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CASE SERIES

Halo pin positioning in the temporal bone; parameters for safe halo gravity traction

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Abstract

Introduction Halo gravity traction (HGT) is increasingly used pre-operatively in the treatment of children with complex spinal deformities. However, the design of the current halo crowns is not optimal for that purpose. To prevent pin loosening and to avoid visual scars, fixation to the temporal area would be preferable. This study aims to determine whether this area could be safe for positioning HGT pins.

Methods A custom made traction setup plus three human cadaver skulls were used to determine the most optimal pin location, the resistance to migration and the load to failure on the temporal bone. A custom-made spring-loaded pin with an adjustable axial force was used. For the migration experiment, this pin was positioned at 10 predefined anatomical areas in the temporal region of adult cadaver skulls, with different predefined axial forces. Subsequently traction force was applied and increased until migration occurred. For the load-to-failure experiment, the pin was positioned on the most applicable temporal location on both sides of the skull.

Results The most optimal position was identified as just antero-cranial to the auricle. The resistance to migration was clearly related to the axial tightening force. With an axial force of only 100 N, which corresponds to a torque of 0.06 Nm (0.5 in-lb), a vertical traction force of at least 200 N was needed for pin migration. A tightening force of 200 N (torque 0.2 Nm or 2 in-lb) was sufficient to resist migration at the maximal applied force of 360 N for all but one of the pins. The load-to-failure experiment showed a failure range of 780–1270 N axial force, which was not obviously related to skull thickness.

Conclusion The temporal bone area of adult skulls allows axial tightening forces that are well above those needed for HGT in children. The generally applied torque of 0.5 Nm (4 in-lb) which corresponds to about 350 N axial force, appeared well below the failure load of these skulls and much higher than needed for firm fixation.

Keywords Halo-gravity traction · Pin force · Pin positioning · Temporal bone · Bone strength

Introduction

Halo gravity traction (HGT), first used by Perry and Nickel in 1959 [1], is a well-established treatment strategy to improve the surgical outcome of patients with severe scoliosis [2, 3]. For extreme types of scoliosis, it has become the standard and it is highly preferred by experienced surgeons [4, 5]. This is not only because of curve reduction, but also because of the general improvement of patient condition [2, 3, 6–9].

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Although HGT has shown to be safe, there are obvious and less obvious disadvantages. The traction itself is an obvious disadvantage although it is tolerated very well and, in our experience, most patients even indicate to feel better in traction. Less obvious are the disadvantages of the halo crown. In general, the halo crown that is used most for these children has not been designed for the purpose of traction, but for stabilizing the head of adults who sustained unstable cervical spine injuries. Therefore, the crowns are relatively heavy and the halo shape is not optimal for traction. Due to the sometimes altered anatomy of the children, oversized crowns are needed with extra-long pins. Due to the longer lever arm, such longer pins increase the risk of loosening and therefore migration of the pins. Another disadvantage of the current halo crowns is the need for fixation pins in the frontal skull which results in undesirable scars. Finally, as also mentioned by others [10–12], it is difficult to maintain a constant and sufficiently high level of axial force on the pins, which is cumbersome for long traction periods as anticipated for HGT. Therefore, for HGT purposes, improvement of the halo crown is desirable. This involves a more customized design combined with a different shape to improve pin positioning and tension maintenance.

Based on literature research and a design cycle we determined that the most optimal design would consist of an arch similar to a Gardner tong or Mayfield clamp [13–15]. This better allows a continuous and self-correcting force on the skull pins, obviates the need for frontal pins and easily aligns with gravity. However, for out of the hospital and long term use at least two pins per side would be desirable, preferably independent of each other. Therefore, in addition to the placement of pins in the generally accepted mastoid area, pins should also be positioned in the temporal region. Theoretically, this area is less optimal because of the thinner bone and the presence of the temporal muscle [3, 16]. After evaluation of the anatomy and discussions with maxillofacial surgeons, we argued that the area where the muscle is relatively thin would not be as painful as suggested [16]. Concerning the bone quality, it is currently unknown if a proper pin fixation for traction is possible in this area. Factors that influence this are the force that can be applied and resistance to migration.

To determine feasibility in the temporal area, some requirements have to be fulfilled. First, the cranium should allow at least 2 mm of pin penetration [11]. Second, the bone should withstand a compressive force that allows secure fixation without migration. In adults, this is achieved with a torque of 0.7–0.9 Nm (6–8 in-lb) [11, 17]. For children, this may be lower as in general a torque of 0.3–0.5 Nm (3–4 in-lb) is recommended since they have thinner and softer bone [18].

The current study aims to determine whether the temporal region is feasible for pin position in an optimized HGT crown design. We determined the most optimal anatomical position in the temporal region, the relationship between the axial pin force and resistance to migration and the axial load to failure in that area.

Materials and methods

Study design

Three human cadaver skulls were used for the experiments. To investigate resistance to migration, a spring-loaded pin was designed to allow controlled axial loading, and a special setup was implemented that allows accurate measurement of traction force on this pin. This pin was positioned with representative axial loads and pulled cranially until migration. Subsequently, the spring-loaded pin was loaded until failure of the bone.

Specimens

Fresh frozen skulls of two women (76 and 93-years old) and one man (81) who died of natural causes were selected for the experiments after CT confirmation of normal condition. We determined the position and thickness of the temporal muscle, before all soft tissues were removed to observe any migration.

Halo crown

A conventional halo crown (Bremer Medical Co., Jacksonville, US) with standard titanium conical pins was used. This crown is made of an aluminum alloy and has a posterior open double C-shaped design with the two C-structures in the transverse and frontal plane.

Spring-loaded pin

A complicating factor in interpreting the literature on pin forces is that it is unclear what force is actually transmitted to the skull, since torque cannot be easily converted to force. Research from Whitesides et al. showed this depends on the shape and material of the halo crown and on whether the pin is lubricated or not. They determined that in general, a torque of 0.5 Nm (4 in-lb) can be converted to about 350 N axial force [19] (Fig. 1). To better control this force an adjustable spring-loaded pin was used (Fig. 2). The pin tip was designed to resemble the pin that we use clinically (Bremer Halo Skull Pin) with a tip length of 3 mm, which is comparable to most commercially available pins [20]. The spring-loaded pin was threaded on the outside to enable insertion into the halo crown. After the pin tip touched the skull and the spring-loaded pin was screwed in further, the

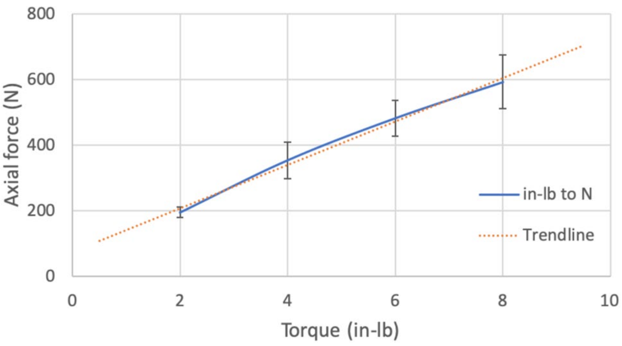

Fig. 1 Axial pin force (N) plotted against torque (in-lb) according to data from Whitesides (blue) [14] and an extrapolated trendline (dotted orange)

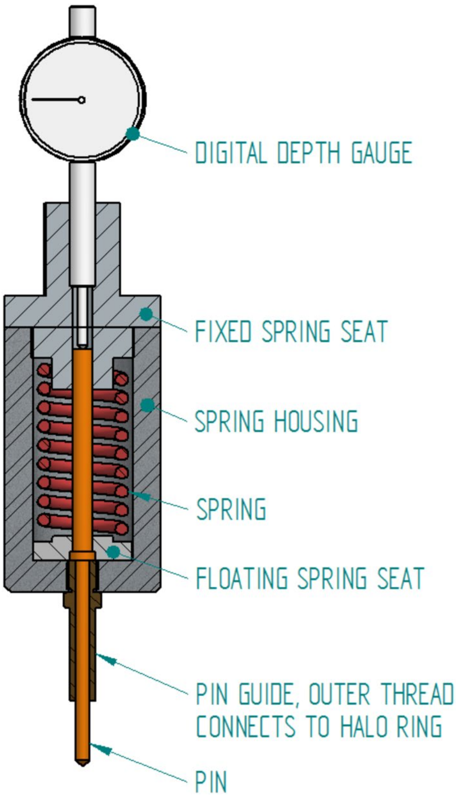

Fig. 2 Customized spring-loaded pin

spring was compressed. As the pin was connected to the spring by means of a spring seat, the spring force equals the force of the pin to the skull. With compression of the spring, the distal end of the pin was pushed outwards against a digital depth gauge. According to Hooke's law: $F = kX$, the axial spring load can be calculated with the known spring constant (k) and the compression depth (X). For sufficient accuracy, a selection of two springs was made: one light version for the migration tests with a spring constant of 25.2 N/mm and a heavy version with a spring constant of 74.0 N/mm for the failure tests. The linearity between the spring load and compression of the spring-loaded pin was verified with a calibrated force tester.

Traction setup

A traction setup was developed that allows exact determination of the traction force on the instrumented pin. In experimental research reported in literature, Halo gravity traction is applied using a standard protocol, using four pins to connect the halo or traction device to the skull. The traction force is assumed to be equally divided over the pins. However, if more than three pins are used this is not a valid assumption. Also, migration of one pin is dependent on migration of other pins [10]. In order to avoid this, we used three pins in the halo crown. On one side of the skull we position the spring-loaded pin while the other two are positioned on the contralateral side of the skull, acting as pivot point, see Fig. 3. Rather than loading the halo, traction load is directly applied to the spring-loaded pin. A pulley system and weights are used to apply the traction force, making the use of a force transducer superfluous.

Migration experiment

After exposure of the temporal area, the skull was fixated to a workbench and the halo-crown was fixated as indicated above (Fig. 3). In each of the 10 predefined anatomical areas in the temporal region below the equator, three migration experiments were carried out: one with axial loading of 100 N, one with 150 N and one with 200 N, reflecting a torque of 0.06, 0.1 and 0.2 Nm (0.5, 1.2 and 1.9 in-lb) respectively, based on the extrapolated data from Whitesides [19] (Fig. 1). For each skull, both temporal regions

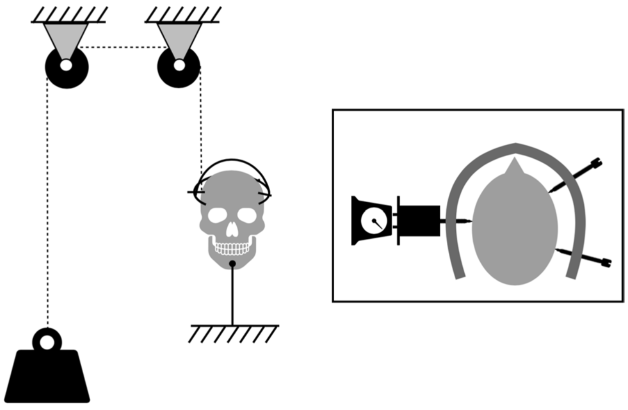

Fig. 3 Setup of the pin migration experiment. Traction on the spring-loaded pin is applied as near to the skull possible. The traction weight was transferred to the pin by means of a cord and two fixated pulleys

were used, leading to a total of 60 migration measurements. Each time after having loaded the pin, the traction force was increased by increments of 0.5 kg per 10 s until the pin migrated. The maximum traction force was limited to 36 kg (± 360 N) for reasons of safety and availability. In between the experiments, the tip of the pin was visually inspected for consistent sharpness and straightness.

Load-to-failure experiment

For the load-to-failure experiment, the halo crown was positioned similar to the migration experiment; however, a metal plate was placed between the two conventional pins and the skull to distribute the pin force over a larger area. Then the spring-loaded pin was placed in the region that we selected as most appropriate (between positions 7 and 8, see Fig. 4) and loaded at a rate of 20 newtons per 30 s until failure of the skull bone. Failure was defined as complete relaxation of the spring in the spring-loaded pin due to loss of resistance. Only one failure per side of the skull was investigated.

Radiographic measurements

Standard 1 mm slice CT scans of the cadaver skulls were made before and after the experiment to determine bone quality and thickness of the skull. After the failure experiment the breakthrough points were examined for fracture pattern and the relation to local thickness of the skull.

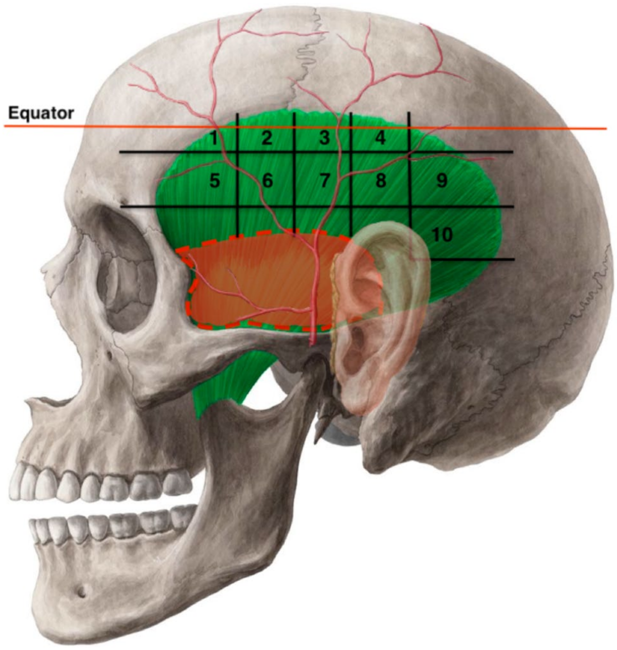

Fig. 4 Ten predefined anatomical positions in the temporal area below the equator. The red sinewy area should be avoided to prevent discomfort and pain, the green area defines the relatively thin part of the temporal muscle. We identified the area between 7 and 8 as most optimal

Statistical analysis

Descriptive statistics were used. The inter-quartile range (IQR) was used to identify and correct for outliers. Thereafter, all measurements per individual skull for a certain axial force were averaged to provide a robust measurement of that sample. The inter-individual average and SD are given for each axial force in Table 1. To determine the effect of increasing axial force, a paired 2-tailed *t*-test was performed with SPSS (IBM SPSS Statistics for Macintosh, Version Statistics Standard 22. Armonk, NY: IBM Corp.).

Results

Based on the anatomy of the skulls and thickness of the temporal muscle, we determined the area 7–8 to be most optimal for pin positioning. This area is 2–3 cm cranial and just anterior to the meatus, below the equator, in the thin part of the temporal muscle (see Fig. 4). The CT scans of the selected skulls showed no pathologies, and the inner to outer distance varied from 4.2 to 6.9 mm at the selected location, which appeared to be relatively thick for the temporal area according to our observations.

Resistance to migration

We observed a clear relationship between axial force and resistance to migration. Loaded with only 100 N, on average 19 kg traction (95% confidence intervals) was needed to cause migration whereas with an axial tightening force of 150 N this was substantially higher, 28 kg ($p < 0.001$). With 200 N axial force, only one pin migrated below the maximum vertical traction of 360 N, therefore the average could not be determined. The relation is visualized in the plot (Fig. 5).

Table 1 Vertical force (kg) at which pin migration occurred with respect to axial tightening force of the pin (N)

Axial force	100 N	150 N	200 N[b]
Skull 1 (kg)	19.3	28.3	36.0
Skull 2 (kg)	17.8	26.9	> 36.0
Skull 3 (kg)	20.0	28.4	> 36.0
Mean	19.0 ± 1.2[a]	27.9 ± 0.8[a]	> 36.0

[a] Paired t-test showed a significant difference between 100 and 150 N ($p < 0.001$)

[b] Only one of the 60 pins migrated, the others resisted the maximum of 36 kg, therefore no statistics were done

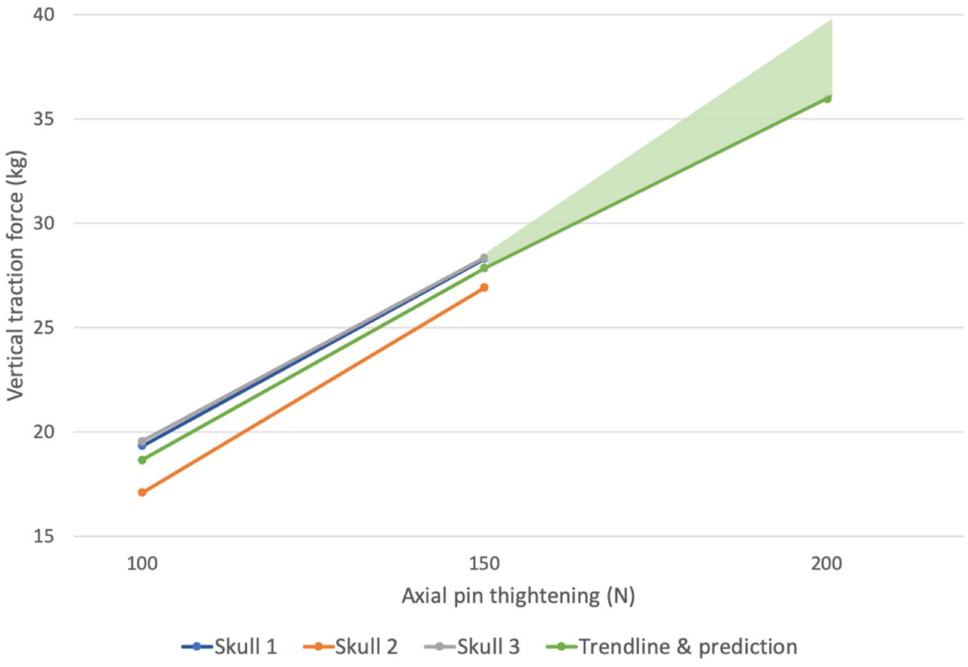

Fig. 5 Axial tightening force versus vertical traction to cause migration. At 200 N axial tightening, only one of the pins migrated at the maximum traction weight of 36 kg, the green area reflects the uncertainty

Load-to-failure

All skulls withstood 780 N (range 780–1270 N) which is far more than the generally applied 350 N. The failure mode was typically perforation of the outer table and fracture of the inner table. Obviously, there were differences in failure load but there was no clear relation between that load and thickness (Table 2 and Fig. 6).

Discussion

In this study, we investigated the feasibility of halo crown pin positioning in the temporal region of the skull. We believe this position has important advantages for halo gravity traction like avoidance of visual scars and a biomechanically more ideal position to maintain continuous opposed loads on the pins. However, there are issues that need attention before this location can be used. First, the temporal bone is relatively thin and may not be able to bear sufficient axial pin loads, which could result in fracture and epidural hematoma. Second, inserting pins through the temporal muscle, which covers this area, may result in painful mastication and finally, the temporal artery should not be damaged. Based on the minimal thickness of the temporal muscle, the distance to the temporal artery and ease of positioning, we selected an area anterocranial of the auricle which would be most appropriate. To address the most important concern of sufficient fixation, we tested the limits of this fixation on cadaver skulls in the whole temporal area. We used a similar approach as Karnes et al. [10] and found a similar linear relationship between tightening force and resistance to migration. In our experiments, the selected temporal skull area could be loaded well above what is needed for safe traction. In fact, considerably lower axial forces than currently used for children (350 N obtained with a torque of 0.5 Nm = 4 in-lb) appeared to be sufficient for halo gravity purposes, with the remark that the experimental pin did not experience any resistance to torque by the soft tissues. One of

Table 2 Failure load versus skull bone thickness

	Skull #1 Female 76 year		Skull #2 Male 81 year		Skull #3 Female 93 year	
	Left	Right	Left	Right	Left	Right
Force (N)	784.6	1038.4	1153.8	915.3	1269.2	1315.3
Mean	911.5		1034.6		1292.3	
Bone thickness (mm)	4.2	5.4	6.9	5.0	5.1	4.9
Mean	4.8		6.0		5.0	

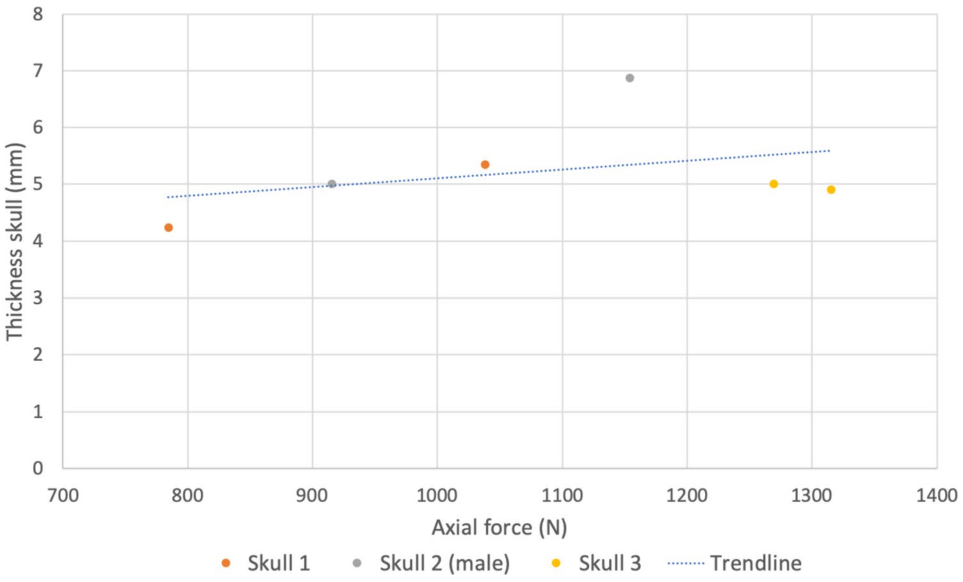

Fig. 6 Load-to-failure in relation to skull thickness. The R^2 and slope of the trendline are respectively 0.01 and 0.002 which indicates little or no relation between the thickness of the skull and maximal load capacity in this experiment

the explanations for this is that any pin below the equator of the skull will initially be forced deeper with cranial traction. Obviously, this only holds true for well-opposed pins in a rigid construct. Another comforting finding was that the forces that were needed to break through the temporal bone area in the geriatric skulls were well above the currently used force of 350 N. We realize that the findings of geriatric skulls may not be representative for the halo gravity population. Unfortunately, we did not find studies which relate geriatric to juvenile or pediatric skull bone quality. In an attempt to translate findings, the difference in skull thickness may be considered. Loder et al. investigated skull thickness in CT scans of children (1–16 year) and found an increase with age from about 3 mm < 1 year to 5 mm above 10 years [21]. The relevance of this is difficult to interpret because the cortical quality is likely more important than its thickness. In the current study, there was no obvious relation between local skull thickness and failure load. Comparable studies that investigated adult skulls found very high axial loads are needed to penetrate the skull. For the generally thicker frontal skull bone (7.4 mm), Ebraheim et al. [22] reported a torque of 1.4–2.0 Nm (12–18 in-lb) which corresponds to an axial load of > 1000 N when we translate the data of Whitesides et al. [19] (Fig. 1). Even if there would be a linear relation between skull thickness and strength, a 3.2 mm pediatric skull should be able to resist 500 N axial force which corresponds to a torque of about 0.7 Nm (6 in-lb). A more practical approach to determine the safety of this axial load in the same temporal area in children is to consider currently used forces with the Mayfield clamp (Integra life sciences France) that is positioned similarly [15]. The adjustable pin is typically loaded to max 260 N (60 lbs) in children, although a special pediatric version is available with a maximal axial load of about 80 N (18 lbs) [23].

Several shortcomings should be considered. First, the skulls were geriatric and therefore only give a general indication as discussed above. Second, we only investigated the initial fixation strength and did not consider a time effect. Due to creep and plastic deformation, it can be expected that the tightening force will decrease in time. This effect is applicable to all halo fixations and a reason to regularly check the torque of the pins. It should be recognized that we addressed the fixation strength of one pin specifically and not of the entire construct. This improved our understanding of the force–effect relations, but limits extrapolation to the clinical situation and comparison to currently used devices. Obviously, the resistance to migration decreases together with the number of pins. Especially in children with compromised bone quality like osteogenesis imperfecta, that can be a reason to use more than four pins.

In conclusion, we identified a pin position in the temporal bone, just antero-cranial to the earcup, which is through the thin part of the temporal muscle, allows avoidance of the temporal artery and in a relatively thick bone area. The resistance to migration with conventional torque of 0.5 Nm (4 in-lb) or below was more than enough for halo traction purposes and the axial force with this torque was far below the failure load. For that reason, we now use this area for selected patients with a torque of 0.3 Nm (3 in-lb).

Author contributions KS, EEGH, AS, MCK: substantial contribution to conception and design of the study, analysis and interpretation of the results. Also contributed to a critical review for the realization of the final result. These authors agreed with the publishing version and accept responsibility for the accuracy or integrity of the study. MG,

JB: substantial contribution to conception and design of study, experimental set-up, and creation of required materials. Also contributed to a critical review for the realization of the final result. Both authors agreed with the publishing version and accept responsibility for the accuracy or integrity of the study.

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Compliance with ethical standards

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

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