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Research article

Lumbar reconstruction with hyperlordotic cages: Prediction of neuroforaminal height in comparison to established age and sex dependent reference values

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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

Interbody cages are routinely used in lumbar reconstruction surgery of deformity cases for restoration of lordosis and sagittal balance of the spine. However, if hyperlordotic implants are inserted into the intervertebral space, special consideration has to be taken concerning the height of the neural foramen during cage implantation. The greater the lordotic angle of the cage is, the higher the posterior size of the cage needs to be in order to avoid neuroforaminal nerve root impingement. In this technical communication, we propose and clinically validate a stepwise mathematic model to predict neuroforaminal height in patients undergoing lumbar reconstruction with hyperlordotic cages. The length of the superior and inferior vertebral end plates including the height of the neural foramen are measured before implantation of the cage in standing sagittal view x-rays. By assumption of an isosceles triangle in combination with the posterior height and the lordotic angle of the cage, the neuroforaminal height after cage implantation can be estimated. By comparison of the predicted neuroforaminal height with age and sex dependent reference values, nerve root impingement can be avoided by selection of the necessary posterior height of the hyperlordotic cage while still gaining sufficient lumbar lordosis.

1. Introduction

In adult spine deformity (ASD), the ambition for a balanced spine within the cone of economy [1] and as a consequence the correct readjustment of primarily lumbar lordosis depending on various spine shapes are widely accepted concepts in deformity surgery of the degenerative spine [2]. Either reconstruction of lumbar lordosis can be achieved by purely posterior approaches applying for example different types of osteotomies or by combined anterior, lateral and/or posterior strategies with hyperlordotic interbody cages using surgical access routes frequently through the retroperitoneal space [3]. By these approaches, interbody cage sizes with large footprints and hyperlordotic angles (>10°) may be deliberately implanted in the intervertebral spaces [4,5]. However, the application of hyperlordotic cages may indirectly lead to a decrease of the neuroforaminal height and potentially to a nerve root impingement within the neural foramen. Indeed, post interventional nerve root irritation is a known phenomenon and a listed complication in lumbar reconstruction surgery using hyperlordotic cages [5–7]. Of note, reference values for the normal height of the neural foramen have been extensively analyzed and documented in age and sex dependent investigations [8]. By use of a trigonometric approach, the

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neuroforaminal height after cage implantation can be estimated using the preoperative length of the vertebral end plates in sagittal 2D x-rays including the angle of the cage and its posterior height. By selection of the necessary height of the posterior aspect of the cage while maintaining the required extent of lordosis of the cage, the height of the neural foramen can be reliably reconstructed. By comparison of the calculated neuroforaminal height after cage implantation to the available age and sex dependent reference values, nerve root impingement may be avoided while sufficient lumbar relordosation can be achieved (Fig. 1A–C). In this technical communication, we introduce a stepwise trigonometric approach to estimate the neuroforaminal height after the implantation of hyperlordotic cages in ASD surgery in order to avoid potential nerve root impingement within the neural foramen. Further, a clinical validation of the proposed calculation is presented in a case series of four patients.

2. Material and methods

2.1. Patient selection

Indication for anterior and posterior lumbar reconstruction surgery due to sagittal imbalance and the calculation of the necessary extent of lordosis correction were based on current guidelines [2]. Only patients with a one and/or two segment disease who underwent a combined anterior and posterior surgical approach using hyperlordotic cage implants (>10°) were investigated in this study. All patients provided informed consent for further use of their clinical data for scientific purposes and publication of their anonymised case details and images. Due to the available informed consents, the limited study population and the retrospective design of the investigation, the study is not subject to approval by the local ethics committee (Ethikkommission Nordwest-und Zentralschweiz, EKNZ; Req-2023-01097). The study fully adheres to the ethical principles for medical research involving human subjects as outlined in the declaration of Helsinki.

2.2. Estimation of neuroforaminal height

The mathematic model for the estimation of neuroforaminal height was established in collaboration with a mathematician and software engineer. All equations are based on the assumptions that the prolongation of the sagittal vertebral endplates of a spinal segment results in an isosceles triangle and that the interbody cage is located in the anterior two thirds of the intervertebral space. By measurement of the length of the vertebral endplates in a sagittal view 2D x-ray of the spine before implantation of a hyperlordotic cage, the knowledge of its lordotic angle including the height of the posterior aspect of the cage, the post-surgical height of the posterior aspect of the intervertebral space (discal part) can be calculated using trigonometry. The summary of both the posterior bony and discal parts of the vertebral bodies provides a prediction of the neuroforaminal height after cage implantation (Fig. 2A–B). A comparison to established age and sex dependent reference values of neuroforaminal height then allows to select the minimal necessary height of the dorsal part of the cage while still using a hyperlordotic implant as required for sufficient relordosation [8].

2.3. Post-surgical validation of neuroforaminal height

In a case series of four consecutive patients pre- and post-surgical height of the neural foramen was measured and compared to the calculated values by the established trigonometric model to predict neuroforaminal height after cage implantation. In addition, postoperative neuroforaminal height was compared to available age and sex reference values. Due to the normal distribution of the

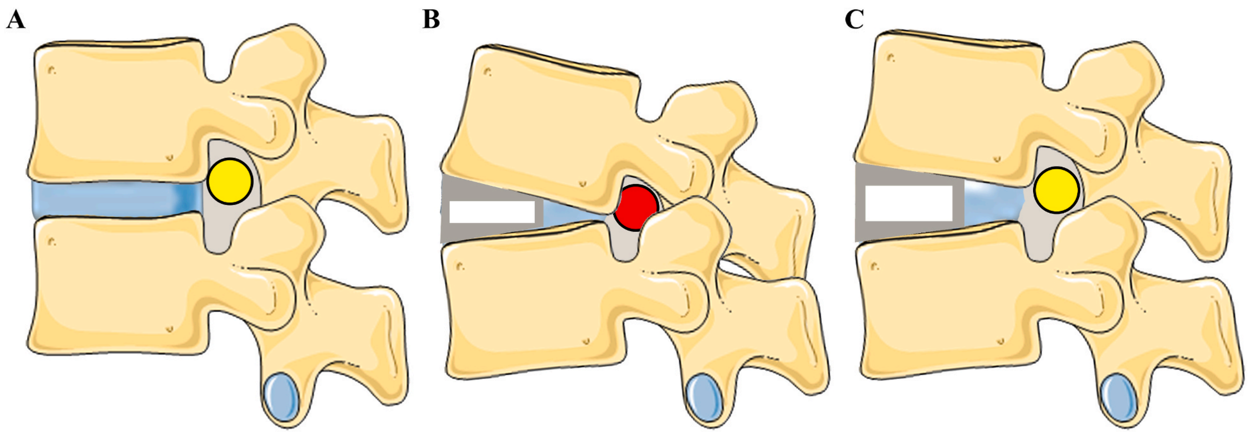

Fig. 1. Change of neuroforaminal height using hyperlordotic cages. In a healthy and non-degenerated spine with an intact intervertebral disc, the nerve root (yellow) has sufficient space within the neural foramen (A). By implantation of a hyperlordotic cage with an insufficient size of the posterior aspect of the cage, the nerve root (red) might be impinged within the neural foramen (B). If the posterior aspect of the hyperlordotic cage has a sufficient size, the height of the neural foramen remains large enough while sufficient lordosis is still achieved in the respective segment (C). The figure was partly created using Servier Medical Art, provided by Servier, licensed under a Creative Commons Attribution 3.0 unported license.

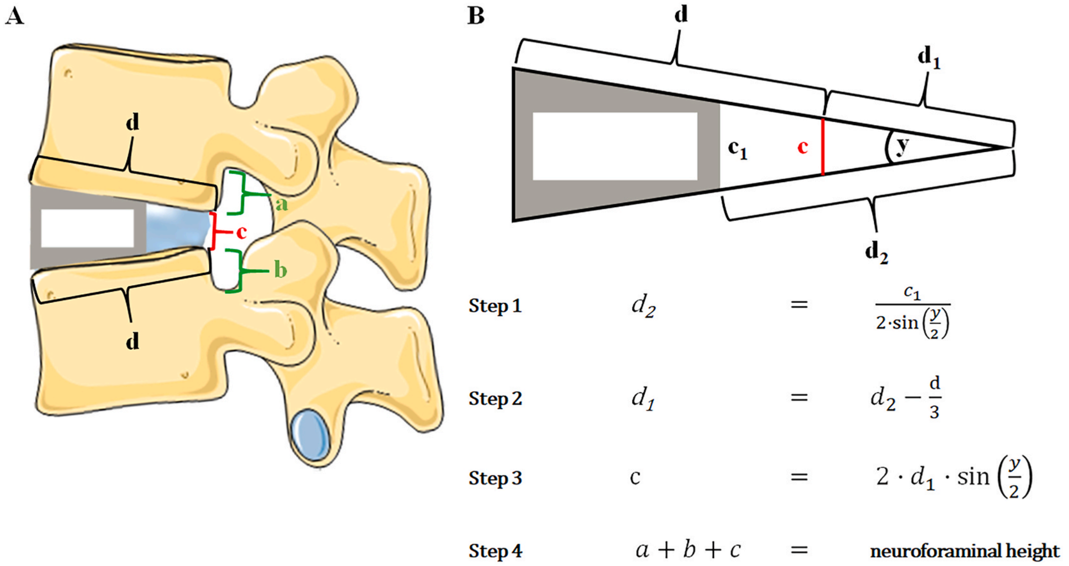

Fig. 2. Estimation of the neuroforaminal height by a trigonometric approach. A: The length of the vertebral end plates (d) and the bony height (a, b) of the neural foramen can accurately be measured in a sagittal view 2D x-ray of the spine. The height of the disc part (c) of the neural foramen is variable and depending on the amount of the lordotic angle of the cage (y) as well as by the size of the posterior aspect of the cage (c1). B: By assumption of an isosceles triangle and the consecutive four distinct steps (step 1 to 4), the height of the disc part (c) of the neural foramen can be estimated by use of the length of the vertebral endplates before surgery (d), the angle of the cage (y), and the height of the posterior aspect of the cage (c1). The total height of the neural foramen is then given by the simple sum of the bony (a, b) and disc parts of the neural foramen (c). Important remark: The formula is only valid if the cage is placed in the anterior two thirds of the intervertebral disc space assuming postoperative rigidity of the segment by posterior instrumentation. Panel A of the figure was partly created using Servier Medical Art, provided by Servier, licensed under a Creative Commons Attribution 3.0 unported license.

data (as confirmed by Kolmogorov-Smirnov test) a paired *t-test* was applied to validate the mathematic model (SPSS software, version 28, IBM).

3. Results

A case series of four consecutive patients (2 females and 2 males) underwent lumbar reconstruction due to sagittal imbalance and deformity of the spine (Table 1, Fig. 3A–B). The mean age was 48.7 ± 13.6 years. Two patients were operated on the vertebral lumbar segment L4/5 only and two patients on both segments L4/5 and L5/S1.

Pre-surgical neuroforaminal height as measured in sagittal 2D view x-rays was 15.0 ± 0.6 mm. All patients received hyperlordotic cages. The mean lordotic angle of the cages was 18.0 ± 3.4° and the mean height of the posterior aspect of the cages was 8.2 ± 1.0 mm. Post-surgical neuroforaminal height was 17.8 ± 1.4 mm. The increase of neuroforaminal height after cage implantation in comparison to the state before surgery was significant (2.8 ± 0.9 mm, $p < 0.001$). The mean gain of lordosis in the operated segments was 17.6 ± 4.8°, $p < 0.01$. The post-surgical neuroforaminal heights were comparable to the normal age and sex reference values (17.8 ± 1.4 mm vs. 19.1 ± 1.0 mm, p = not significant, NS). The mathematic model adequately predicted neuroforaminal heights as compared to post-surgically measured neuroforaminal heights (17.9 ± 1.4 mm vs. 17.8 ± 1.4 mm, p = NS). In consideration to the fact that an exact placement of a cage in the anterior two thirds of the intervertebral disc is often demanding and usually not mathematically precise, our formula allows a certain amount of tolerance. None of the patients showed post-surgical signs of cage subsidence nor nerve root impingement of the surgically treated segments.

Table 1
Patient baseline characteristics

	Total	Females	Males	p-value
Age (years)	48.7 ± 13.6	53.2 ± 11.1	44.2 ± 18.6	p = NS
Sex (n, %)	4, 100%	2, 50%	2, 50%	p = NS
	Before surgery		After surgery	
Lordosis L1–S1 (degree)	30.5 ± 12.4		45.7 ± 14.1	<0.05
Segmental lordosis (degree)[a]	14.0 ± 10.0		31.7 ± 11.4	<0.01
Neuroforaminal height (mm)	15.0 ± 0.6		17.8 ± 1.4	<0.001

[a] Refers to operated segments only. Parameters are given as mean ± standard deviation. NS = not significant.

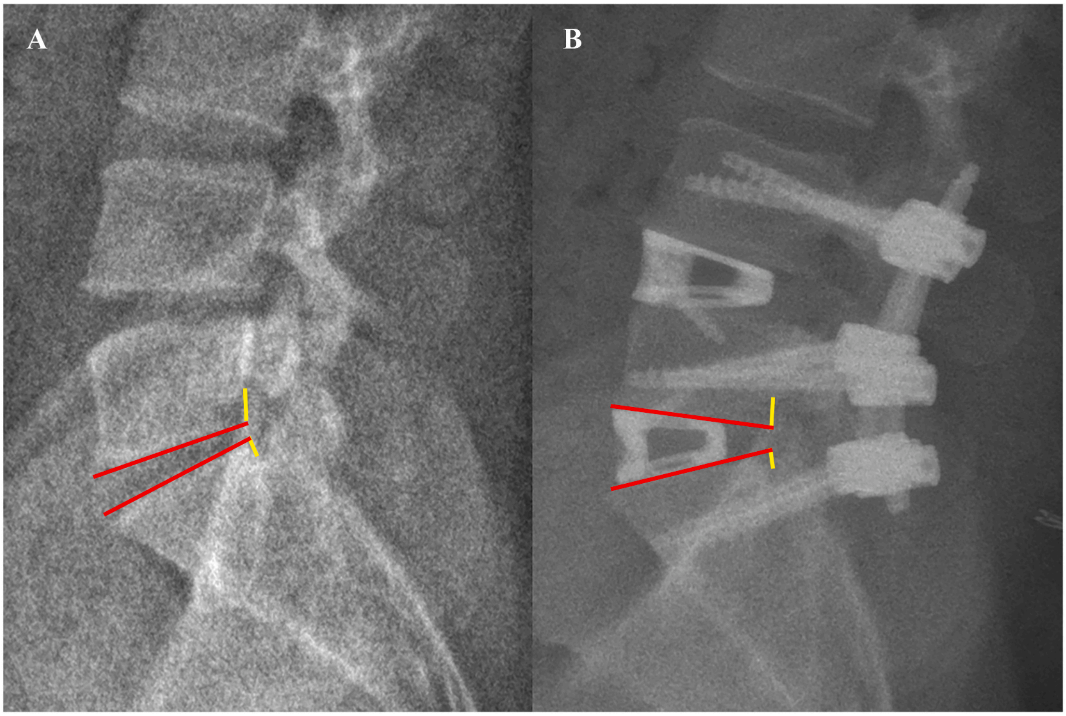

Fig. 3. Reconstruction of the lumbar spine using a combined anterior (anterior lumbar interbody fusion, ALIF) and posterior (pedicle screws) surgical access route. Pre- (A) and post-surgical (B) height of the neural foramen after a combined anterior and posterior approach using a hyperlordotic cage (16° lordotic angle). The length of the bony vertebral endplates (red lines) including the height of the bony part of the neural foramen (yellow lines) can be measured in sagittal view 2D X-rays and together with the selected cage parameters (lordotic angle and posterior height of the cage) the post-surgical height of the neural foramen can be estimated. Therefore, the correct size of the cage can be chosen while sufficient reconstruction of lumbar lordosis can still be achieved.

4. Discussion

Low back pain is frequently triggered by spinal deformities and/or sagittal imbalance of the spine [9]. Thus, restoration of sagittal alignment and balance of the spine in patients suffering from a clinically symptomatic spinal deformity can currently be perceived as a state-of-the-art treatment strategy [10]. Either purely posterior or combined anterior, lateral and/or posterior surgical approaches are applied to achieve a balanced spine. In combined approaches, frequently hyperlordotic cages are inserted into the intervertebral space to reconstruct lumbar lordosis. If the height of the posterior aspect of the cage is too small and the lordotic angle too large, neuroforaminal height may decrease and nerve root impingement can occur. Although intraoperative neuromonitoring is able to detect sensory or motor impairment, the somatosensory evoked potentials (SSEP) are not a reliable predictor for neuropathic pain [11]. In this study, we present a simple stepwise mathematic model to predict postsurgical neuroforaminal height depending on the configuration of the treated vertebral segment and the dimensions of the inserted hyperlordotic cage. If the calculated post-surgical neuroforaminal height is aligned with age and sex dependent reference values of normal neuroforaminal height [8], nerve root impingement may be successfully avoided while still sufficient lumbar lordosis of the segments can be achieved. Our formula was validated using a case series of four patients who underwent combined anterior and posterior restoration of sagittal deformity. None of these patients suffered from signs of nerve root impingement after surgery while sagittal parameters were sufficiently recompensed.

Cage dimensions and in particular the footprint of the cages play an important role in restoration of lumbar lordosis. The larger the footprint, the less subsidence has been documented [12]. As a consequence of this, large and hyperlordotic cages are usually implanted by anterior and/or anterior-lateral approaches to the spine, i.e. by the transpsoas or the anterior to psoas surgical access route. Our estimation of the neuroforaminal height may only apply for cage types which adequately support the vertebral apophysis and as such are less frequently subject to cage subsidence. The mathematic formula might deliver inaccurate values if posterior access routes of cage implantation are used, i.e. by posterior or transforaminal lumbar interbody fusion in which only smaller cage dimensions may be implanted. Further, we also consider the release of the anterior spinal ligament [13] and, if feasible, fixation of the cage by screws or plate in the intervertebral space another important factor to avoid cage subsidence and achieve persistent reconstruction of lumbar lordosis, in particular when using hyperlordotic cages [14]. In addition, surgical cases with anticipated insufficient quality of the vertebral bone (i.e. in patients with osteopenia or osteoporosis) might be demanding with regard to reconstruction by hyperlordotic implants due to the higher risk of subsidence as compared to the population with normal bone quality. Finally, reconstruction of lumbar segments with hyperlordotic cages should, whenever feasible, be combined with dorsal stabilization while stand-alone use of these cages should be avoided. On the one hand, subsidence rates are higher in stand-alone cases and on the other hand, fusion rates are lower with an increased risk for pseudarthrosis [15].

Neuroforaminal height has extensively been investigated in various studies and significant differences have been found depending on age and sex [8]. During the aging process the intervertebral disc loses water content and as such the neural foramen gradually decreases in height. Further, the mean proportions of a female as compared to a male body differs significantly in weight and size which consequently results in smaller dimension of the neural foramen in women than in men [8]. This is of importance when planning the reconstruction of lumbar lordosis in a spine deformity case as the segmental target height of the neural foramen cannot be generalized but age and sex has to be taken into consideration. Moreover, not only cage height and angle but also the footprint need to be both variable and available in different sizes for optimal correction of sagittal imbalance. Unfortunately, only very few studies investigating normal values of the balance and alignment of the spine consider sex as an important discriminator while age has been repetitively taken into consideration [16–18].

Fusion rates using hyperlordotic implants are frequently discussed in the current literature [19,20]. The higher the introduced amount of lordosis per vertebral segment, the more frequent the treated vertebral segment is subject to pseudarthrosis (non-union), particularly if using the cages as stand-alone implants [21]. The use of bone substitutes, i.e. recombinant human bone morphogenetic protein-2 (rhBMP-2) and other bone growth promoting analogs, might help to diminish non-union rates and trigger bony fusion [22]. In our experience, the rate of correction per segment with hyperlordotic cages should not surpass approx. 30° in L5/S1, 20–25° in L4/5, and 15° in L3/4 and L2/3 in order to avoid both cage subsidence but also pseudarthrosis. Combined anterior and posterior approaches for relordosation of the lumbar spine are further limited by the degree of degeneration of the facet joints. Advanced facet joint degeneration as well as touching spinal processes (Baarstrup phenomena) decrease the amount of correction possibilities by hyperlordotic cages. In such cases, a purely posterior approach using an adequate surgical technique with or without the application of different types of osteotomies should be surgically preferred over the implantation of hyperlordotic implants alone [23]. Finally, reimbursement should also be considered: While hyperlordotic implants are rather expansive tools with regard to the amount of lumbar correction which can be achieved, purely posterior approaches might still represent the gold standard and the most efficient surgical strategy when it comes to correction of sagittal imbalance of the spine.

The following limitations in this investigation need to be pointed out: This study should be regarded as concept generating and caution is advised before generalizing our findings. Although the mathematic model was validated against several deformity cases, the study population is limited and subject to a potential measurement bias. As a consequence, further and ideally prospective investigations with larger numbers of surgical cases using not only simple 2D x-ray but also computed tomography (CT) should be performed in order to strengthen the validity of the estimation of postoperative neuroforaminal height. Moreover, the presented mathematic model with the assumption of an isosceles triangle represents a simplified approximation of reality and as such understandably includes a certain bias in prediction of neuroforaminal height. In addition, the positioning of the hyperlordotic cage in the target segment as well as the degree of resection of posterior elements (i.e. by partial or complete facet joint resection) might significantly impact the extent of relordosation and could falsify the suggested mathematic model. Its assumed validity only applies if the cage is implanted in the anterior two thirds of the vertebral segment and posterior stabilization is performed without corrective osteotomies. Further, our suggested estimation of neuroforaminal height holds true only in cases with simultaneous posterior instrumentation and not for stand-alone interbody fusion without posterior instrumentation. Finally, in any case of cage subsidence or spondylolisthesis the validity of the mathematic estimation of neuroforaminal height may lose its applicability.

5. Conclusions

Reconstruction of sagittal alignment and balance of the spine in deformity cases is of high importance when surgically treating low back pain with the aim to avoid adjacent segment degeneration. Combined anterior and posterior surgical approaches using hyperlordotic cages are widely used for corrective surgeries and in particular to reconstruct lumbar lordosis. A major risk of hyperlordotic cages is a potential nerve root impingement in the respective segment. By our mathematic model, the post-surgical neuroforaminal height can be predicted and compared to age and sex dependent neuroforaminal height of the general population. Therefore, the correct size of the hyperlordotic cage can be determined in advance to omit potential post-surgical nerve root impingement while still achieving the necessary amount of lumbar lordosis to rebalance the spine. With this concept generating investigation, we believe that treatment strategies in adult deformity surgery will be tailored towards a more personalized patient care.

Data availability statement

The data that support the findings of this study are available from the Swiss Paraplegic Center, Spine and Orthopedic Surgery. However, restrictions apply to the availability of these data. Thus, the data is not publicly available. However, data can be made available from the authors upon reasonable request and with permission of the local ethics committee (Ethikkommission Nordwest- und Zentralschweiz, EKNZ). The corresponding author can be contacted for guidance concerning such a data request.

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None to declare.

CRediT authorship contribution statement

Denis Bratelj: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing, Project administration, Resources. **Phillip Jaszczuk:** Formal analysis, Investigation, Validation, Writing – review & editing. **Crescenzo Capone:** Formal analysis, Investigation, Validation, Writing – review & editing. **Cristian Dragalina:** Investigation, Writing – review & editing. **Tobias Pötzel:** Conceptualization, Formal analysis, Investigation, Resources, Supervision, Validation, Writing – review & editing, Methodology, Project administration, Software. **Michael Fiechter:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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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