Anterior support reduces the stresses on the posterior instrumentation after pedicle subtraction osteotomy: a finite-element study

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Abstract

Study design The investigation was based on finite-ele-ment simulations.

Objective Pedicle subtraction osteotomy (PSO) is an effective but technical demanding surgical technique, associated with a high risk of rod failure. The present study aims at investigating the role of the anterior support in combination with PSO, with a numerical comparative analysis.

Methods An osteotomy was simulated at the L3 level of a lumbosacral spine. An implantation of various combina-tions of devices for the anterior (1 or 2 cages of different material) and posterior stabilization (1 or 2 rods) was then performed. ROM, loads, and stresses acting on the rods were calculated.

Results A 4–8% reduction of the ROM was obtained introducing one or two cages in the instrumented model. However, the anterior support had only a minor influence on the ROM. The load on the posterior instrumentation decreased up to 8% using one cage and about 15% with two anterior devices. A 20–30% reduction of the stresses on the rods was calculated inserting one cage and up to 50% using two cages. Following the introduction of the anterior support, the greatest stress reduction was observed in the model having two cages and spinal fixators with two rods.

Conclusions The use of cages is crucial to ensure anterior support and decrease loads and stresses on the posterior instrumentation.

Keywords Pedicle subtraction osteotomy, Lumbar spine, Osteotomy, Finite elements, Cages, Rods, Spinal fixators

Introduction

Pedicle subtraction osteotomy (PSO) in the last 30 years has become an effective technique for the treatment of fixed sagittal imbalance. It consists in the resection of a wedge of vertebral body and posterior elements, ensuring a correction up to 30-35 [1–3]. The surgery is ideally performed between L2 and L4 to achieve the maximum correction at the apex of the deformity [1]. Despite the improvements achieved in terms of both surgical technique and instrumentation, it remains a very complex procedure associated with a high risk of complications, often involving the mechanical failure of the rods [2–4]. Although a few indications about the best configuration of devices to be used to prevent hardware failure are available yet [1, 2, 5], this technique is widely used nowadays.

Enercan et al. [3] suggested the use of interbody cages above and below the osteotomy to prevent the risk of pseudoarthrosis and hardware failure. Only one biomechanical study analyzed the role of the cages following PSO [6], by performing biomechanical tests on human specimens. The authors investigated the stiffness and the fatigue behavior of the spine with and without an anterior support above and below the osteotomy. Results showed

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that interbody fixation with cages had the potential to improve the spine stability; however, no data about the stresses in the posterior rods and possible consequent effects of the cages on the risk of hardware failure have been provided.

The aim of this paper was to study the effect of the anterior support following PSO, by means of a numerical comparative analysis. Several configurations of interbody stabilization by means of cages were analyzed to identify the solution that, from a biomechanical point of view, may reduce the risk of failure of the posterior instrumentation.

Materials and methods

This study was performed using a calibrated nonlinear finite-element model of the human lumbosacral spine (L1–S1). The PSO was then simulated on L3 obtaining an improvement of the lordosis of about 30°, following the removal of a wedge of vertebral body. Details about the intact model as well as the simulation of the osteotomy technique are reported in literature [7].

The model was then stabilized using polyaxial screws and rods: the description of the discretization and the mesh sensitivity are described in a previous paper [8]. Moreover, intersomatic cages were inserted in the model, to ensure an anterior support: two devices commonly used in the clinical practice, transforaminal lumbar interbody fusion (TLIF), and extreme lateral interbody fusion (XLIF) cages were modeled (Fig. 1a), under the supervision of an experienced surgeon and preserving part of the intervertebral disc according to the surgical technique. In the models with the TLIF cage, one side of the annulus fibrosus was conserved (contralateral with respect to the insertion point of the cage), whereas in the XLIF models, the disc was removed only in the central part preserving as much as possible the anterior and posterior areas. The mesh was created using the same element seeding (0.8 mm) previously described for rods and screws. The total number of elements of the models was around 292,200 with small differences between the models depending on the number of rods and cages.

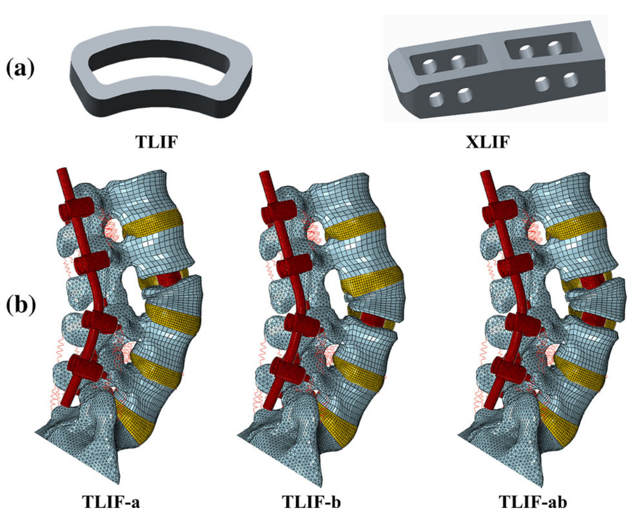

Fig. 1 In the *upper part* (**a**), the geometry of the TLIF and XLIF intersomatic cages is shown. In the *lower part* (**b**), the instrumented models having an anterior support above the osteotomy level ("TLIF-a", *left*), below ("TLIF-b", *middle*), and above and below ("TLIF-ab", *right*) are shown

Several configurations of spinal fixators and cages (Table 1) were studied, to investigate:

- effect of anterior support: models with cages compared with a model having posterior fixation (TLIF-Peek vs. OL3-Ti);
- effect of cage position: cage above, below, and both above and below the osteotomy, as shown in Fig. 1b (TLIF-Peek-a vs. TLIF-Peek-b vs. TLIF-Peek-ab);
- effect of material: peek or titanium alloy cages (TLIF-Ti vs. TLIF-Peek);
- effect of two rods: models with one or two rods at the osteotomy level (TLIF-2rods-Peek vs. TLIF-Peek);
- effect of design: TLIF and XLIF (TLIF-Ti vs. XLIF-Ti).

A standard loading condition was considered to simulate the standing: 500 N of follower load in combination with pure moments of ±7.5 Nm in flexion–extension, lateral bending, and axial rotation applied to the cranial endplate of L1. Moreover, the sacrum was fully constrained. The results were evaluated in terms of range of motion (ROM) of the whole lumbar tract, in flexion–extension, lateral bending, and axial rotation. In addition, the load acting on the instrumentation (as well as the load on the anterior part of the spine) and the maximum von Mises tensile stresses at the osteotomy site were calculated.

Results

The ROM of L1–S1 was similar for all the models created (Fig. 2). The reduction of the ROM due to the insertion of one cage is about 4%, and using two cages, the difference is up to 8%. Comparing only the models with the anterior support (all the models except OL3-Ti), the variations are always less than 4%.

The use of one cage, in comparison with the OL3-Ti model, led to a 3–8% decrease of the load insisting on the rods, whereas employing two cages an even higher reduction (about 15–17%) was found (Table 2). No significant differences could be appreciated using only one cage either above or below; nevertheless, an 8–12% variation with respect to the single rod configurations was calculated using two rods as a posterior fixation.

Table 1 Schematic description of all the models created within the finite-element study

Posterior fixation	Anterior support	Cage material	Cage position	Model
1 rod	NO	–	–	OL3-Ti
1 rod	TLIF	PEEK	Above osteotomy	TLIF-Peek-a
			Below osteotomy	TLIF-Peek-b
			Above/below osteotomy	TLIF-Peek-ab
1 rod	TLIF	Titanium alloy	Above osteotomy	TLIF-Ti-a
			Below osteotomy	TLIF-Ti-b
			Above/below osteotomy	TLIF-Ti-ab
2 rods	TLIF	PEEK	Above osteotomy	TLIF-Peek-a-2rods
			Below osteotomy	TLIF-Peek-b-2rods
			Above/below osteotomy	TLIF-Peek-ab-2rods
1 rod	XLIF	Titanium alloy	Above osteotomy	XLIF-Ti-a
			Below osteotomy	XLIF-Ti-b
			Above/below osteotomy	XLIF-Ti-ab

The number of rods of the instrumentation, the type, material, and position of the anterior support are highlighted

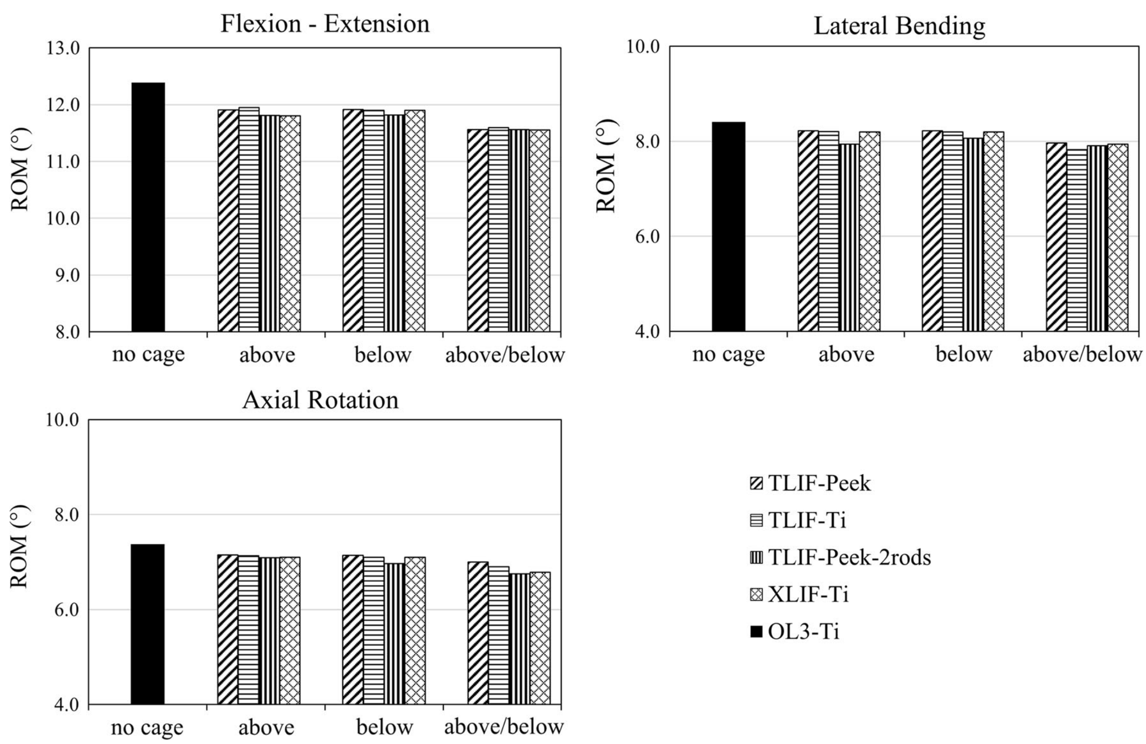

Fig. 2 Global ROM (L1–S1) of the instrumented model without cages (*no cage*) compared with the models having an anterior support above (*above*), below (*below*), and both above and below (*above/below*) the osteotomy level

A marked reduction of the maximum von Mises tensile stress in the posterior rods was calculated for all the movements following the insertion of an anterior support (Tables 3, 4): about 20–30% with respect to posterior fixation only with the use of one cage and between 42 and 51% using two cages. Therefore, using two cages instead of one had a significant effect in reducing the stresses in the instrumentation. In contrast, no relevant differences were found when comparing stresses predicted in the rod, if either a single cranial or a caudal interbody fixation was performed (Fig. 3). The use of a Titanium cage (instead of a PEEK one), as well as of a larger cage (XLIF rather than TLIF), induced a slight reduction of the stresses on the rods (Tables 3, 4). As expected, the biggest stress reduction on the principal rod can be noted using two bilateral rods.

Table 2 Compressive force acting along the fractured surfaces (F anterior) and on the rods at the osteotomy level (F rods), calculated after the imposition of the follower load

Model	F anterior (N)	F rods (N)	Load anterior (%)	Load rods (%)
OL3-Ti	312	188	62	38
TLIF-Peek-a	349	151	70	30
TLIF-Peek-b	343	157	69	31
TLIF-Peek-ab	384	116	77	23
TLIF-Ti-a	349	151	70	30
TLIF-Ti-b	349	152	70	30
TLIF-Ti-ab	389	111	78	22
TLIF-Peek-a-2rods	298	202	60	40
TLIF-Peek-b-2rods	291	209	58	42
TLIF-Peek-ab-2rods	352	147	70	30
XLIF-Ti-a	335	165	67	33
XLIF-Ti-b	326	174	65	35
XLIF-Ti-ab	396	112	79	21

The percentage variation of the force with respect to the follower load is also reported

a above the osteotomy level, *b* below, *ab* above and below the osteotomy level

Table 3 Maximum von Mises tensile stress, expressed in MPa, calculated in the rods at the osteotomy level

	Flexion (MPa)	Extension (MPa)	L. bending (MPa)	R. bending (MPa)	L. rotation (MPa)	R. rotation (MPa)
OL3-Ti	178.5 (13.2)	84.1 (4.3)	133.1 (5.5)	153.1 (8.5)	154.9 (2.3)	123.9 (15.1)
TLIF-Peek-a	136.0 (11.8)	53.5 (3.9)	93.1 (10.1)	118.4 (7.4)	122.9 (4.8)	90.6 (10.8)
TLIF-Peek-b	136.0 (12.0)	61.3 (8.5)	94.7 (9.8)	120.1 (8.6)	123.8 (5.1)	89.9 (14.6)
TLIF-Peek-ab	86.7 (12.9)	41.1 (7.8)	62.6 (9.1)	88.7 (6.6)	79.9 (15.4)	62.6 (9.1)
TLIF-Ti-a	133.8 (13.9)	53.7 (8.9)	87.8 (10.7)	119.1 (6.4)	118.2 (4.4)	90.7 (11.6)
TLIF-Ti-b	133.7 (12.1)	54.1 (8.5)	89.3 (11.2)	120.5 (7.5)	119.2 (4.5)	90.9 (10.8)
TLIF-Ti-ab	76.5 (11.4)	34.4 (6.5)	56.1 (5.2)	78.0 (7.2)	80.2 (5.1)	57.5 (6.6)
TLIF-Peek-a-2rods						
Rod 1	63.2 (1.9)	47.8 (20.3)	51.1 (3.3)	58.9 (1.8)	47.8 (19.2)	44.7 (3.2)
Rod 2	86.8 (9.8)	46.8 (8.9)	61.7 (16.9)	63.1 (11.2)	70.4(6.0)	59.7 (10.6)
TLIF-Peek-b-2rods						
Rod 1	70.5 (0.9)	38.2 (5.6)	59.0 (14.1)	65.0 (3.3)	50.9 (25.2)	50.3 (0.6)
Rod 2	84.5 (9.6)	49.0 (6.4)	61.3 (19.3)	66.3 (7.0)	70.0 (6.1)	59.7 (10.4)
TLIF-Peek-ab-2rods						
Rod 1	38.5 (1.8)	25.3 (5.3)	42.0 (5.3)	46.3 (3.6)	38.0 (8.2)	36.0 (2.0)
Rod 2	56.3 (9.0)	36.1 (7.0)	40.9 (19.9)	46.8 (6.8)	49.2 (7.3)	38.7 (10.6)
XLIF-Ti-a	132.2 (13.7)	51.7 (9.3)	85.8 (10.6)	117.0 (8.7)	116.2 (4.3)	87.9 (13.2)
XLIF-Ti-b	140.4 (11.7)	57.3 (9.1)	86.8 (9.5)	127.3 (8.4)	117.5 (1.8)	98.8 (14.1)
XLIF-Ti-ab	70.5 (12.0)	33.7 (5.3)	50.8 (6.7)	76.0 (7.7)	76.4 (3.2)	56.6 (6.6)

The average value between left and right side is listed below. The range between the maximum and minimum value is reported in brackets. For two rods configurations, Rod 1 is the principal rod while Rod 2 indicates the secondary rod

a above the osteotomy level, *b* below, *ab* above and below the osteotomy level

Discussion

The goal of this paper was to perform a comprehensive numerical analysis of the devices that can be used to support the spine following PSO, with a particular focus on those that ensure an anterior support. To the author's knowledge, only one experimental study was focused on the use of cages following PSO (performed at the L3 level) [6]. Moreover, one paper described a computational study about PSO where a TLIF cage was employed [9]. However, the simulated scenarios concerning both the destabilization and the spinal instrumentation are different from the goal of the present study, and no specific result about the cages was provided. Thus, in the literature, most of the

Table 4 Maximum percentage variation of the von Mises stresses in the rods at the osteotomy level

	Flex (%)	Ext (%)	L bend (%)	R bend (%)	L rot (%)	R rot (%)
Effect of anterior support						
TLIF-Peek-a vs. OL3-Ti	−24	−36	−30	−23	−21	−27
TLIF-Peek-b vs. OL3-Ti	−24	−27	−29	−22	−20	−27
TLIF-Peek-ab vs. OL3-Ti	−51	−51	−53	−42	−43	−50
Effect of position						
TLIF-Peek-b vs. TLIF-Peek-a	0	15	2	1	1	−1
TLIF-Peek-ab vs. TLIF-Peek-a	−36	−23	−33	−25	−28	−31
TLIF-Peek-ab vs. TLIF-Peek-b	−36	−33	−34	−26	−28	−30
Effect of material						
TLIF-Ti-a vs. TLIF-Peek-a	−2	0	−6	1	−4	0
TLIF-Ti-b vs. TLIF-Peek-b	−2	−12	−6	0	−4	1
TLIF-Ti-ab vs. TLIF-Peek-ab	−12	−16	−10	−12	−10	−8
Effect of 2 rods						
TLIF-Peek-a-2rods vs. TLIF-Peek-a	−54	−11	−45	−50	−61	−51
TLIF-Peek-b-2rods vs. TLIF-Peek-b	−48	−38	−38	−46	−59	−44
TLIF-Peek-ab-2rods vs. TLIF-Peek-ab	−56	−38	−33	−48	−57	−42
Effect of design						
XLIF-Ti-a vs. TLIF-Ti-a	−1	−4	−2	−5	−2	−6
XLIF-Ti-b vs. TLIF-Ti-b	5	6	−3	6	−1	9
XLIF-Ti-ab vs. TLIF-Ti-ab	−8	−2	−9	−3	−5	−1

In the two rods models, the evaluation was performed on the principal rod
a above the osteotomy level, *b* below, *ab* above and below the osteotomy level

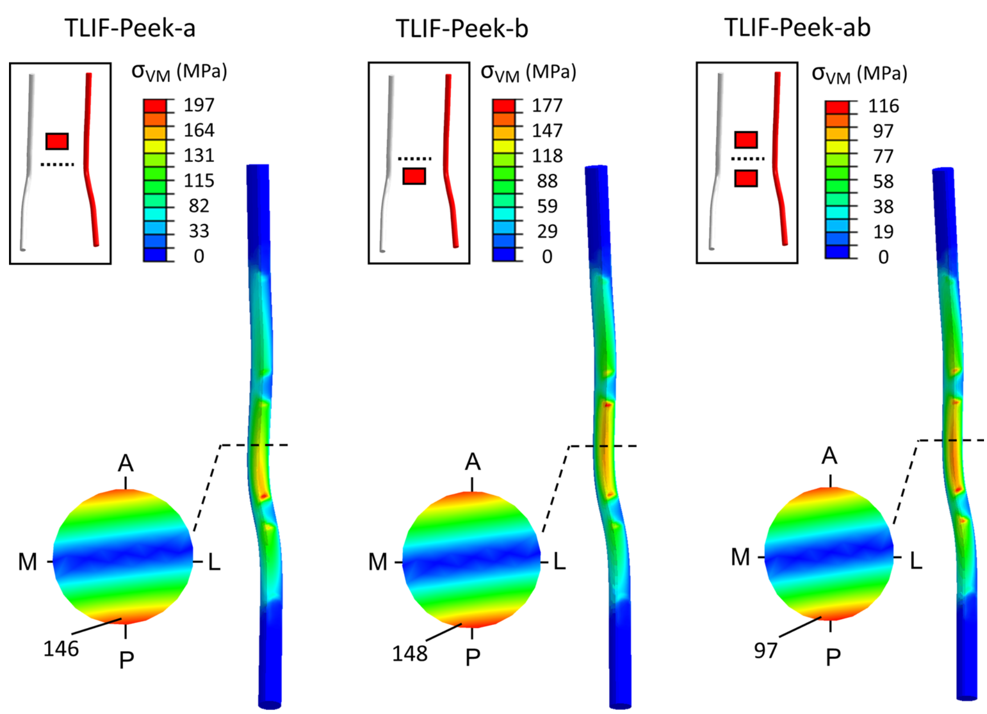

Fig. 3 Comparison of the distribution of the con Mises stresses in the right rod (*A* anterior, *P* posterior, *M* medial, *L* lateral) for different configurations of interbody fixations (TLIF cage in PEEK implanted only above, below, and both above and below the osteotomy level)

information can be found in reviews of clinical cases where only the description of the surgical technique or clinical recommendations based on surgeon's experience are presented [1–3, 5]. To quantify this clinical perception, several configurations of devices were simulated, investigating the comparison between cages having different positions, materials, and geometries. As expected, only minor variations among the global ROMs could be appreciated. This is probably due to the presence of the posterior fixators, which stabilize the spine effectively, independently on the presence of further devices in the anterior spine. In terms of ROM, a negligible difference can, therefore, be noted using one or two cages. In addition, in the biomechanical study found in literature [6], the variations of the ROM in similar conditions were not significant. However, the absolute values of the ROM calculated in the literature study could not be directly compared with our work, because the instrumented levels were different (they included also S1) and also the material of the rods was not the same (chromium–cobalt instead of titanium alloy).

In the present study, we calculated either loads acting on the anterior and posterior columns and the stresses on the rods. A balance of these parameters is fundamental to ensure a reliable fixation able to support a highly destabilized spine but, at the same time, to promote the bone healing stimulating adequately the fractured vertebra.

The evaluation of the forces acting in fractured bone surface versus the posterior instrumentation highlighted some differences among the various configurations. The most important finding was that the use of at least one cage increases the global stiffness of the spine, modifying the load path toward a higher load supported by the anterior spine. In addition, when using only one cage, its position did not affect the load distribution. However, using two cages further increased the force acting on the anterior surface thus unloading the rods. Using the double bilateral rods configuration, the increased stiffness of the instrumentation changed the load distribution and decreased the force acting in the anterior column. Interestingly, using cages having the same design but different materials did not significantly affect the load sharing between the anterior and the posterior structures. On the other hand, a different geometry slightly modifies the load transfer (2–3%).

The analysis of the stresses revealed again that the use of an anterior support preserves the rods, in agreement with the previous clinical studies suggesting the use of cages to reduce the risk of the need of a revision surgery [1, 2, 5, 6]. When two cages were inserted, half of the rod stress at the osteotomy level was calculated with respect to posterior fixation alone. Again, the position of the cage above or below the osteotomy was not important when only one device is used. In particular, considering the fixation with a TLIF cage, only a 1–2% variation in the rod stress was noted for all the movements (except extension where the difference was about 15%). The XLIF cage exhibited higher differences with a 9–12% stress variation in extension, right bending, and right rotation, while in flexion, left bending and left rotation less than 6% of variation were predicted. Using a cage of titanium alloy instead of PEEK, the stress on the rods slightly decreased (about 8–16% with two cages but less significant with only one cage). This is probably explained by the increased stiffness of the anterior spine, even if only a marginal difference was noted in the load distribution in the anterior/posterior column. Finally, comparing a TLIF cage with an XLIF, the stress variation was less than 10%, when using two cages, and even lower when a single cage was implanted.

As usual, some limitations affect this study: the interaction between the various components of the posterior fixation was simplified, using embedded elements and tie constraints. Moreover, the shape of the rods was created following the curvature of the spine but without considering the stresses induced by the French Bender in the clinical practice. This led to calculate maximum stresses far from the critical threshold of the materials, impeding considerations on the absolute values obtained. However, this analysis was very powerful in comparing different configurations of devices and highlighting the most prone to overload.

The addition of at least one cage is fundamental to increase the stiffness of the anterior spine, favorably changing the load distribution and consequently decreasing the stress on the instrumentation and possibly facilitating bone healing and fusion. Nevertheless, the identification of the best solution for a specific clinical case remains challenging, due to the mechanical and biological complexity of the problem. However, the models with single rods and two cages proved to be effective in reducing the load insisting on the rods. Therefore, even taking into account that the outcome of a PSO surgery is dependent on several biological and clinical factors that cannot be simulated with a numerical model, the hypothesis that the use of an anterior support may prevent the rod overload seems to be confirmed by the present numerical models.

Compliance with ethical standards

Conflict of interest The authors declare that they have any potential conflicts of interest.

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