have led to a downtrend in the UK use of CoC bearings.[10,11]

The choice of bearing use after a ceramic fracture is controversial, with studies reporting repeat revision rates as high as 31% within four years.[15] Following ceramic bearing failure, the literature leans towards using a CoC bearing without a consensus, as disastrous results have been reported when revising to a MoP construct, and CoP bearings are controversial.[3,15,16] In order to prevent a secondary ceramic fracture, careful assessment of the components is paramount during surgery and components should be revised as necessary. Damage to the taper can cause stress risers, which increase the rate of fracture of the femoral head.[2,17,18] For this reason, if not revising the femoral component, the use of a metal alloy sleeve with the ceramic head is recommended.[19] Similarly, if the locking mechanism of the cup is damaged it should be exchanged to prevent complications with liner dissociation or damage to the revised liner. Alignment of the femoral and acetabular components should also be assessed and revised if not satisfactory, as malposition can contribute to edge loading, and impingement making fractures more prevalent.[2] As there are no reported CoP wear rates after ceramic fracture, we have to look to other bearings, with Sharma et al[16] reporting on the wear of five patients receiving MoP bearings (chromium cobalt) following ceramic fracture and radical synovectomy. Their yearly steady state linear wear rate from one year was reported at 0.11 mm/year (0.8 to 0.14), which is higher than our findings of 0.08 mm/year (SD 0.06) in this series. Two of our patients with consistently higher rates of wear were only aged 54 and 58 years at the time of revision, followed-up to 4.8 and 5.1 years, and had mean wear rates of 0.17 mm/year and 0.14 mm/year, respectively. They were both ASA grade II; one had a BMI of 31 kg/m^2 and was revised to a 32 mm head with an uncemented cup, while the other had a BMI of 32 kg/m^2 and was revised to a 28 mm head with a cemented cup. Gehrke et al[20] reported that younger, more active patients are at increased risk of accelerated polyethylene liner wear, and their systematic review of catastrophic wear in CoP THAs showed that 28 mm and 32 mm heads were common in such cases. The average time to catastrophic failure was 11.6 years; however, the time from presentation to failure was a mere seven months, leading to the recommendation of prompt revision in patients with signs of accelerated wear to allow a more simple, pre-failure procedure. No catastrophic failure was seen in our series; however, we agree it would be prudent to follow up such patients closely to identify signs of accelerated wear to enable early intervention, thus minimizing morbidity. Apparent linear wear rates in primary CoP bearings are accelerated in the first year as the polyethylene 'beds in' due to creep in the material, and a reasonable amount of head penetration in this study may reflect this 'bedding in' phenomenon given the short follow-up. However, currently there is no standard for when 'steady state' wear begins as this may reflect acetabular design, differing patient populations, and types of polyethylene used.[21] McCalden et al[21] suggested starting measurements at 12 to 24 months postoperatively when most bedding-in should be complete. The studies referenced in this paper report wear including and excluding this bedding-in phase; reassuringly, our wear rate at 0.08 mm/year (SD 0.06) falls within the reported range showing a comparable rate to primary THAs regardless of inclusion of the initial bedding-in phase. We felt it was important to include measurements of early wear, given that catastrophic wear and failure of revision components was a concern following revision for ceramic fracture. As described above, implant failure can occur within seven months of presentation,[20] and the measurement of early wear versus primary implants, inclusive of the universal bedding-in phase, could therefore have clinical utility when describing what is expected following revision for ceramic fracture. Prior results from our institution have shown a wear rate of 0.13 mm/year observed in the first year following primary THA CoP bearings, falling to 0.034 mm/year at years one to four, and again to 0.007 mm/year at latest follow-up for a mean of 0.0147 mm/year over the life of the implant.[11] This initial 'bedding-in' period appears to be no different following ceramic fracture, given that our wear rates are consistent with those reported for primary THA.

Polyethylene wear becomes a problem when it creates sub-micrometre particles, stimulating a macrophage response via cytokine pathways, leading to aseptic loosening.[22] The key concern after ceramic fracture, in using a CoP bearing, is that the third body wear from ceramic fragments will lead to increased polyethylene wear, resulting in accelerated aseptic loosening of the implants. As aseptic loosening is the leading cause of revision for primary THA in the NJR, the concerns seem valid.[23] To address the ceramic third body particles, radical synovectomy and lavage has been shown to improve outcomes, but even after this it is likely some fragments will persist.[15] Trebše et al[24] observed that their MoP revisions performed worse compared to CoC, with radiological evidence of osteolysis and wear of the metal head. During further revision and implant retrieval they found ceramic particles embedded in the polyethylene liner, which, being harder than the metal head, had caused damage to the head while protecting the liner. A proposed theory in CoP bearings after ceramic fracture is that the ceramic fragments will embed in the polyethylene and, as they are of similar hardness to the ceramic head articulating with the asperities, they will not cause increased wear of the polyethylene. This theory is supported by the in vitro investigation we undertook. Ceramic particles were embedded into THA bearing surfaces and then articulated in a short-term wear simulator test. MoP bearings showed much higher increases in head surface roughness compared to CoP (0.004 to 0.012, and 0.002 to 0.068 microns, respectively). Increased surface roughness leads to higher polyethylene wear.[25] CoP bearings after a ceramic fracture are poorly reported in the literature, with Trebše et al[24] including one case in their study with no detrimental findings on the serial postoperative radiographs. Lee et al[26] reported poor outcomes of MoP revision bearings following ceramic failure, with three of the nine in their series subsequently developing metallosis, and two being re-revised to a CoP bearing and one to a CoC bearing. More severe consequences resulting from MoP revision bearings have been reported, including cobalt toxicity progressing to fatal cardiomyopathy.[3] In contrast, Sharma et al[16] had good radiological results with MoP bearings following ceramic fracture and revision with radial synovectomy at 10.5 years with no revisions in eight hips. Our study is limited due to its relatively short follow-up time; longer-term follow-up is required to determine if CoP bearing following ceramic fracture is a safe and cost-effective option. However, our initial results are promising.

In conclusion, although the data are limited and there is no consensus regarding the preferred bearing after ceramic fracture in THA, we have shown that in the short term CoP is a safe bearing with good radiological results and no catastrophic failure. An in vitro study supports this finding, showing no increase in head roughness when ceramic particles were embedded into CoC and CoP THA bearings surfaces. However, a significant increase in the head surface roughness was observed in MoP bearings.

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Data sharing

The data that support the findings for this study are available to other researchers from the corresponding author upon reasonable request.

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Ethical review statement

This project was reviewed by our institutional ethical review board who concluded that formal ethical approval was not required.

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