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ORIGINAL ARTICLE

Optimal medial transforaminal lumbar interbody fusion approach with five extensive options: A simulated study on three-dimensional digital reconstructed images

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Abstract *Objective:* The objective of this study is to use 3D digital lumbar models to investigate and simulate the optimal posterior operative approach for safe decompression and insertion of an interbody cage.
Methods: Thirty lumbar spine (L3-S1) computed tomography data are collected for 3D reconstruction. We cut medial half part of the superior facet and define the distance between the margin of the operative side of the spinous process and the medial margin of the cut superior facet as "medial distance (MD)". Then, we cut the total superior facet and define the distance between the margin of the operative side of the spinous process and the lateral side of the junction of the pedicle and the vertebral body as "extend distance (ED)". The feasible insertion of the current standard width size (10 mm and 12 mm) interbody cages was assessed by the two aforementioned MD and ED approaches. Besides the ED, we also simulate four other extensive options of lateral upper, lateral lower, vertical upper and lower and transmedian contralateral decompression on 3D digital lumbar model.

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Results: The MD increased from 13.48 ± 1.28 mm at L3/4 to 18.05 ± 1.43 mm at L5/S1, and the ED increased from 16.64 ± 1.34 mm at L3/4 to 21.12 ± 1.62 mm at L5/S1. To insert a 10-mm-wide cage, 16.7% (left) and 13.3% (right) of MD for L3/4 is not enough, 60.0% (left) and 46.7% (right) of MD for L3/4 is subsafe, 13.3% (left) and 16.7% (right) of MD for L4/5 is subsafe and all others are safe. To insert a 12-mm-wide cage, 76.7% (left) and 60.0% (right) of MD for L3/4 is not enough, 20.0% (left) and 30.0% (right) of MD for L3/4 is subsafe, 13.3%% (left) and 16.7% (right) of MD for L4/5 is not enough, 63.3% (left) and 56.7% (right) of MD for L4/5 is subsafe and 6.7% (left) and 10.0% (right) of MD for L5/S1 is subsafe, whereas 33.3%% (left) and 30.0% (right) of ED for L3/4 is subsafe, 3.3% (left) and 3.3% (right) of ED for L4/5 is subsafe and all others are safe. Besides the ED, on 3D models, four other extensive options could be simulated too and may need to be performed for different special individuals.
Conclusion: Our 3D digital image study provides a feasible optimal medial transforaminal lumbar interbody fusion approach with five extensive options on lower lumbar region. It can provide safe lumbar decompression and interbody fusion in most population. In addition, surgeons can choose the different extensive options for special individual conditions.
The translational potential of this article: Transforminal lumbar interbody fusion is very common used for lumbar degenerative diseases. The optimal medial transforminal lumbar interbody fusion with five options provide a safe and precise approach for surgeons in treatment of lumbar degenerative diseases.

Introduction

The spondylolisthesis, disc herniation, spinal stenosis, segmental instability and discogenic low back pain are common lumbar disorders [1—7], mainly occurring in the lower lumbar region (L3-S1). The methods of treatment include nonoperation and operation [8,9]. It was estimated that 46,500 patients had undergone lumbar spine fusion in 1990 in USA [10], and the number was increased to 350,000 in 2000 [11]. Posterior lumbar interbody fusion (PLIF) and transforaminal lumbar interbody fusion (TLIF) are the two main techniques in treatment of the aforementioned lumbar disorders [12—15].

PLIF technique was firstly described by Cloward et al [16] and modified by Lin et al [17]; in the operative procedure of PLIF, the laminotomy was performed, and the facet was preserved. It permits the direct decompression and discectomy; however, the midline approach of interbody bone graft or cage implantation causes retraction of cauda equina and dural sac which will result in the iatrogenic nerve injury. The rate of intraoperative nerve injury ranges from 9.0 to 24.6% [18,19]. To avoid the retraction of cauda equina and dural sac, TLIF technique was developed by Blume and Rojas [20]. It can achieve discectomy, interbody bone graft or cage implantation by unilateral facetectomy through intervertebral foramen [21,22]; it is more towards lateral side and therefore decreases the risk of nerve injury by retraction of cauda equina and dural sac due to PLIF. However, the standard TLIF is too lateral side, which needs more dissection of posterior muscles; moreover, the lateral side has an amount of vein plexus, which will increase the intraoperative blood loss and operative time to stop the bleeding.

Thus, it is important to avoid the disadvantages of both PLIF and TLIF and find the optimal approach to perform the decompression, discectomy and bone graft or cage implantation. The three-dimensional (3D) reconstruction technique can help us to create the 3D digital spine model accurately [23,24] and simulate the operative procedure on it [25,26]. In the present study, 3D digital lumbar models will be created and help us to find the optimal posterior operative approach.

Methods and materials

This study is approved by the Institutional Review Board of the Ninth People's Hospital, Shanghai Jiaotong University School of Medicine, and written informed consent was obtained from all computed tomography (CT) scan participants. The research was performed following the Declaration of Helsinki principles.

The CT scan data (digital imaging and communications in medicine (DICOM) format) of 30 patients with a normal lumbar anatomy (without any spinal abnormality such as fracture, scoliosis or tumour) are collected and randomised. Because the PLIF and TLIF are mainly performed on L3-S1 levels, in the present study, only the levels of L3-S1 are 3D reconstructed for research. All CT scans are performed on a 128-slice CT scanner (Philips Medical Systems, Eindhoven, the Netherlands) with cut thickness of 0.45 mm. The age of the selected patients ranges from 29 to 60 years (average 44.6 years). Then, the CT data are imported into Mimics software (Materialise, Leuven, Belgium) for 3D digital lumbar (L3-S1) model reconstruction [23]. Each of the two adjacent vertebrate (L3-L4, L4-L5 and L5-S1) is regarded as a functional segmental unit and saved for further research.

The aim of the present study is to find the optimal operative approach, avoiding over retraction of cauda equina and dural sac by PLIF and too lateral side dissection

of standard TLIF. Therefore, the spinous process is preserved, and we set the operative side of the spinous process as the margin of the medial side of the operative approach, and the retraction of cauda equina and dural sac is not permitted beyond this margin to make sure the safe intraoperative retraction. The lamina is cut at this margin medially, and the upper cut line can be determined at upper 1/2—1/3 site of lamina; then, the lower lamina with the inferior facet will be removed (Figure 1). The superior facet is still on the lower vertebra now; if the standard TLIF is to be performed, the whole superior facet needs to be removed. In our present study, we do not want to make the approach too lateral side as standard TLIF; thus, we cut medial half part of the superior facet first (Figure 1). If the region is enough, no more lateral part will be cut; otherwise, we will extend the lateral side and cut the total superior facet (Figure 2).

To determine the region size, two parameters are measured (Figure 3): 1) medial distance (MD): the distance between the margin of the operative side of the spinous process and the medial margin of the cut superior facet, which represents the region of our optimally designed approach for decompression, discectomy and bone graft or cage implantation; 2) extend distance (ED): the distance between the margin of the operative side of the spinous process and the lateral side of the junction of the pedicle and the vertebral body, which represents the region for decompression, discectomy and bone graft or cage implantation if we extend laterally to cut the total superior facet.

Currently, the width of the commonly used interbody cage is 10 mm or 12 mm. We define "not enough region" as having less than 1 mm gap at the both medial and lateral sides when implanting the interbody cage, "subsafe region" as having $\geq$1 mm but $<$2 mm gap at both the medial and lateral sides when implanting the interbody cage and "safe region" as having $\geq$2 mm gap at the both medial and lateral sides when implanting the interbody cage. Therefore, for a 10-mm-wide interbody cage, the "not enough region" is the distance less than 12 mm, the "subsafe region" is the distance $\geq$12 mm but $<$14 mm and the "safe region" is the distance $\geq$14 mm, whereas for a 12-mm-wide interbody cage, the "not enough region" is the distance less than 14 mm, the "subsafe region" is the distance $\geq$14 mm but $<$16 mm and the "safe region" is the distance $\geq$16 mm.

Statistical analysis

Statistical analysis is performed using IBM SPSS Statistics (SPSS v22; IBM Corp., Armonk, NY, USA). Comparison of the data between the left and right is carried out by paired *t* test. The level of significance is set at $P < 0.05$. The results are represented as "mean standard deviation".

Results

Both MD and ED are gradually increased from L3/4 to L5/S1. The MD is from 13.48 $\pm$ 1.28 mm to 18.05 $\pm$ 1.43 mm, and the ED is from 16.64 $\pm$ 1.34 mm to 21.12 $\pm$ 1.62 mm. There was no

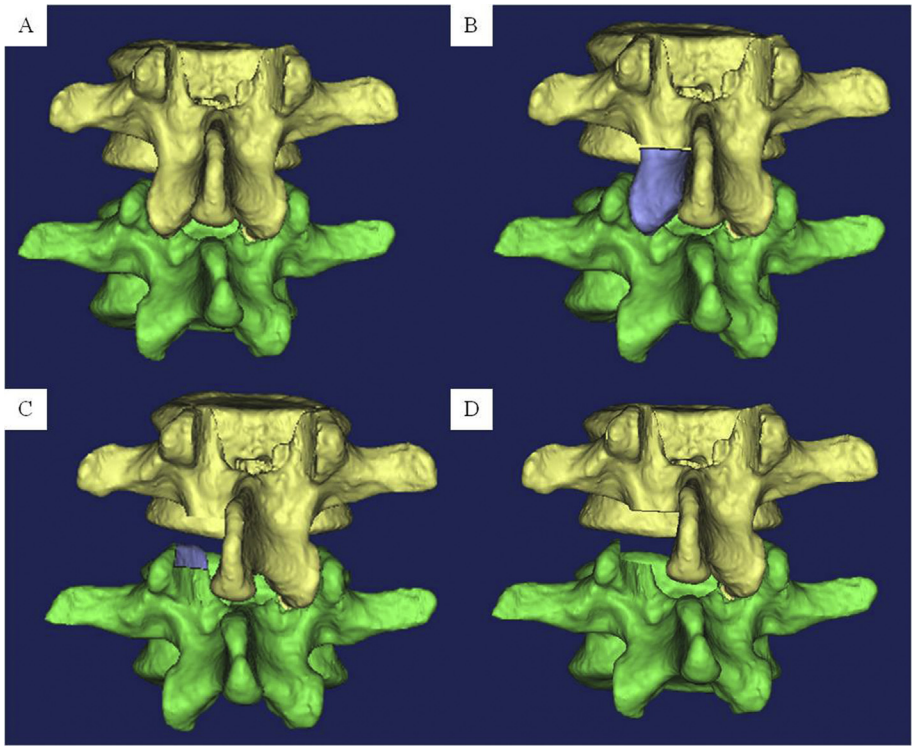

Figure 1 The procedure and region of optimal medial transforaminal lumbar interbody fusion (OM-TLIF) approach. (A) The intact 3D digital model of L3/4; (B) we set the operative side of the spinous process as the margin of the medial side of OM-TLIF, the lamina is cut at this margin medially and the spinous process is preserved; the upper cut line is at upper 1/2—1/3 site of lamina; (C) the medial half part of the superior facet is cut; (D) The region of OM-TLIF approach after removing the lamina, inferior facet and half part of the superior facet.

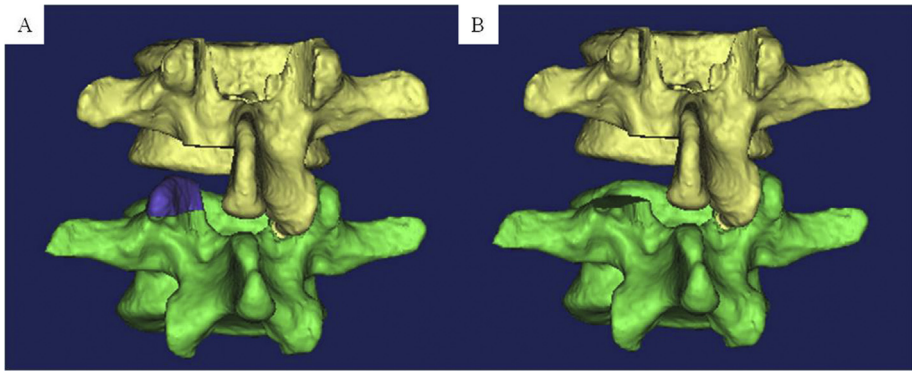

Figure 2 If the region of OM-TLIF is not enough, the total superior facet is cut and extended to more lateral side. (A) The region of cut superior facet; (B) the region after the superior facet is cut and removed.
OM-TLIF = optimal medial transforaminal lumbar interbody fusion.

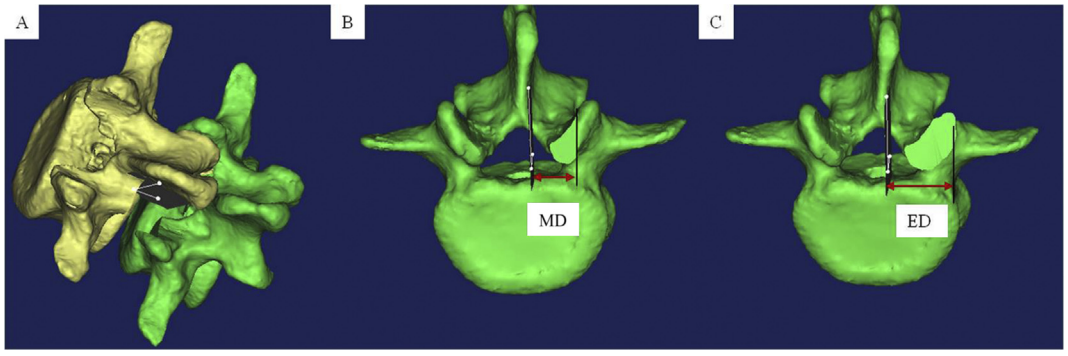

Figure 3 The measurements of medial distance (MD) and extend distance (ED). (A) A block panel set at the operative side of the spinous process, the retraction of cauda equina and dural sac is not permitted beyond this panel to make sure the safe intraoperative retraction; (B) the measurements of MD: the distance between the margin of the operative side of the spinous process and medial margin of the cut superior facet; (C) the measurements of ED: the distance between the margin of the operative side of the spinous process and the lateral side of the junction of the pedicle and the vertebral body.

significant difference between the data of left and right sides. The data of MD and ED are summarised in Table 1.

In the level of L3/4, to implant the 10-mm-wide interbody cage, if we perform our optimal medial transforaminal lumbar interbody fusion (OM-TLIF) approach, it only cuts the medial half part of the superior facet at the lateral side. There are five of 30 (16.7%) cases on the left side and four of 30 (13.3%) cases on the right side regarded as not having enough region, majority of them [18/30 (60.0%) cases on the left side and 14/30 (46.7%) cases on the right side] are regarded as having a subsafe region and only seven of 30 (23.3%) cases on the left side and 12 of 30 (40%) cases on the right side are regarded as having a safe region. However, if the total superior facet is cut and extended to a more lateral side, we found 30 of 30 (100%) cases regarded as having a safe region. To implant the 12-mm-wide interbody cage, if we perform our OM-TLIF approach, only one of 30 (3.3%) cases on the left side and three of 30 (10.0%) cases on the right side were regarded as having a safe region, and majority of them [23/30 (76.7%) on left side and 18/30 (60.0%) on right side] are regarded as not having enough region. If the total superior facet is cut and extended to the lateral side, there are still 10 of 30 (33.3%) cases on the left side and nine of 30 (30.0%) cases on the right side regarded as having a subsafe region (Table 2). Therefore, we recommend using the 10-mm-wide interbody cage for most cases of L3/4 levels, and the total superior facet may

Table 1 The medial and extend distance of included 30 participates.

Lumbar levels		Left (mm)	Right (mm)	*T*	*P*
L3/4	Medial distance	13.48 ± 1.28	13.72 ± 1.39	−1.373	0.180
	Extend distance	16.64 ± 1.34	16.76 ± 1.32	−1.213	0.235
L4/5	Medial distance	15.45 ± 1.38	15.37 ± 1.50	0.722	0.476
	Extend distance	19.77 ± 1.78	20.09 ± 1.85	−1.612	0.118
L5/S1	Medial distance	18.05 ± 1.43	17.66 ± 1.46	1.898	0.068
	Extend distance	21.12 ± 1.62	20.91 ± 1.44	1.577	0.126

Table 2 The percentage of cases that can be implanted safely of included 30 participates.

Lumbar levels		10-mm-wide cage			12-mm-wide cage		
		Not enough region	Subsafe region	Safe region	Not enough region	Subsafe region	Safe region
L3/4 MD	Left	5 (16.7%)	18 (60.0%)	7 (23.3%)	23 (76.7%)	6 (20.0%)	1 (3.3%)
	Right	4 (13.3%)	14 (46.7%)	12 (40%)	18 (60.0%)	9 (30.0%)	3 (10.0%)
L3/4 ED	Left	0	0	30 (100%)	0	10 (33.3%)	20 (67.7%)
	Right	0	0	30 (100%)	0	9 (30.0%)	21 (70.0%)
L4/5 MD	Left	0	4 (13.3%)	26 (86.7%)	4 (13.3%)	19 (63.3%)	7 (23.3%)
	Right	0	5 (16.7%)	25 (83.3%)	5 (16.7%)	17 (56.7%)	8 (26.7%)
L4/5 ED	Left	0	0	30 (100%)	0	1 (3.3%)	29 (96.7%)
	Right	0	0	30 (100%)	0	1 (3.3%)	29 (96.7%)
L5/S1 MD	Left	0	0	30 (100%)	0	2 (6.7%)	28 (93.3%)
	Right	0	0	30 (100%)		3 (10.0%)	27 (90.0%)
L5/S1 MD	Left	0	0	30 (100%)	0	0	30 (100%)
	Right	0	0	30 (100%)	0	0	30 (100%)

ED = extend distance; MD = medial distance.

need to be cut and extended to a more lateral side for some cases.

In level of L4/5, to implant the 10-mm-wide interbody cage, none of them are regarded as having not enough region, and only four of 30 (13.3%) on the left side and five of 30 (16.7%) on the right side are regarded as having a subsafe region; all others had a safe region, and most of them do not need the total superior facet to be cut and extended to more lateral side. To implant the 12-mm-wide interbody cage, four of 30 (13.3%) on the left side and five of 30 (16.7%) on the right side are regarded as having not enough region, and 19 of 30 (63.3%) on the left side and 17 of 30 (56.7%) on the right side are regarded as having a subsafe region. If the total superior facet is cut, only one of 30 (3.3%) on the left and right sides is regarded as having a subsafe region, and all others have a safe region (Table 2). Therefore, we recommend using the 10-mm-wide interbody cage for most cases of L4/5 levels. Few cases may need the total superior facet for safe region to be cut; however, if the surgeon needs to use the 12-mm-wide interbody cage for some special condition, more percentages of cases need the total superior facet to be cut for safe region.

In level of L5/S1, to implant the 10-mm-wide interbody cage, all the cases in our present study are regarded and having a safe region. To implant the 12-mm-wide interbody cage, only two of 30 (6.7%) on the left side and three of 30 (10.0%) on the right side are regarded as having a subsafe region; all others have a safe region (Table 2). We recommend that the 12-mm-wide interbody cage can be safely used on most L5/S1 cases without having the total superior facet to be cut.

Besides the ED that extend to the lateral side, on 3D models, other four extensive options that could be simulated too, although without quality data, include the following: 1) extension to the superior-lateral side to decompress the traversing nerve root (Figure 4A); 2) extension to the inferior-lateral side to decompress exiting nerve root (Figure 4B); 3) extension to both upper and lower margin for some special individual decompression (Figure 4C) and 4) extension to the contralateral lateral recess and foramen to decompress the contralateral side (Figure 5).

Discussion

Currently, the posterior lumbar interbody fusion and transforaminal lumbar interbody fusion are the two main techniques for lumbar degenerative diseases [3,12,15,27,28]. However, both the techniques had their disadvantages, such as the retraction of cauda equina and dural sac of the posterior lumbar interbody fusion which will cause the iatrogenic nerve injury [19] and the transforaminal lumbar interbody fusion being more towards the lateral side which will increase the intraoperative blood loss and surgical trauma.

In the present 3D digital study, we provide a safe region for most patients with L3-S1 disorders who need be performed the interbody fusion and name this operative approach as "optimal medial transforaminal lumbar interbody fusion (OM-TLIF) approach". Briefly, this OM-TLIF approach is to cut the lamina at the medial margin of the operative side of spinous process (spinous process preserved) and upper 1/2—1/3 line of lamina and at the medial half part of the superior facet of the lower vertebra. We found that this approach can avoid the disadvantages of over retraction of cauda equina and dural sac of PLIF and too lateral side dissection and lateral veins' bleeding of standard TLIF.

Although our OM-TLIF approach can provide a safe region for most patients to perform decompression, discectomy and implantation of the interbody cage, in L3/4 level, 16.7% cases on the left side and 13.3% cases on the right side are still regarded as not having enough region, and 60.0% cases on the left side and 46.7% on the right side are regarded as having a subsafe region. For these patients, the region will be changed to safe if we cut the total superior facet of the lower vertebra and extend to more lateral side. Clinically, the L3/4 level is much less than the L4-S1 level. Our present study found that the OM-TLIF had a safe region for L4-S1 levels at almost all patients, and only 13.3—16.7% of cases need the total superior facet to be extended to more lateral side at L4-5 level and none at L5-S1 level.

The biomechanical study found that the larger cage had better segmental stiffness [29]. However, for individuals,

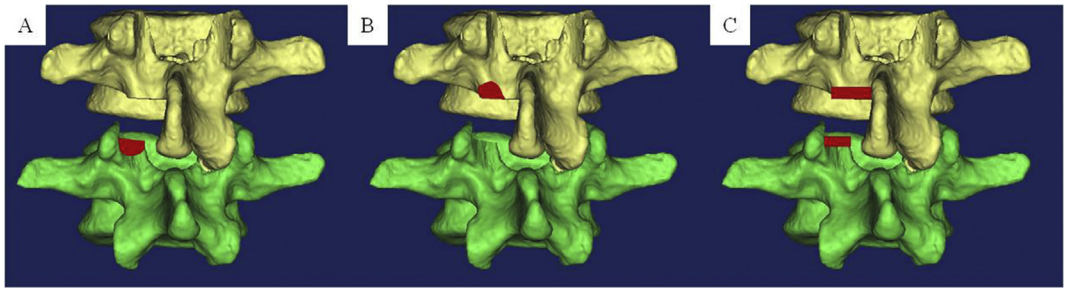

Figure 4 The extension of inferior-lateral side, superior-lateral side and upper-lower side of the OM-TLIF. (A) The traversing nerve root is located at the inferior-lateral side (red area); if some patients have compression of traversing nerve root here, the decompression can be easily extended to this area; (B) the exiting nerve root is located at the superior-lateral side (red area); if some patients have the compression of exiting nerve root, we can extend to expose and decompress the exiting nerve root at this area; (C) no strict limitation of the upper and lower side of OM-TLIF approach; surgeons can extend to the upper and lower margin (red area) to the necessary extent for special individual decompression.
OM-TLIF = optimal medial transforaminal lumbar interbody fusion.

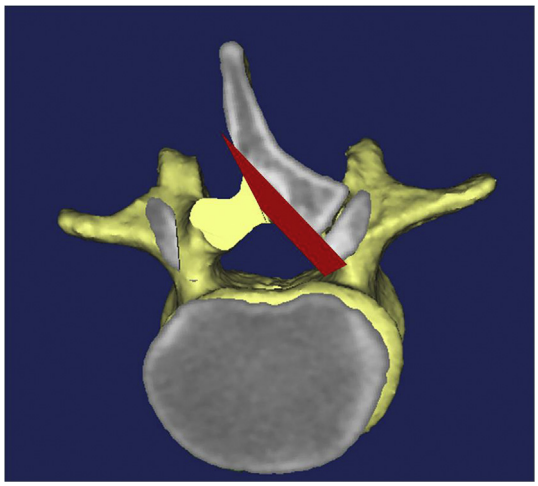

Figure 5 We can remove the part underneath bone of the spinous process and deep cortical surface of contralateral lamina (red area), extend to the contralateral lateral recess and foramen and perform decompression.

we should balance the segmental stiffness and risk of nerve injury. If it is safe to use a 12-mm cage, we recommend using a 12-mm-wide cage; if the 12-mm-wide cage is considered to be subsafe or unsafe, using a 10-mm-wide cage is recommended. If the intervertebral space is more than 14 mm, may be a 10-mm-wide cage is too thin, in which case, it is recommended for the surgeons to cut more part of the upper facet joint and use a 12-mm-wide cage. In fact, the cut percentage of the superior facet is depending on the special condition of individual patients. Although we use the cut of 1/2 part of the superior facet as the definition of optimal approach, some patients may need only 1/3 or the need may extend to 2/3 or 3/4, therefore, we suggest a preoperative surgical plan may be helpful to make precise cut for individual patients. We define this extension to lateral side option as one of the five extensive options of our OM-TLIF approach.

The traversing nerve root is located at the inferior-lateral side of the site of OM-TLIF approach; if some patients have compression of traversing nerve root here, the decompression can be easily extended to this area (the second option) (Figure 4A). The exiting nerve root is located at the superior-lateral side of the site of OM-TLIF approach. We do not need to expose the exiting nerve root for most patients, but for some patients who have the compression of exiting nerve root, we can remove some bone of superior-lateral side, expose and decompress the exiting nerve root (the third option) (Figure 4B). The fourth option is that with no strict limitation of the upper and lower margin of our OM-TLIF approach, surgeons can extend to the upper and lower margin to the necessary extent for special individual decompression (Figure 4C).

The fifth option is to decompress the contralateral side. We can remove the part of the spinous process underneath bone and deep cortical surface of contralateral lamina, extend to the contralateral lateral recess and foramen and perform decompression; this unilateral approach for bilateral decompression was clinically proved to have less operative time and blood loss [30] also had satisfactory outcomes for degenerative lumbar spondylolisthesis with stenosis [31]. Therefore, our OM-TLIF approach with five extensive options can provide safe lumbar decompression and interbody fusion for most individual patients, but there are several limitations of our present study. First, our study is based on normal anatomic populations and 3D digital images without *in vivo* information and cannot present the complex clinical conditions. The patients with severe deformity such as scoliosis or congenital dysplasia may need a detailed preoperative surgical plan to achieve an optimal approach for decompression and interbody fusion. Moreover, although we set operative side of the spinous process as the margin of the medial side of the operative approach, for some patients, the dural sac and nerve root are hard to retract to this margin; for this condition, to cut more part of the superior fact and extend to lateral side is a good option. Finally, the safe region means there is enough space to perform the discectomy and insertion of interbody cage; the surgeon should protect the dural sac and nerve root intraoperatively, and no one can guarantee to avoid the iatrogenic nerve injury caused by careless operation.

Conclusion

Our 3D digital imaging study provides a feasible OM-TLIF approach with five extensive options on lower lumbar region (L3-S1). It can provide safe lumbar decompression and interbody fusion in most population. In addition, surgeons can choose different extensive options for special individual conditions.

Author contributions

AM Wu, XL Li, HJ Tian and J Zhao contributed to the study concept and design. AM Wu, XL Li and HJ Tian performed acquisition of data. K Zhang, CQ Zhao and SR Sheng performed analysis and interpretation of data. AM Wu, XL Li and HJ Tian drafted the manuscript. Y Lin, WF Ni, XY Wang and J Zhao revised the manuscript critically for important intellectual content. All authors approved the version of the manuscript.

Conflicts of interest

All authors report there are no conflicts of interest related to the present article.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jot.2018.07.004.

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