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UP-TO DATE REVIEW AND CASE REPORT • HIP¨- ARTHROPLASTY

Modular femoral neck failure after revision of a total hip arthroplasty: a finite element analysis

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Abstract

The authors report on a case of modular femoral neck fracture which appeared 21 months after revision of acetabular component. The revision surgery was performed 8 years after the primary total hip arthroplasty due to aseptic loosening of the acetabular component. During acetabular revision, the primary implanted short (*S*, −3.5 mm) femoral head was also exchanged with extra-long (*XL*, +7.0 mm) femoral head fitting the modular femoral neck with a longer lever arm. Numerical analysis has shown that this has resulted in a 19.9% increase in tensile stress at the neck–stem coupling during normal walking cycle. This could result in microcrack initiation and propagation and finally lead to modular neck failure of the otherwise well-fixed stem. Surgeons should avoid excessive loading of the exchangeable neck (dual-modular) femoral stem designs as the stem–neck couplings are subject to corrosion and are not as reliable as monoblock stems.

Keywords Total hip arthroplasty · Dual-modular stem · Modular femoral neck fracture · Profemur Z · Revision surgery · Finite element modelling

Introduction

The modular femoral neck is a recent innovation in primary uncemented total hip arthroplasty (THA). The advantage of this type of stem is better controlling of the femoral offset, leg length and hip stability [1]. The Profemur Z stem (Wright Medical Technology, Arlington, TN, USA) is a dual-tapered titanium alloy (Ti_6Al_4V) stem that was among the first globally marketed modular neck–stem designs. However, the increasing number of modular neck failures made from titanium alloy forced some producers to remove their implant from the market or change the neck material to cobalt-based alloys [2–4]. In this article, we present a case of modular neck fracture in a well-fixed femoral stem and describe surgical and technical aspects that increased the risk of such complication.

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Case report

A 60-year-old male (height 178 cm; weight 88 kg; body mass index (BMI) 27.8 kg/m^2) presented in December 2007 with 6 months of right hip pain. Radiographs and computer tomography scanning revealed avascular necrosis of the right femoral head (stage Ficat IV). The patient was treated with uncemented right THA through a standard lateral approach. A press-fit titanium-alloy acetabular shell size 56 mm with polyethylene insert (Procotyl L, Wright Medical Technology, Arlington, TN, USA) was inserted, and the femoral component used was a size 7 tapered, fully grit-blasted titanium-alloy modular stem (Profemur Z, Wright Medical Technology) with long 8° varus modular neck of the same material and 28-mm alumina ceramic (Biolox Forte, CeramTec, Plochingen, Germany) femoral head with a −3.5 mm (short, *S*) length. The patient recovered with no post-operative complications.

However, in 2015 the patient presented with progressive pain and instability of the right hip which accentuated suddenly in November making the patient unable to walk. Radiographs revealed decentralisation of the femoral head (Fig. 1), and the patient was revised. At revision, polyethylene liner was found broken and the acetabular shell damaged and in retroverted position. The femoral head, acetabular

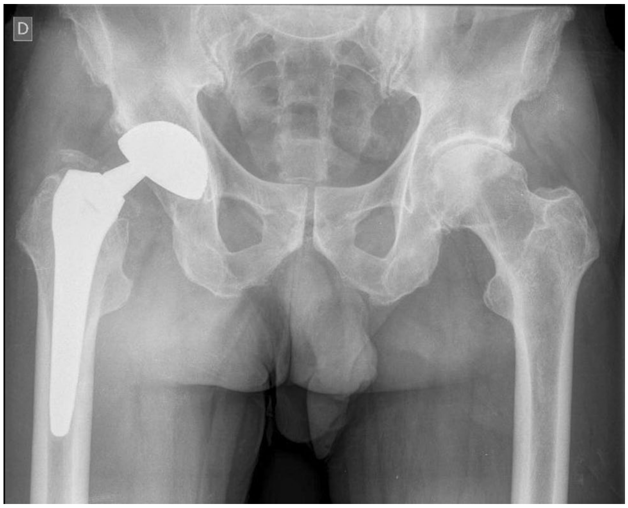

Fig. 1 Anteroposterior view of the pelvis 8 years after primary THA showing femoral head decentralisation in the socket

liner and acetabular shell were replaced. (It was impossible to disengage the modular neck from the femoral taper.) The acetabular component used was the size 56-mm Continuum titanium-alloy shell with Trabecular Metal coating (Zimmer, Warsaw, Indiana, USA) with alumina-composite ceramic inlay (Biolox Delta, CeramTec) and was mated to a 36-mm alumina-composite ceramic femoral head (Biolox Delta, CeramTec) with a +7 mm (extra-long, *XL*) length to obtain stability (Fig. 2). The difference in femoral head length before and after revision was therefore 10.5 mm.

The patient's post-operative course was uneventful. He remained asymptomatic and active until August 2017, when he suddenly experienced sharp pain in his right hip when walking the stairs. Emergency room radiograph revealed fracture of the modular femoral neck (Fig. 3) which led to the second revision. The stem of the prosthesis with fractured femoral neck was extracted via single longitudinal proximal splitting and two-chisel technique [5]. After the proximal femur has been cerclaged with 3 cerclage wires, an Alloclassic Zweymüller SLL revision stem (Zimmer Biomet, Indiana, USA) size 8 with a 36-mm alumina-composite ceramic (Biolox Delta, CeramTec) femoral head [+7 mm (*XL*) length] was implanted. There were no intraoperative or post-operative complications. Twelve months after the second revision, the patient was complaining of mild occasional pain, ambulated without shoe lift, and used a single crutch for long walks only (Harris Hip score = 87; UCLA activity score = 7 [6]). Radiographs at 1 year after the second revision surgery demonstrated stable fixation of all components (Fig. 4).

Finite element modelling

A finite element model was made for presenting stress fields of the femoral neck and shaft (ABAQUS explicit 6.13 solver, Dessault Systems, 2018). The model was made as a 3D solid body with deformable finite elements and was subjected to a bending moment that corresponded to the weight of the patient during normal walking cycle, when forces of 3-times body weight appear, and to the bending moment when patients stumble, when peak hip resultant joint forces reach up to 8-times body weight [7, 8].

Finite element analysis has shown that maximum stress fields occur at the junction between the femoral stem and the modular neck. Maximum stress on the femoral stem

Fig. 2 Anteroposterior view of the hips 3 months after revision arthroplasty without replacing the femoral stem and modular neck. Acetabular shell is properly placed, and femoral head is centralised

Fig. 3 Anteroposterior view of pelvis 21 months after revision arthroplasty showing modular femoral neck fracture

Fig. 4 Anteroposterior view of the right hip 12 months after second revision with femoral stem replacement

appeared on the medial side of stem–neck junction, and on the modular neck, maximum stress appeared on the lateral side. Given the patient's body weight and lever arm corresponding to the sum of modular neck length and attached *S* femoral head (− 3.5 mm) length, tensile crack-opening stress at the crack initiation location has reached up to 185 MPa under the load of a normal level walking (applied force of 2590 N) (Fig. 5).

During the first revision surgery the *S* (− 3.5 mm), femoral head was exchanged to an *XL* (+ 7.0 mm) femoral head. Therefore, the lever arm was lengthened for 10.5 mm increasing the femoral offset by 7.5 mm [9]. Consequently (with patient's body weight and modular neck length staying unchanged), the tensile stress on modular femoral neck has increased to 231 MPa (+ 19.9%) at applied force of 2590 N during normal level walking. This additional stress could be responsible for opening and/or faster growing of micro-cracks on the surface of the femoral neck at the neck–stem coupling (Fig. 6).

In the patient's primary THA situation with the *S* (− 3.5 mm) femoral head implanted, the tensile stress momentarily increased during stumbling up to 501 MPa at applied force of 6906 N and for pre-strained field around contact region. The total peak tensile stress appears at the upper contact region which is the driving force for fatigue crack initiation and propagation in the modular neck (Figs. 7 and 8).

After the first revision with femoral head exchanged to *XL* (+ 7 mm), the tensile stress during stumbling reached up

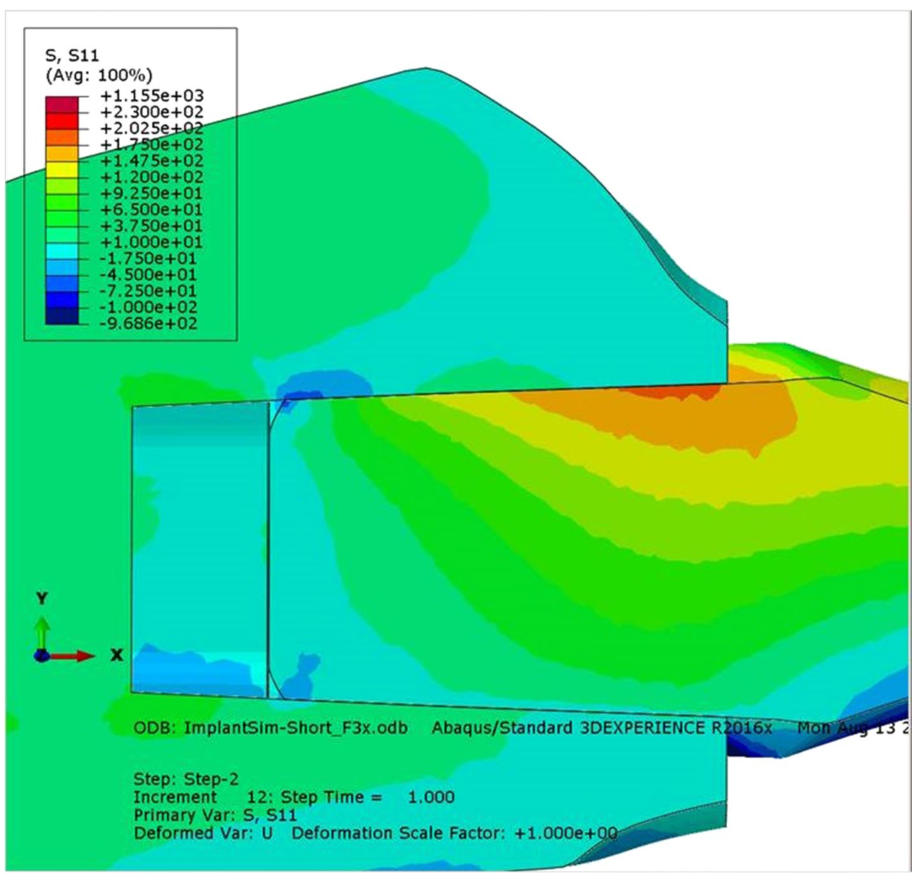

Fig. 5 Detail view of the stress analysis with − 3.5 mm (*S*) femoral head during level walking

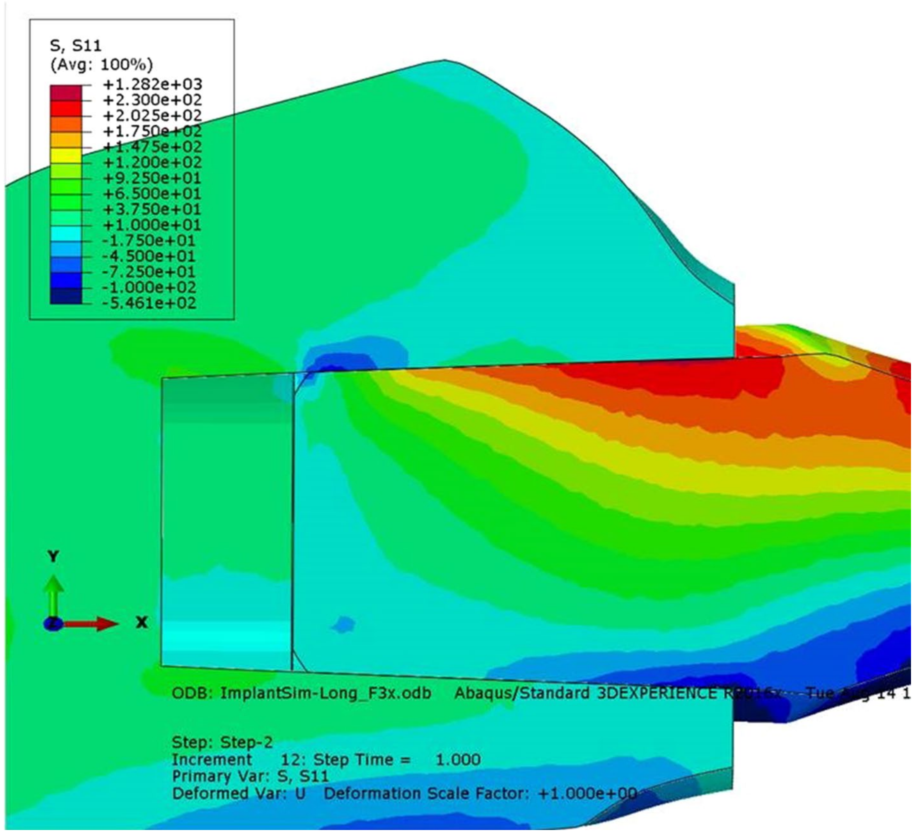

Fig. 6 Detail view of the stress analysis with +7 mm (*XL*) femoral head during level walking

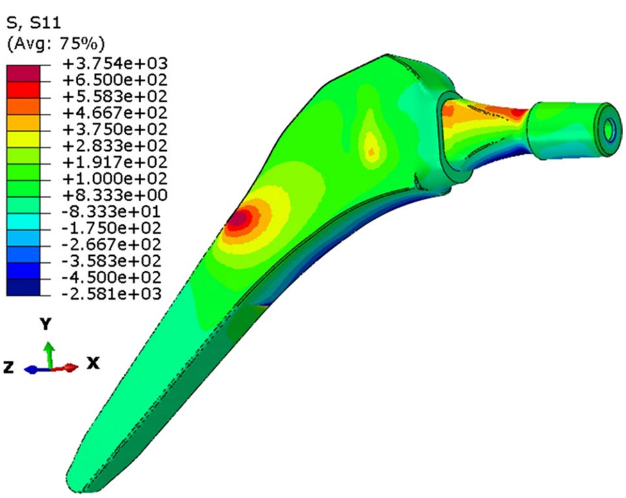

Fig. 7 Finite element stress analysis of primary implanted modular femoral stem with −3.5 mm (*S*) femoral head during stumbling

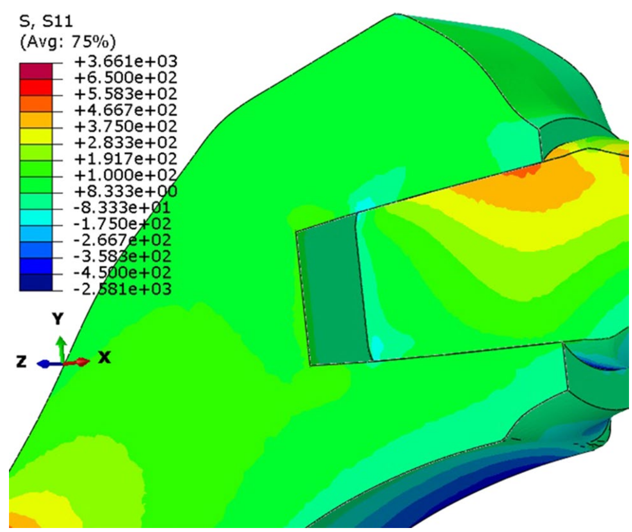

Fig. 8 Detail view of the stress analysis with −3.5 mm (*S*) femoral head during stumbling

to 644 MPa at applied force of 6906 N and for pre-strained field around contact region (Figs. 9 and 10).

Discussion

Modular hip prosthesis gained their popularity by offering the surgeon an intraoperative choice of neck version and length independently of the stem size, enabling the

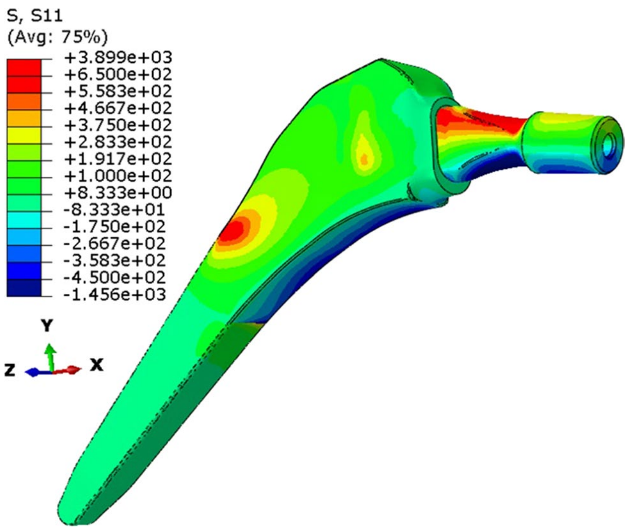

Fig. 9 Finite element stress analysis of primary implanted modular femoral stem with +7 mm (*XL*) femoral head during stumbling

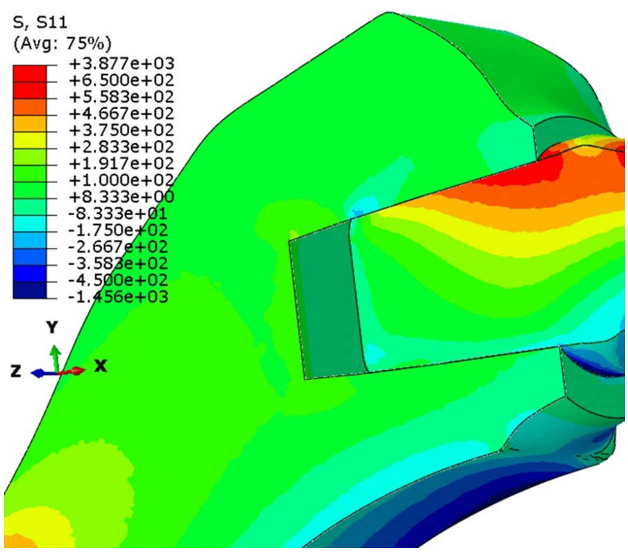

Fig. 10 Detail view of the stress analysis with +7 mm (*XL*) femoral head during stumbling

possibility of restoring natural anatomical conditions in half of all patients with just 8 different neck variations [10]. Important differences in femoral neck length, shaft diameter, caput-collum-diaphysis (CCD) angle, neck version and offset between men and women were reported, and modularity enables the orthopaedic surgeon to adapt to those differences [1]. Duwelius et al. [11] studied two groups of THA patients looking for the differences in anatomical hip restoration and revision rates between monoblock and modular stem designs. A total of 284 patients with nonmodular stems (Zimmer M/L Taper) and 594 patients with modular stems (Zimmer M/L Taper Kinectiv) were followed-up with a mean of 2.4 years (maximum 5.9 years). Clinical and radiographic measurements of leg length and offset were done before and after the surgery. Clinical evaluations included Harris Hip and SF-12 scores, respectively. Although a greater proportion of patients with modular stems had equal (< 5 mm) leg length and smaller offset differences than the nonmodular group, there were no differences in revision rates, complications and outcome scores. The authors found no modular neck fractures in the modular group. With no differences in outcome scores, the authors concluded that modular stems offered no added value over standard nonmodular stems [11].

Several case reports of Profemur Z modular neck fractures appeared from 2010 onwards presenting patients aged 30–67 years with BMI ranging from 26 to 39 kg/m^2; all necks were long, and the majority were in varus position [2, 12–15].

In 2015, the Italian Emilia-Romagna Registry (RIPO) reported on 692 Profemur Z dual-modular stems implanted between 2000 and 2012 [16]. With the mean follow-up time of 9 years, only 2 revisions (0.3%) were noted due to long modular neck fractures and both appeared in overweight males. (Accurate BMI was not reported.) The first author of the reported study was an employee of MicroPort Orthopedics Inc., the new owner of Wright Medical Technology [16]. However, in the single-surgeon series Pour et al. [17] reported on 277 THAs with uncemented dual-modular stems (107 Profemur Z and 170 Profemur E) with the mean follow-up of 4.2 years. These authors have detected a 6% modular neck fracture rate for the Profemur Z modular stems. Gofton et al. [18] reported on single-centre experience on 809 THAs with Profemur TL or Profemur Z stems in combination with titanium modular necks with a mean follow-up of 5.7 years. The authors noted 4 atraumatic modular neck fractures, all that appeared in males, giving the overall neck fracture rate of 0.5%; 3 of the mentioned fractures occurred with Profemur Z modular stems [18]. In a nationwide study on 4000 implanted titanium-alloy modular neck stems, which besides Profemur Z stems also included two previous (forerunners of Profemur Z) fully modular stems (An.C.A. Fit and GSP, Cremascoli Ortho, Milano, Italy) with the same neck–stem (oval Morse taper) junction design, the authors recorded 24 modular neck fractures, resulting in overall neck fracture rate of 0.6% [19].

Incidence of modular neck fractures might be determined by femoral stem design [20]. Recently, in a study of 317 cases with modular stems of a different neck–stem (elliptical Morse taper) junction design (H-MAX M, Lima Corporate, San Danielle, Italy), only one modular neck fracture occurred [21]. The patient was male, his BMI was 30 kg/m^2, and long titanium neck was implanted.

However, a French nationwide cohort study of 324,108 THA patients identified through the national health-insurance databases has shown higher cumulative revision incidence in modular stems compared to their monoblock counterparts [22].

Specific corrosion processes at the stem–neck interface were found responsible for modular neck failures. In 2004, Mumme and colleagues pointed out that in vitro serum level of metal ions increases after submerging standardised alloys ($TiAl_6V_4$, $CoCr_{29}Mo$, FeCrNiMoMnNbN) and pure titanium in human serum causing electrochemical corrosion without the need for mechanical load [23]. Mechanically induced crevice corrosion at neck adapter–femoral stem contact was shown to release metal debris that caused local tissue reactions like those found in failed THA-s [24–27].

According to Sharan [28], titanium alloy seems very suitable for monoblock stems, because it forms a protective oxide layer. Within it, the alloy is shielded from uniform corrosion. In modular versions, however, micromovements occur and the oxide layer in the neck–stem junction falls off. That exposes titanium to bodily fluids and the crevice corrosion occurs [28, 29]. Apart from crevice corrosion, titanium modular prostheses are also subjected to pitting and fretting corrosion [28].

Gilbert et al. [30] had shown that a crack can start on the medial proximal side of the neck–stem taper surface. After a small crack is made, the corrosion can continue without external loads on the femoral neck. Autocatalytic corrosion is a result of severe chemical changes within the crevice fluid [30]. Ongoing corrosive attack at the tip of the crack with combination of oxide-driven crack-opening stress also adds to the crack propagation without the necessity of increased mechanical load [31].

Grupp's [32] study concluded that cobalt–chrome (Co–Cr) alloy has twice as high module of elasticity as titanium, so there should be less micromovements at the neck–stem junction. The authors proposed that titanium-alloy necks should be replaced with Co–Cr necks for increased safety [32]. However, Co–Cr necks have not been proven to be a safe alternative, since they present a chance for additional galvanic corrosion. The earliest reported neck fracture of cobalt–chrome alloy neck occurred only 2 years after the implantation [4, 33].

Some modular neck and head combinations (e.g. long-varus neck and *XXL* head) could be dangerous due to enlarged offsets that they create. Even though the manufacturer would allow such combinations, they should be used with great caution or rather, if possible, avoided [8].

Our study has several limitations. To start with, the femoral head implanted at the first revision was not only longer, but it also had larger diameter (36 mm) than the femoral head that was implanted at primary THA (28 mm) and this was not taken into consideration. Reito et al. [34] had shown that larger femoral heads exert greater stress on the implanted neck and may cause even fractures of monoblock stems made of Co–Cr alloy.

Secondly, at the revision, the aseptically loosened acetabular socket was exchanged, and the alumina-composite ceramic inlay was implanted providing the patient with ceramic-on-ceramic articulation. This represents the hard–hard bearing surface, which might also influence faster crack propagation in the patient with the active lifestyle.

Conclusion

If modular stems are to be used in the future, corrosion resistance at the neck–taper interface should be substantially improved. Furthermore, since the risks for failure were not detected in in vitro laboratory settings but only after in vivo implantation presenting as an unpredicted and serious complication exposing the patient to major risks of revision surgery, regulators should change or accordingly adapt the testing protocols.

In THA, dual-modular femoral stems enable the achievement of better anatomical relations between structures of the hip, but in current versions the results regarding durability are worse than with monoblock stems. Since fully modular stems for primary THA have not shown any clinical benefits for the patients, they should be abandoned to avoid unnecessary complications.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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