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COMMENTARY

Fostering Excellence in Knee Arthroplasty: Developing Optimal Patient Care Pathways and Inspiring Knowledge Transfer of Advanced Surgical Techniques

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Abstract: Osteoarthritis of the knee is common. Early sports trauma or cartilage defects are risk factors for osteoarthritis. If conservative treatment fails, partial or total joint replacement is often performed. A joint replacement aims to restore physiological biomechanics and the quality of life of affected patients. Total knee arthroplasty is one of the most performed surgeries in musculoskeletal medicine. Several developments have taken place over the last decades that have truly altered the way we look at knee arthroplasty today. Some of the fascinating aspects will be presented and discussed in the present narrative review.

Keywords: knee, arthroplasty, replacement, implant, materials, robotic, artificial intelligence

Introduction

Osteoarthritis of the knee is common.[1–3] Especially after early sports traumata with persisting cartilage injuries, OA can also manifest itself much earlier.[4–7] If conservative treatment fails, partial or total knee arthroplasty is often performed.[8–10] A joint arthroplasty aims to generate again a stable joint with smoothly articulating surfaces to free the patient of joint pain, to correct prior deformities and thus restore the disrupted function of the degenerated joint.[11–13] Total knee arthroplasty (TKA) is one of the most commonly performed surgeries in the musculoskeletal field,[14–16] with 173,625 cases in 2020 in Germany alone.[17,18] Several developments have taken place over the last decades that have truly altered the way we look at TKA today.[19–21] Some of the fascinating aspects will be presented and discussed in the present study.

Types of Implants

Historically, TKA meant knee resurfacing of the total knee with a bicondylar femoral component, a total tibial plateau requiring the resection of the anterior cruciate ligament and potentially also the posterior cruciate ligament and, if necessary, the use of a retropatellar polyethylene implant.[22,23] Hinged knee replacements with stemmed fixation were the backbone of revision surgery. Over the years, this portfolio has widened enormously.

The concept of a unicompartmental knee replacement emerged, however, in the 1940s.[24,25] Due to its highly variable clinical results total implantation rates in comparison to total knee replacement were marginal for a long time.[26,27] In recent years, better implants and implant positioning techniques and a better understanding of selecting the right indications for this prosthesis design have led to a strong increase in its use.[28,29] For example, the incidence of unicompartmental TKA in the US ranged from 6570 implants in 1998 to 44,990 in 2005.[30] Even small implants addressing focal cartilage defects have been placed on the market such as the UniCAP (Arthrosurface Inc, Franklin, MA, USA).[31] Difficulties in achieving the required precision when implanting these devices led to high failure rates in

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the first postoperative years,[32] with a cumulative revision rate of over 50% after seven years in the Australian Joint Registry.[33] With the advent of patient-specific instrumentation based on preoperative 3D planning, patient-specific implants for focal cartilage lesions have been introduced (Episurf, EPISEALER, 4 Medical s.r.l., Cinisello Balsamo, Italy), the first clinical results of which appear promising with a revision rate of 2.5% after 2 years.[34,35] Even isolated replacements of the trochlea have been introduced. While data are also scarce in the literature, revision rates appear to be critically high.[36–38]

Also in the other direction, technical developments have opened new options for surgeons. The traditional portfolio of a cruciate retaining (CR, retaining the posterior cruciate ligament), a posterior stabilised (PS, replacing also the posterior cruciate ligament) and a rotational hinge and/or total hinge design have now been augmented by various PE configurations that are intended to bridge the gap between still completely intact collateral ligaments and collateral ligament deficiency. The so-called condylar constrained coupling offers an intermediary stability that can support collateral ligaments that are still present, but not strong enough anymore to completely secure functional knee stability.[39] This solution has the advantage that knee kinematics can largely be preserved while at the same time, maximum stress shear on the bone-implant interface is reduced due to the lack of a rigid coupling. Condylar-constrained coupling is usually achieved by high conformity of the PE with the femoral component using a deep dish and/or a central intercondylar strong post resembling the one from a PS design, however much more prominent. This vast portfolio of implant designs now offers the possibility to more specifically address a patient problem and it reduces the likelihood of overtreating a problem.

Fixation

Traditionally bicondylar TKA was fixed at the implant-bone interface using bone cement (polymethyl-methacrylate).[40–42] For the fixation of hinged prostheses, stems were required that could either be cementless or cemented. While for decades this concept has shaped the arthroplasty landscape, powerful new ideas and implants have emerged over the last few years.

Concerning primary arthroplasty, early attempts to repeat the success of cementless hip arthroplasty were met with high rates of early failure due to implant loosening.[43–45] Improvements in implant design and manufacturing technology have, however, provided surgeons with roughened or even three-dimensional porous surfaces which are usually based on titanium or tantalum alloys. These surfaces already provide substantial primary stability in cancellous bone[46] thus limiting micromotion before osteointegration.[47–50] Their surfaces also strongly promote osseointegration through the bone on- or ingrowth.[51] One reason why the topic of cementless implant fixation in TKA is also more and more relevant is the fact, that a cemented interface never osseointegrates and thus also does not allow bone-remodelling according to functional requirements placed on it. Especially in the elderly osteoporotic bone with receding trabeculae and impaired bone metabolism, may lead to high failure rates in the long run. With more TKAs being implanted also in patients aged 65 years or younger,[52] the mid-term stability of the bone-implant interface needs to be increased due to the higher functional demands placed on the implant.[47] Indeed, data from the British National Joint Registry demonstrate that younger patients undergoing cemented primary TKA have a higher risk of revision when compared to their older counterparts.[53] In a systematic meta-analysis Prasad et al, 2020, found that based on the present literature, there is no difference in implant survival between cemented and cementless primary TKAs.[47] The authors nevertheless argue in favour of cementless fixation due to a lack of cement-induced third body war and better preservation of bone stock in case of revision. It needs to be pointed out, however, that the latest 3D surfaces have not been on the market long enough to allow for a reliable long-term follow-up analysis concerning implant survival. If cementless fixation eventually outperforms cemented techniques in TKA time will have to tell.

In revision arthroplasty, Morgan-Jones et al, 2015, proposed a three different zones concept for revision-implant fixation.[54] Zone 1 being the epiphysis and zone 3 being the diaphysis had long been used to fix a combination of a tibial plateau with a long stem. As the geometrical centres of the epiphysis and diaphysis are often not in line, an offset adapter may be required to match the positional requirements of the tibial plateau especially an uncemented stem.[54] Epiphyseal defects had to be filled with augments consisting of metal, polyethylene (PE) or polymethyl-methacrylate (PMMA) cement to ensure a solid fixation in zone 1. The new aspect highlighted by Morgan-Jones et al was a possible fixation in zone 2, the metaphysis. The authors stipulated, that a fixation in 2 of the 3 zones would already be sufficient for good implant fixation. With the metaphysis being directly adjacent to the epiphysis, an offset correction is obsolete. When using an implant to achieve metaphyseal stability, only short stems are required to fixate the implant within the metaphyseal stabilisation. This offers the additional advantage of bone preservation and it also avoids problems with sagittal anterior translation due to the femoral bow of the diaphysis.[54] While good simple cemented fixation by filling in the metaphysis is technically challenging, new implants have been brought on the market that strongly facilitate this surgical technique. These sleeves or cones can be placed press-fit into the metaphysis, thus also closing potential local defects in the bone circumference. In addition to their press-fit, their 3D surface structure usually allows fast bone ingrowth for permanent secondary stability. Once in place, the epiphyseal implant component with its distally cementless or cemented shaft is cemented onto and into the metaphyseal implant. Respecting this concept could finally break with the dogma that in knee revision surgery stems would always get longer. The popularity of this technique is clearly on the rise,[55] the long-term success will still need to be evaluated. The first results are, however, highly promising.[56,57]

Bearing

The traditional bearing surface is that of a cobalt–chrome (CoCr-) femur against a PE insert mounted on the tibial plateau. Especially concerning polyethylene, powerful improvements could be achieved over the past decades. Denoted by the formula $(C_2H_4)n$, n can differ depending on molecular size.[58] Sir John Charnley introduced the long-chained ultra-high molecular weight (UHMW) PE in the 1960s in hip arthroplasty,[59] the success of which also paved the way for its use in TKA.[60] As a further development to improve the wear resistance of the still soft UHMWPE, gamma or electron beams were applied to break the carbon-hydrogen chains to create highly cross-linked UHMWPE (HXLPE).[61,62] This HXLPE was, however, prone to fatigue-crack propagation due to its lower elasticity.[63] These XHLPE, therefore, still have to be post-treated: To reduce the concentration of free radicals created by radiation, annealing of these ends is performed at a temperature just below melting, which adequately preserves the mechanic characteristics.[62] The latest development is the creation of 2nd generation HXLPE where other methods are used to eliminate free radicals. The most popular manufacturing process is the addition of the antioxidant vitamin E, which makes heat annealing after radiation obsolete and thus even better preserves the mechanic properties of the PE.[61]

The use of a cobalt-chrome alloy for the femur has always been highly successful from a biomechanic point of view. Yet, a relevant number of patients show a metal hypersensitivity to one of its components. Most patients with such a hypersensitivity react to nickel, while cobalt and chromium are less frequent. In dermal testing, some patients also show reactions to beryllium and less frequently to tantalum, titanium and vanadium.[64] Ions released by corrosion of metallic wear debris may play a critical role and metal particles can be found in the soft tissues surrounding the implant.[65] According to the 2016 Australian Arthroplasty Register, approximately 2% of revision TKAs are attributed to "metal-related pathology".[66] Moreover, one of the main reasons for knee revision surgery remains aseptic loosening[67] which is often attributed to particle wear.[68,69]

For these main reasons, new materials were developed that would reduce particle wear and allow the successful treatment of patients hypersensitive to metal ions.[70] For TKA, two main approaches have been chosen: the manufacturing of full-thickness ceramic implants and the creation of ceramic surfaces.[48–50]

To date, the company PETER BREHM GmbH (Weisendorf, Germany) is the only manufacturer worldwide that offers an all-ceramic primary knee endoprosthesis (BPK-S INTEGRATION Ceramic). Smith & Nephew (London, England) additionally provides a prosthesis (LEGION) where, even if not the tibial component, at least the femoral component is made of solid ceramic consisting of Zirconium and Niob. Although not reported yet in the literature, one major concern regarding a monolithic ceramic component is that the geometry of standard femoral or tibial implants is often not ideal for ceramics and the material still has a high brittleness and low tensile strength when compared to metal components. One strategy to counter this phenomenon has been modifying the countersurface rather than using a monolithic ceramic component.[71]

The so-called coating of the femoral component is usually performed with combinations of Zirconium, Niob, Titanium and/or Nitrid. Indeed, ceramic surfaces in knee resurfacing achieve a drastic reduction in wear rates,[72] not only of metal ions but also of PE[71] which is attributed to the lower coefficient of friction of ceramic surfaces. In addition, ceramic wear particles are less (bio)reactive compared to polyethylene particles or metal ions.[71] A recent review article analysing 14 studies reporting on ceramic total knee replacements mid- and long-term survival and knee function were comparable to their metallic femoral counterparts.[73] If expectations concerning increased long-term survival based on reduced aseptic loosening will be met future studies and registry data still have to tell.

Alignment

From its first description by Insall in 1985[74] but at least after Leo Whiteside publicised "Ligament Balancing of in Total Knee Arthroplasty" in 2004[75] it was considered standard of care to perform a mechanical alignment that would be "biomechanically friendly". Respecting the mechanical axis in the frontal plane of a straightened leg with the Mikulicz line going centrally and perpendicularly through the joint reduces the risk of accelerated PE wear, early implant loosening at the implant-bone interface and patella instability. The axial rotational alignment of the femoral component was suggested to be externally rotated by 3° about the posterior condylar line to compensate for the then corrected 3° varus orientation of the proximal tibia joint-line found in the majority of patients.[76] The remaining functional restrictions of the knee would then be balanced by an elaborate technique of soft tissue release. Being technically demanding, such a soft tissue release also always bore the risk of leading to post-operative either imbalanced or unstable conditions.

Although this standardised technique worked solidly for the majority of cases, historically up to 20% of patients complained about persistent knee pain and functional limitations even in cases of a radiologically well-aligned implant. Even modern literature still reports a figure of about 10% of patients suffering from chronic pain after TKA.[77] Accompanying improvements in wear resistance of newer implant materials and better fixation techniques at the implant-bone interface, this purely mechanical approach has been increasingly challenged over the past few years.[78] Alternative alignment strategies proposed try to be more anatomical and patient-specific, better-respecting ligament tension and geometry of the articulating partner's.[79] To improve at least flexion gap balancing, axial femoral rotation was adjusted to the ligament tension in flexion.[80] As the usual tibiofemoral joint line is usually oriented 3° ascending from medial to lateral (called valgus orientation),[81] a technique was proposed respecting this orientation thus called anatomical alignment.[82] While theoretically already sound in the 1980s, this concept found no widespread use at the time. With the imprecision of traditional extramedullary tibial instrumentation being around 2° (plus outliers up to 5°)[83] a targeted 3° varus position easily ended in an excessive malposition of the tibial implant with devastating effects.[84]

A modern way in conventional TKA that can be considered a compromise between mechanical alignment and anatomical alignment is the so-called adjusted mechanical alignment. In this case, the tibial plateau is targeted perpendicular to the mechanical axis of the tibia. At the same time, the femoral component is implanted in a way, that the preoperatively existing axis deviation is undercorrected.[85,86] For an overview of different present alignment concepts see Figure 1.

Modern robotic-assisted surgery techniques promise a highly precise implant positioning.[83,87] Such precision but especially reliability in placing implant components has opened the window for a radically different implantation concept: kinematic alignment.[88] In this concept, the patient's anatomy and ligamentous needs are maximum respected.

Short-term clinical results of this technique seem to be excellent[89,90] but there is some concern as to the long-term results due to the fear of mechanical failure of the PE or the implant-bone interface. It is also conceivable, that patients with a strong deformity preoperatively, might not benefit from restoring this anatomy at all.[91]

Especially among surgeons who still have to rely on conventional navigation, restricted kinematic alignment has become quite popular over recent years. First described in 2017,[92] literature on that topic has strongly increased in the last three years. While generally trying a kinematic alignment, implantation follows a strict algorithm that sets clear safety limits concerning maximum implant deviation from a mechanical alignment. It is thus a hybrid technique between mechanical alignment and kinematic alignment.[92] The exact safety limits are still a matter of debate. They have to take into account the safety limits of the articulating surfaces which depend on implant size, shape and used materials and their fixation technique to the bone (eg bone quality, cementation, use of stems). Due to greater variations in implant positioning with conventional techniques, safety margins have to be put narrower than when performing this technique computer navigated. In both cases, thorough preoperative planning and intraoperative evaluation are essential. Data regarding the clinical benefit of using such a technique are still scarce. The first results suggest a slight benefit when compared to mechanical alignment.[93,94]

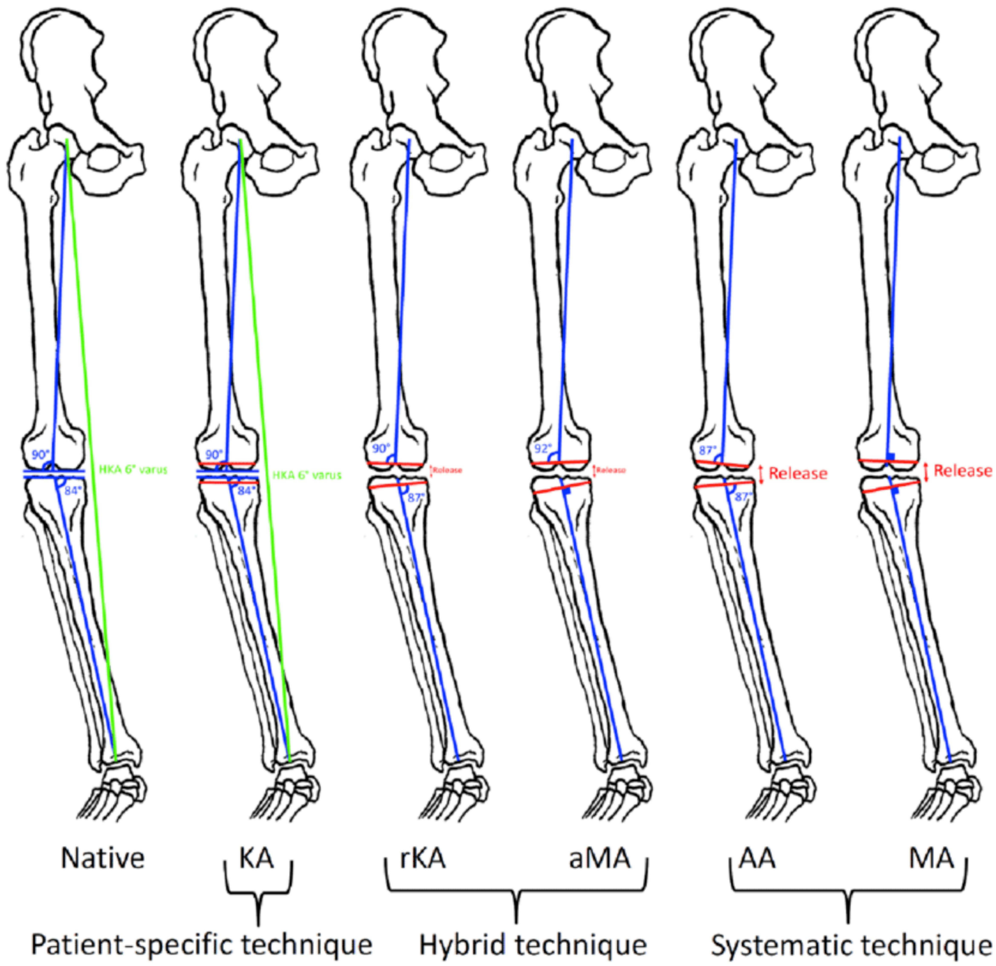

Figure 1 Different techniques for alignment in total knee arthroplasty.
Notes: Reprinted from Riviere C, Lazic S, Boughton O, Wiart Y, Villet L, Cobb J. Current concepts for aligning knee implants: patient-specific or systematic? *EFORT Open Rev*. 2018;3(1):1–6. Creative Commons.[79].
Abbreviations: KA, kinematic alignment; rKA, restricted kinematic alignment; aMA, adjusted mechanical alignment; AA, anatomic alignment; MA, mechanical alignment.

Robotics and Navigation

Robotic-assisted TKA refers to the use of devices which assist the surgeon. Both image-dependent and imageless systems are available in robotic-assisted TKA. Image-dependent robotic-assisted TKA generate a virtual three-dimensional computational model of bony anatomy from pre-operative computed tomography (CT) or magnetic resonance imaging (MRI). On the other hand, imageless systems create bony surfaces and joint kinematics intra-operatively, sparring imaging costs and radiation risk.[95,96] Robotic systems can be further divided into passive, semi-active, and active. Passive systems are based on navigation or computer-assisted technology which provide three-dimensional guidance via an overhead monitor but do not perform bone cuts.[97–99] Semi-active systems incorporate safety constraints (eg haptic feedback) which guide the surgeon during specific tasks and advise the same if the action might result in a change in the pre-determined computational plan. On the other hand, active systems perform the bony resections independently under supervision without real-time guidance.[97,100] An overview of the available robotic-assisted TKA is shown in Table 1. An important limitation of the current robotic systems is their implant specificity (closed platforms), which limits the implant choice tailored to the patient's anatomy.[101] Moreover, their cost efficacy is also debated and long-term studies are required. Despite the progress in robotic systems, whether these improve long-term outcomes and implant survivorship is still unknown.

Table 1 Overview of the Available Robotic-Assisted TKA

Name of the Robotic System	Manufacturer	Robotic System
Mako Robotic-Arm Assisted System	Stryker, Mako Surgical Corp., Fort Lauderdale, FL, USA	Image-dependent semi-active system
Navio CORI surgical system	Smith & Nephew, Inc., Memphis, TN, USA	Imageless semi-active system
ROSA Knee robotic system	Zimmer Biomet, Warsaw, IN, USA	Image-dependent or imageless active system
OMNIBotics knee system	OMNIlife Science, Inc., Raynham, MA, USA	Imageless semi-active system
TSolution One	Think Surgical Inc., Fremont, CA, USA	Imageless active system
VELYS	DePuy Synthes, Raynham MA, USA	Imageless active system

Artificial Intelligence

The founding father of the discipline of artificial intelligence (AI) described it as making a machine behave in ways that would be called intelligent if a human were so behaving.[102] The term "artificial" contrasts it with the natural intelligence of humans or animals. AI is a cross-disciplinary approach to understanding, modelling and creating intelligence of various forms.[103] It encompasses several subdisciplines such as machine learning, neural networks including deep learning, natural language processing, robotics or machine perception. The central thesis behind AI is that many aspects of learning and intelligence depend crucially on the careful probabilistic representation of uncertainty. A machine can use such AI models to make predictions about future data, and decisions that are rational given these predictions.[104] AI is based on data-driven algorithms which simulate the processes of human intelligence through the creation and application of algorithms integrated into a dynamic computing environment to learn, reflect, reason, consider, and perform cognitive functions.[105–107] To date, AI is still largely limited to task-specific. Numerous tools using AI are, however, available. Concerning their use in knee surgery, several applications are already in use or on the horizon for introduction. Predictive modelling, for example, estimates prognostications for specified outputs in complex systems that are otherwise difficult to grasp due to the high number of variables. Briefly, predictive models provide information to ascertain the association between variables (eg, patient characteristics) and events (eg, surgical complications) useful for decision-making, surgical planning, and postoperative rehabilitation.[107–109] Computer vision has also seen powerful improvements over the past few years. Computer vision based on AI can now also extract information from images and videos. AI allows to automate of the process of image quality,[110] it can screen for implant loosening on radiographs,[111] it can measure knee alignment,[112] and postoperatively evaluate joint replacement.[113]

Advances in computer vision have also accelerated developments in augmented reality. Augmented reality interacts with the human senses and provides additional visual, auditory, haptic, somatosensory or olfactory input.[114] Many AR technologies have been shown to lower provider cognitive burden and reduce operative time and radiation exposure while improving surgical precision in pre-clinical cadaveric and sawbones models.[115]

In TKA, AI eases the choice for patient-specific implants and optimises the decision-making algorithm and resource allocation. AI-based tools can also give estimates and help with pre-TKA-planning, prediction of disease progression, and estimation of treatment outcomes.[116] However, despite several published studies on the application of AI in TKA, there are still several limitations to its application in daily clinical practice. Semi-active and active robotic-assisted TKA are recent AI-based tools (Table 1). Data collected consider the three-dimensional bone surface, and computational algorithms on implant alignment and soft tissue balancing. These data are integrated to plan the surgery adjusting it to the surgeon's and patient's needs and goals. Semi-active and active robotic-assisted TKA indicate (semi-active) or perform (active) bone resections and suggest implant positioning with real-time haptic feedback. Doing so, implantation precision could be strongly increased.[117–119] Whether this precision actually translates into a clinical benefit still needs to be evaluated.[119]

Outpatient Regimes

The average hospitalisation following TKA reduced from 9 days to 3–4 days in the past decades.[120,121] This reduction is associated with the introduction of fast-track regimes, early mobilisation, improve in anaesthetic modalities, multimodal pain control strategies, perioperative care, and physiotherapy protocols.[121–123] As a result, the concept of outpatient TKA has been introduced.[124,125] Outpatient TKA requires a careful patient section and several morbidity scoring systems have been elaborated to select eligible patients.[126,127] Local infiltration analgesia (LIA) and nerve blocks are associated with improvement in pain control and short recovery.[128,129] The mini-subvastus exposure in TKA was associated with a shorter recovery than the traditional medial parapatellar approach.[13,130,131] Older age, obesity, physical and cognitive impairment, social support at home, cardiovascular, renal and/ or hepatic disorders, and diabetes mellitus represent relative contraindications for outpatient TKA.[132–135] A previous successful TKA at the contralateral side has been positively associated with an outpatient procedure.[136] However, despite these ameliorations, outpatient TKA remains debated.[137] In a recent meta-analysis of 159,219 TKAs, outpatient TKA did not evidence significant advantages to longer hospitalisation regimes at approximately six months of follow-up.[138] There are no clear recommendations and eligibility criteria, and the current evidence is poor and controversial.[120,121,127,139–146] Possible confounders are the different healthcare systems and heterogeneous admission and rehabilitation protocols. Further investigations are strongly recommended to establish consensus on the eligibility and education criteria for outpatient TKA.

Data Sharing Statement

No dataset has been generated during the current study.

Ethical Approval

This study complies with ethical standards.

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Disclosure

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