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Research article

Method for reconstructing femoral head blood supply by anastomosing the intraosseous artery

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A R T I C L E I N F O

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A B S T R A C T

Background: The reconstruction of femoral head blood supply is crucial in the management of avascular necrosis and related conditions. This study presents a method for reconstructing the femoral head blood supply by anastomosing the intraosseous artery.
Methods: The femoral heads of six male Landrace swine were surgically exposed, and subcranial fractures of the femoral neck were intentionally created. Under microscopic guidance, the trophoblastic foramen of the posterior supporting artery was identified. Subsequently, a triangular bone window was carefully crafted to expose the intraosseous artery. Following the fixation of the femoral head, an anastomosis was performed between the intraosseous artery and the posterior inferior supporting artery located at the distal end of the fracture. The assessment of femoral head blood supply was conducted using Kirschner's pinhole and angiography techniques.
Results: The anastomotic intraosseous artery exhibited a vibrant red color, indicating adequate blood perfusion, and demonstrated pulsatile flow. Observation through pinholes in the surface of the femoral head revealed continuous blood flow. Angiography further confirmed the successful circulation, as the contrast agent entered the inferior retinacular artery branch originating from the deep femoral artery. The contrast agent then proceeded to enter the femoral head through the retinacular artery, reaching the anastomosis site of the intraosseous artery. Notably, the angiography also revealed the presence of visible internal branches, highlighting the establishment of a functional vascular network.
Discussion: The method of reconstructing the blood supply to the femoral head through anastomosis of the intraosseous artery enables utilization of the existing blood supply system within the femoral head. This study is just a preliminary study of this innovative technique that has the potential to prevent and/or treat femoral head necrosis following a femoral neck fracture. By restoring adequate blood flow to the affected area, this approach holds promise in preserving the viability and functionality of the femoral head, ultimately improving patient outcomes.

1. Introduction

Femoral neck fractures resulting from high-energy trauma represent a predominant etiological factor for avascular necrosis of the

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femoral head in younger and middle-aged cohorts [1]. Given the elevated functional demands of the hip joint in these demographics, surgical interventions prioritizing the preservation of the native femoral head are deemed optimal [2]. Notwithstanding precise anatomical surgical realignment, there persists a notable risk of avascular necrosis in this patient population [3].

Extensive experimental and clinical studies have elucidated that a compromised blood supply significantly contributes to avascular necrosis of the femoral head following a femoral neck fracture [4]. The femoral head predominantly receives its vascularization from various groups of retinacular arteries. Disruption of the femoral neck consequent to fracture predisposes these arteries to avulsion and rupture. While conventional surgical interventions can realign the fracture fragments, they fall short in re-establishing the native vascular integrity. Techniques such as bone flap transplantation, bone marrow aspirations, and VEGF (Vascular Endothelial Growth Factor) implantation serve as indirect modalities to revascularize the femoral head, showing potential in attenuating the postoperative incidence of avascular necrosis [5–7]. Nonetheless, the prolonged treatment duration, substantial costs, and variable efficacy curtail their universal adoption.

Undoubtedly, repairing the disrupted retinacular artery stands as the most direct and cost-effective strategy to re-establish blood flow to the femoral head. In the context of transcervical femoral neck fractures, anastomosis of the retinacular artery has been proposed [8]. However, the feasibility of this approach is contingent upon the fracture not traversing the head-neck junction and the distal arterial segment being intact and of ample length, thereby limiting its widespread adoption. With the advent of sophisticated microsurgical techniques and a comprehensive understanding of the internal femoral head artery's architecture, the scope of this reparative method has expanded. Directly accessing the internal femoral head artery via the fracture site to facilitate anastomosis with the internal osseous artery can enhance vascularization to the femoral head, even in cases of more severe femoral neck fractures. Consequently, this research sought to employ microvascular repair methodologies to directly address the intraosseous artery in the porcine femoral head, with the overarching objective of reinvigorating its vascular supply.

2. Materials and methods

2.1. Materials

The study protocol was approved by the Institutional Animal Care and Use Committee, Suzhou Ruihua Orthopedic Hospital, Suzhou, China (Approval number: RX2021007). Six common-grade 10-month-old male landrace swine weighing (100 ± 10) kg (Wujiang Tianyu Biotechnology Co., Ltd., certificate number: SCXK Suzhou 2016–0006) were used in this study. The swine were housed in a clean environment at a temperature of (22 ± 2) °C and a humidity of 60 %–70 %. Surgical anesthesia consisted of xylazine hydrochloride (Jilin Huamu Animal Health Products Co. Ltd.), propofol (Xi'an Libang Pharmaceutical Co. Ltd.) and inhaled sevoflurane (Lunan Bette Pharmaceutical Co. Ltd.). Additional equipment included an angiography machine FD20 (Royal Philips) and a surgical light microscope ZC-X-4A (Zhenjiang Zhuochuang Medical Technology Co. Ltd.).

2.2. Preoperative preparation and anesthesia

The experimental animals were subjected to a 6-h fasting period prior to surgery, and their skin was prepared for aseptic surgery. Swine were oriented in a supine position, with both hind limbs maximally abducted (Fig. 1a). Anesthesia was induced via intramuscular injection of xylazine hydrochloride (2.2 mg/kg) into the hock muscle. If deeper anesthesia was warranted after 15 min, an additional dose of xylazine hydrochloride (30 mg) was administered. Venous access was established through the marginal ear vein, followed by intravenous administration of propofol (2 mg/kg) to augment the anesthetic effect. Subsequent to endotracheal intubation, the swine were attached to a mechanical ventilator. For sustained anesthesia, a combined intravenous-inhalation technique utilizing propofol and sevoflurane was implemented. The inspired oxygen fraction (FiO2) was kept constant at 100 %, delivered at a flow rate of 2 L/min. The concentration of inhaled sevoflurane was regulated between 1.5 % and 2.0 %, while the propofol infusion was set at a rate of 0.5 ml/min.

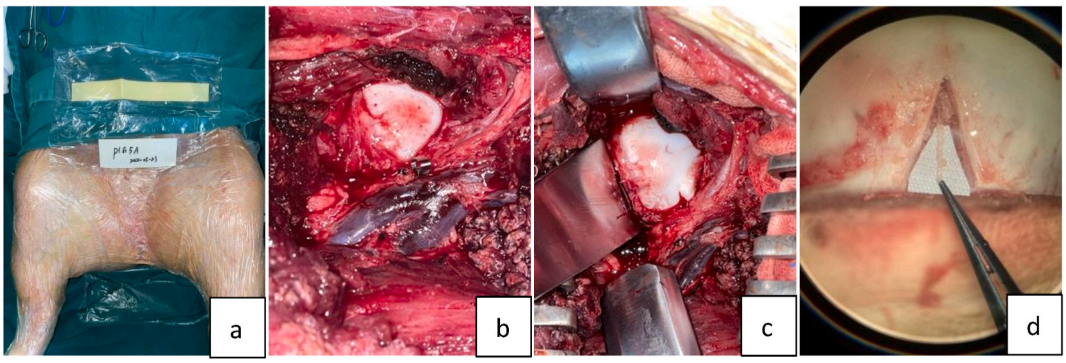

Fig. 1. Surgical methods. a. Operative position. **b.** Hip joint capsule and femoral head. **c.** The femoral head was cut off at the head neck junction. **d.** The intraosseous artery was exposed.

2.3. Surgical methods

Initially, the surgical site was subjected to three rounds of disinfection using sterile gauze impregnated with Anerdian, employing a centripetal technique that began at the core of the operative field and expanded outward. The disinfected territory spanned from the inferior rib margin to the hind limbs and the tail's extremity, extending laterally to the posterior axillary line. Following standard disinfection procedures, radiographic imaging was employed to pinpoint the projected location on the femoral head's surface. A central incision, approximately 10 cm in length, was executed along the groin, aligned with this identified point. Subcutaneous dissection was performed layer by layer until the hip joint capsule was exposed, taking special care to protect vital blood vessels and nerves. The hip joint capsule was incised in a "T" shape and dissected to the sides, exposing the femoral head (Fig. 1b). The round ligament of the femoral head was then severed, and the hip joint was fully dislocated. The femoral neck was amputated at the junction of the femoral head and neck using a bone knife, and adequate hemostasis was achieved upon removal of the femoral head (Fig. 1c).

Once the femoral head was extracted, the nutrient foramen of the posterior inferior retinaculum of the femoral head was identified under a surgical microscope. A triangular bone window, with a bottom edge of 0.6 cm and a height of 1.0 cm centered around the nutrient foramen, was designed (Fig. 1d). Using a no. 15 blade, the cartilage surface was incised along the edges of the triangle, and a curette was employed to scrape the bone from the outer to inner sides, exposing the intraosseous artery fully. A layer of bone wax was applied to the fracture surface, ensuring hemostasis at the distal end of the fracture. The femoral head was clamped with point reduction forceps to anatomically reduce the fracture, and fixation was achieved using either Kirschner wires or cannulated lag screws, ensuring a snug fit between the fractured ends. Following reduction and fixation, the retinacular artery was dissected at the stump of the femoral neck and clamped with a hemostatic clip. Utilizing a surgical microscope, the retinacular artery was then anastomosed to the intraosseous artery using 12-0 microsutures and a two-point method (Fig. 2a and b). The hemostatic clip was released, and the patency of the anastomosed artery was observed. A 2.0-mm diameter Kirschner wire was inserted 1.5 cm above the bone window, 0.5 cm below the cartilage surface, and then withdrawn. The compacted bone surrounding the pinhole was cleaned using a curette and washed with heparin normal saline, enabling continuous visualization through the pinhole.

2.4. Angiography

Preoperative and postoperative angiography was conducted using the posterior edge of the medial side of the contralateral stifle as the reference point. A longitudinal incision of approximately 3 cm was made in the skin, and underlying subcutaneous tissues were dissected. The saphenous artery was located, and a vascular puncture sheath was inserted with the guidance of a guide wire. A single-curved catheter was positioned at the bifurcation of the abdominal aorta, and the first angiography (pressure: 300 PSI; flow rate: 4 ml/

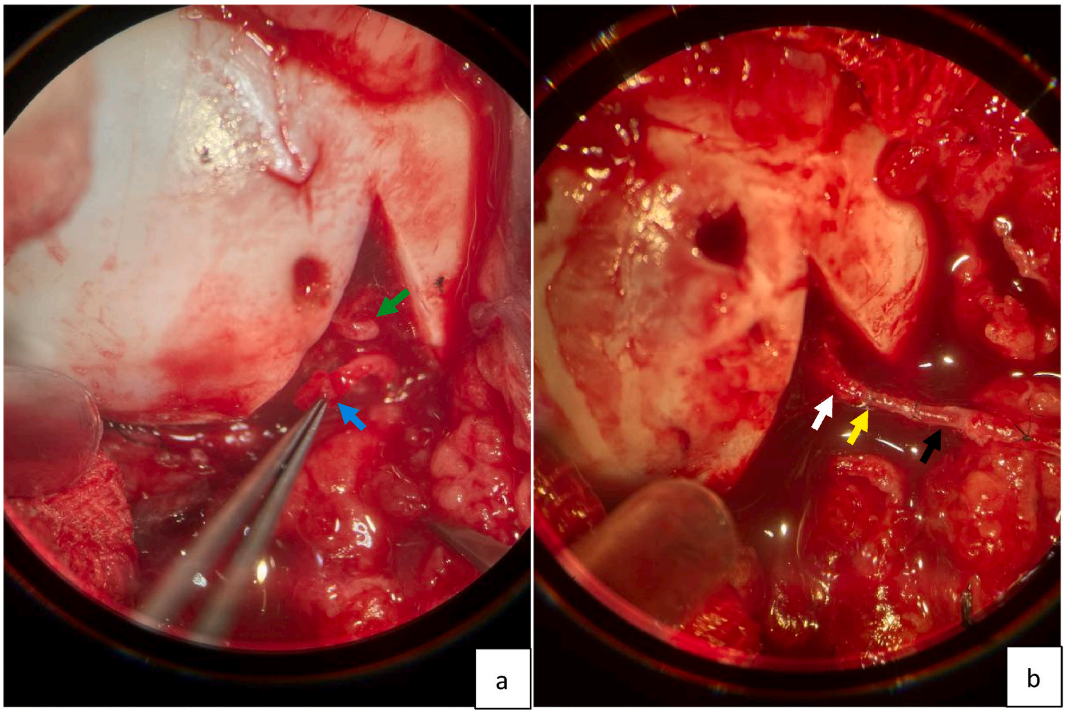

Fig. 2. Anastomosis of the intraosseous artery. a. Prior to anastomosis. The green arrow marks the intraosseous arteries and blue arrow marks the posterior inferior retinaculum artery. **b.** After anastomosis. The white arrow marks the intraosseous artery, the black arrow marks the posterior inferior retinaculum artery, and the yellow arrow marks the anastomosis.

s; angiographic agent: Ioversol, Jiangsu Hengrui Pharmaceutical Co., Ltd; total volume: 12 ml) was performed to visualize the course of the deep femoral artery and its branches. With the assistance of a guide wire under image guidance, the catheter was advanced into the deep femoral artery and placed at the opening of the femoral head vessel branch. A second angiography (pressure: 200 PSI; flow rate: 3 ml/s; total volume: 8 ml) was conducted to confirm the patency of the artery. Upon completion of all procedures, the experimental animals were euthanized by exsanguination under anesthesia.

3. Results

3.1. The intraosseous artery was successfully anastomosed and recanalized

The intraosseous arteries were meticulously exposed under the surgical microscope in all experimental animals. Following successful anastomosis to the retinacular artery, the intraosseous artery manifested a vivid red hue, indicative of optimal blood perfusion. It demonstrated robust fullness and consistent pulsations, signifying the re-establishment of blood flow. Importantly, the anastomotic site was devoid of any hemorrhagic events, confirming a stable union. Additionally, a persistent blood efflux was discernibly evident through a pinpoint aperture on the femoral head's surface, corroborating the restoration of adequate blood circulation (Fig. 3a–c).

3.2. Angiography results

Angiographic assessment illuminated the trajectory of the contrast medium from the deep femoral artery, coursing into the subsidiary branch of the inferior retinacular artery. This pathway extended to the femoral head via the anastomosis between the retinacular and intraosseous arteries. Notably, the contrast agent accomplished effective perfusion of the internal branch as well, as evidenced in Fig. 4a and b.

4. Discussion

4.1. The choice of experimental materials

Humans, as primates, exhibit a unique gait that distinguishes them from other species. The morphology and biomechanics of the femoral head differ among species, presenting challenges in identifying an experimental analogue closely resembling the human femoral head. This investigation sought to develop an innovative methodology for reinstating the blood supply to the femoral head post-femoral neck fracture, intending to mitigate the risk of subsequent traumatic femoral head necrosis. The selection of an appropriate experimental model relied heavily on understanding the structure of the femoral head's blood supply. In humans, the blood supply to the femoral head comprises three groups of epiphyseal vascular branches that anastomose with each other on the epiphyseal plate, forming multiple vertical arterial arches within the epiphysis [9,10]. Additionally, the metaphyseal branches of these three groups of retinacular arteries anastomose below the epiphyseal plate, forming a metaphyseal vascular network. In contrast, the internal femoral head arteries in swine primarily arise from the posterior superior, posterior inferior, and anterior retinacular arteries. Each retinacular artery gives rise to 1–3 branches along its course, forming the retinacular artery group [11]. Upon entering the femoral head through the nutrient foramen at the junction of the head and neck, the retinacular arteries in swine continue to supply the epiphysis. The anatomical characteristics of the internal head artery in swine closely resemble those of the internal femoral head artery

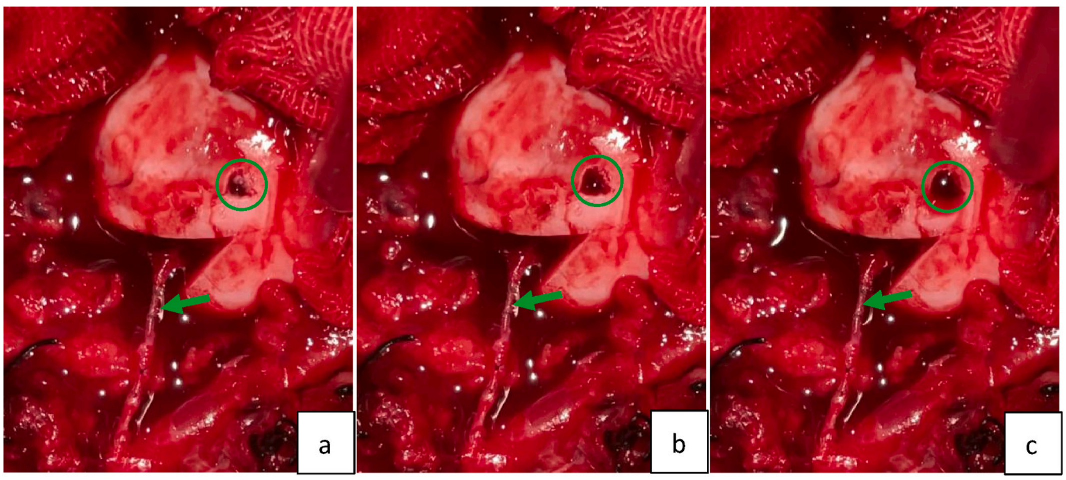

Fig. 3. Blood supply to the femoral head. The three pictures were taken consecutively. The green circle indicates the pinhole and the green arrow indicates the internal bone artery. **a.** No blood within the pinhole. **b.** A small amount of blood appears within the pinhole. **c.** Blood within the pinhole continues to increase.

Fig. 4. Results of digital subtraction angiography. The red arrow indicates the posterior inferior retinaculum artery, and the blue arrow indicates the branches of the blood vessels inside the femoral head. **a.** Preoperative angiography. **b.** Angiography after intraosseous artery anastomosis.

in humans. Consequently, for this research, large swine comparable in size to humans were selected as the experimental model. In human anatomy, the superior retinacular artery plays a central role in supplying blood to the femoral head. However, in swine, this role is notably assumed by the posterior inferior retinacular artery, which, distinct from its human counterpart, presents the largest diameter among the trio of retinacular arteries and stands as the principal vessel sustaining the blood supply to the swine femoral head [9,11]. Mindful of these anatomical variances in the predominant arterial supply between human and swine femoral heads, our strategy was to undertake the reconstruction of the vital posterior inferior retinacular artery, choosing the medial aspect for our surgical approach.

4.2. Current treatment of femoral neck fracture

Surgical intervention remains the cornerstone of treatment for the majority of femoral neck fractures, with objectives centered on reinstating mobility and curtailing potential complications [12]. Yet, only in recent times has the pivotal role of re-establishing the femoral head's blood supply in the context of femoral neck fracture management come to the forefront of clinical consideration. As highlighted by Kregor [13], an overwhelming 84 % of femoral neck fractures culminate in a compromised vascularization of the femoral head, subsequently amplifying the risk of avascular necrosis. Notwithstanding the array of methodologies put forth for vascular restoration, the majority employ indirect strategies, rendering their efficacy somewhat elusive [14].

Vascularized bone grafting is considered a reliable method for restoring blood flow to the femoral head after femoral neck fracture. Zhao et al. [15] confirmed improved blood supply to the femoral head through digital subtraction angiography (DSA) before and after surgery using vascularized bone grafts. Li et al. and Xie et al. [16,17] reported a lower incidence of femoral head necrosis and nonunion when vascularized bone grafts were combined with fracture fixation. However, donor site complications such as fractures, joint instability, and sensory impairment were observed in up to 54 % of cases, requiring additional surgical interventions [18]. The use of autologous bone marrow injections to restore blood supply to the femoral head remains controversial. Although Yang et al. [19] demonstrated that bone marrow mesenchymal stem cells can promote bone angiogenesis in animal experiments, the long-term persistence of this effect remains unreported. Supported by experimental and clinical evidence, a controlled study by Verma et al. [20] concluded that the addition of autologous bone marrow to femoral neck fractures did not accelerate bone healing or reduce the incidence of femoral head necrosis. Treatment modalities such as extracorporeal shock wave therapy (ESWT) and hyperbaric oxygen therapy (HBOT) have shown promise in promoting vascularization during fracture healing, but their long treatment durations of several months have limited their widespread application [21].

4.3. Significance of this study

Historical clinical investigations underscore a direct relationship between the magnitude of ischemia in the femoral head and the displacement resultant from fractures [22]. For younger cohorts with minor fracture displacements, microsurgical revascularization of the femoral head emerges as a feasible recourse. However, its applicability may wane in the context of femoral neck fractures complicated by the detachment of the synovium or compromise of the internal arterial system of the femoral head [8]. Even though meticulous studies have quantified the arterial provisioning to the femoral head [22], the technique of surgical revascularization is not a panacea for all variants of femoral neck fractures.

Zhang et al. [11] have shown that the anatomical structure of the swine femoral head and neck is similar to that of humans. The primary blood supply to the femoral head consists of the posterior superior, posterior inferior, and anterior retinacular arteries, with the posterior inferior retinacular artery being the largest entry artery into the head. The main blood vessels form an intricate network in the epiphyseal region, where the epiphyseal arteries run superficially and directly beneath the cortex of the femoral head. These arteries can replace the retinacular artery in the femoral head and anastomose with the retinacular artery in the femoral neck. In our experiment, under microscopic guidance, a small section of the femoral head cortex was drilled to locate the epiphyseal artery. The fractured epiphyseal artery was then directly anastomosed end-to-end, restoring the original vascular system and immediately reestablishing blood supply to the femoral head. This verifies the feasibility of intraosseous anastomotic artery reconstruction. The demonstrated feasibility of reconstructing the blood supply of the femoral head opens up possibilities for exploring therapeutic measures to restore femoral head circulation under physiological conditions.

This study bears certain caveats that merit attention. To begin with, the modest sample size limits the generalizability of the findings. We haven't conclusively ascertained the feasibility of intraosseous artery anastomosis across a diverse range of femoral neck fractures. More expansive studies with broader sample populations would furnish clearer insights into the versatility of this technique. Furthermore, our methodology hinged heavily on intricate microscopic procedures. Contrasted with conventional surgical avenues, this modality demanded supplementary incisions, which augments the surgical intricacy and elongates the duration of the procedure. Consequently, there's an impending need to refine the surgical protocol. To cap it off, our observational tenure was rather brief. Even though intraosseous artery angiography corroborated the open anastomotic stomas and the partial resumption of blood circulation to the femoral head, the long-term sustainability of the intraosseous artery post-anastomosis warrants deeper investigation. Subsequent research endeavors should pivot towards evaluating the enduring success rate of the anastomotic procedure and its repercussions on the fracture's healing trajectory.

5. Conclusion

This study presents a novel perspective on the issue of femoral head blood supply. By understanding the origin of femoral head perfusion, a new surgical approach and reconstruction method have been proposed. The significant advantage of this technique is its ability to restore the original blood supply to the femoral head in a targeted manner. It is noteworthy that this study is merely a preliminary study, and numerous challenges still remain. Its clinical feasibility and efficacy necessitate further data support. Unlike previous studies that focused on the introduction of exogenous angiogenic mediators, this approach relies on the natural vascular anatomy of the femoral head without the need for external agents. By utilizing the inherent vascular structure, this method aligns more closely with the local biomechanical requirements of the femoral head, potentially prolonging its viability. Further research will concentrate on assessing the long-term effects of this approach and expediting its translation to clinical application in humans.

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Data availability statement

All data and materials are included in the article.

Ethics declarations

The experiments were conducted in accordance with the Animal Research institute Committee guidelines of Institutional Animal Care and Use Committee, Suzhou Ruihua Orthopedic Hospital. Animal care and procedures were approved by the Institutional Animal Care and Use Committee, Suzhou Ruihua Orthopedic Hospital (Approval number: RX2021007). All methods are reported in accordance with ARRIVE guidelines.

Additional information

No additional information is available for this paper.

CRediT authorship contribution statement

Hongyu Wang: Writing – original draft, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dingsong Wang:** Writing – original draft, Validation, Software, Project administration, Investigation, Formal analysis, Data curation, Conceptualization. **Jiaming Wan:** Visualization, Software, Resources, Project administration, Formal analysis, Data curation, Conceptualization. **Xiaosong Wang:** Validation, Resources, Investigation, Funding acquisition, Data curation. **Ruixing Hou:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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