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ORIGINAL ARTICLE

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Biomechanics of stand-alone cages and cages in combination with posterior fixation: a literature review

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Abstract Interbody cages in the lumbar spine have met with mixed success in clinical studies. This has led many investigators to supplement cages with posterior instrumentation. The objective of this literature review is to address the mechanics of interbody cage fixation in the lumbar spine with respect to three-dimensional stabilization and the strength of the cage-vertebra interface. The effect of supplementary posterior fixation is reviewed. Only three-dimensional stabilization evaluations in human cadaveric models are included. These studies involve the application of different loads to the spine and the measurement of vertebral motion in flexion-extension, axial rotation, and lateral bending. There are no published studies which detected any differences between different cage designs. However, it does seem that cages inserted from an anterior direction provide better stabilization to the spine than those inserted from a posterior direction. In general, anterior cages stabilize better than posterior cages in axial rotation and lateral bending. Cages from both directions stabilized well in flexion, but not in extension. Supplementary posterior fixation with pedicle or translaminar screws substantially improves the stabilization in all directions. The strength of the cage-vertebra interface from studies using human cadaveric specimens is also reviewed. The axial compressive strength of this interface is highly dependent upon vertebral body bone density. Other factors such as preservation of the subchondral bony end-plate and cage design are clearly less important in the compressive strength. Supplementary posterior instrumentation does not enhance substantially the interface strength in axial compression.

Key words Interbody cage · Biomechanics · Implant · Stabilization · Strength

Introduction

Interbody cages are porous implants which are placed between two vertebral bodies to facilitate an intervertebral fusion. The concept for these cages was described first by Bagby [3] along with initial animal evaluation [10]. Clinical trials of these cages began in 1991 for degenerative problems of the lumbar spine. Early clinical results and the broader results of multicentre clinical trials have been encouraging [21, 30]. However, some investigators have had less success [19, 25]. Furthermore, recent studies have found that fusion assessment with these cages is virtually impossible with X-rays or CT scans [4, 15], thereby putting into doubt some of the definitive fusion results from the clinical studies. All in all, the effectiveness of stand-alone interbody cages has been questioned, with some investigators claiming that supplementary posterior fixation is required to produce better long-term clinical results [6, 25].

To shed light on this issue, it may be worthwhile to review the basic mechanics of interbody cage fixation. A comprehensive analysis must address both the strength and stability of the spine-implant construct [28]. The strength of the construct relates to the absence of structural failure of either the implant or adjacent vertebral bone. The stability relates to the lack of motion between adjacent vertebrae, which is important to facilitate bone ingrowth and eventual fusion.

The objective of this paper is to review the literature regarding the biomechanical characteristics of interbody cages. Specifically, their three-dimensional stabilization patterns and the compressive strength of the bone-implant construct will be reviewed. For both stabilization and strength, the effectiveness of supplementary posterior fixation will be described.

Three-dimensional stabilization

Many biomechanical studies have been conducted over the last 10 years to address the stabilization characteristics of interbody cages. Only those studies which used a human cadaveric model will be reviewed here. The potential deficiencies of an animal model will be outlined in the Discussion section. Further, only studies which are truly three-dimensional are included. This entails assessment of the stabilization provided by the cage in the sagittal plane (i.e. flexion-extension), the frontal plane (i.e. lateral bending), and the transverse plane (i.e. axial rotation).

In the studies of cage stabilization, well-defined loads are applied to a spine specimen in its intact, non-operated state and after insertion of an interbody cage. Often, the effect of supplementary posterior instrumentation is determined as a final step. In these experiments, the intervertebral motions are measured in the different specimen conditions. Typically, the results are reported as the total range of motion under the maximum load or as the overall stiffness (i.e. load per unit displacement) of the construct. The cage stabilization is assessed as a percentage of the intact spine values.

Different cage designs

In comparative studies of different cage designs, no significant differences have been described for either anterior [27] or posterior [22] cages. Mathematical modelling of these constructs also demonstrates very similar mechanical behaviour for different cage designs [14]. Therefore, the results for different cage designs will be combined in the remainder of this paper. It is possible that subtle differences do exist between cages and that the statistical power of the existing studies was insufficient. However, at this point, we do not know if this is the case.

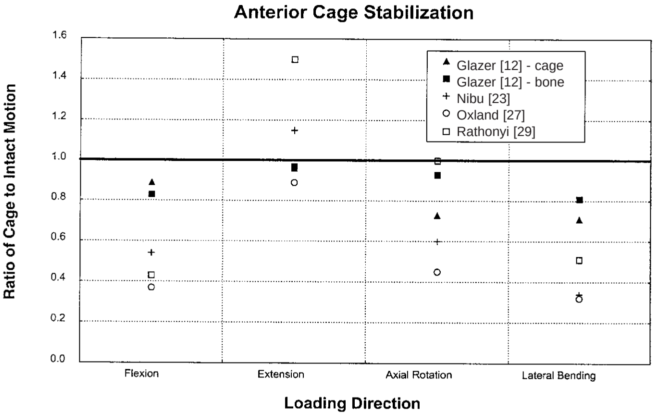

Fig. 1 Summary of three-dimensional biomechanical studies conducted on interbody cages inserted from an anterior approach in a human cadaveric model. The data points represent mean or median values of the range of motion data presented in the original articles. Note that a ratio of 1.0 implies the same motion as intact while a ratio less than 1.0 represents less motion than intact, or stabilization

Anterior approach

Several studies have been reported on interbody cages inserted from an anterior approach which were three-dimensional in human cadaveric specimens. A variety of different interbody cages were tested, including threaded cylinders such as the TIBFD (Sofamor-Danek Group, Memphis, Tenn.) and the BAK cage (Sulzer Spine-Tech Inc., Minneapolis, Minn.) [12, 23, 27, 29], and monobloc devices such as the SynCage (Mathys Medical Ltd., Bettlach, Switzerland) [27]. For comparison, a femoral ring construct has been tested and the results are included herein [12].

Several general observations can be made from a compilation of these studies on cage stabilization from an anterior approach (Fig. 1). In flexion, the intervertebral motion is always less with the cage, on average being about 60% of the intact motion. In extension, the motion with the cage is approximately the same as the intact motion. In other words, the cages do not stabilize the spine in this loading direction. In axial rotation, the cages generally do stabilize the spine such that the cage motion is about 60% of the intact motion. However, there is less stabilization in axial rotation when poor end-plate fixation occurs, as observed by Glazer et al. [12] for femoral ring allograft and as described by Rathonyi et al. [29] for two of their six specimens with BAK cages. In lateral bending, the cages reduce motion to about 50% that of the intact spine.

Posterior approach

A variety of different interbody cages have been tested from a posterior insertion, including a threaded cylinder

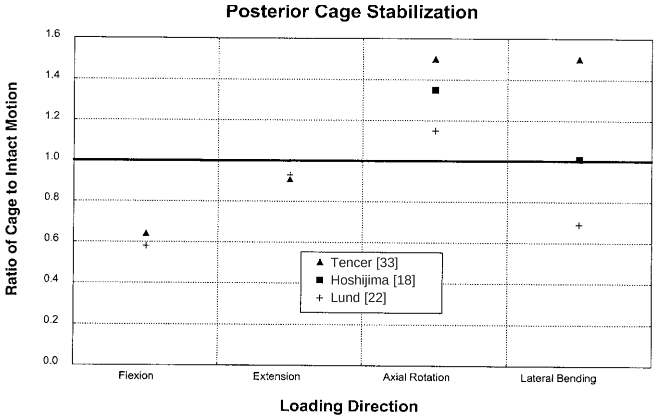

Fig. 2 Summary of three-dimensional biomechanical studies conducted on interbody cages inserted from a posterior approach in a human cadaveric model. The data points represent mean or median values of the range of motion data presented in the original articles. Note that a ratio of 1.0 implies the same motion as intact while a ratio less than 1.0 represents less motion than intact, or stabilization. No values are shown in flextion-extension for the Hoshijima study since the two loading directions were not reported separately

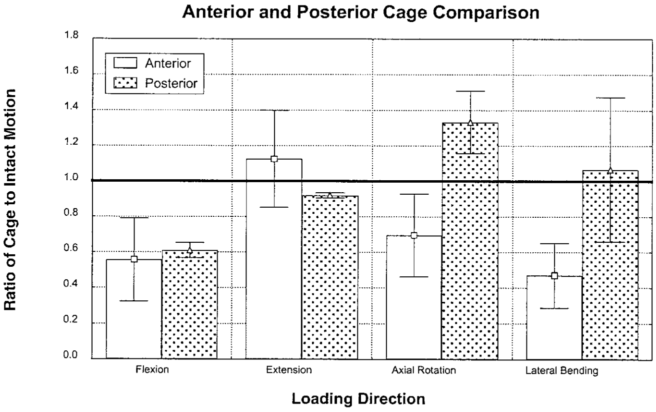

Fig. 3 Summary of the data from anterior and posterior cage studies presented in Figs. 1 and 2. The standard deviation bars represent the variation between the different studies

such as the Ray cage (Surgical Dynamics, Norwalk, Conn.) [22, 33], rectangular devices such as the Brantigan cage (Depuy-AcroMed, Warsaw, Ind.) [18, 22], and a titanium device to fit the end-plate contours such as the Contact Fusion Cage (Stratec Medical Ltd., Oberdorf, Switzerland) [22]. For comparison, a tricortical graft construct has been tested and the results are included herein [18].

Several general observations can be made from a compilation of these studies on cage stabilization from a posterior approach (Fig. 2). In flexion, the intervertebral motion is always less with the cage, on average being about 60% of the intact motion. In extension, the motion with the cage is approximately the same as the intact motion. This implies, as with the anterior devices, that posterior cages do not stabilize the spine in extension. In axial rotation, the motion after cage insertion was always more than in the intact spine by approximately 25%. In lateral bending, variability was observed between studies, with some studies observing significant stabilization [22] and others not [33].

Anterior versus posterior approach

There appear to be some differences between anterior and posterior approaches in the stabilization provided by cages. To enable a quick comparison, the studies summarized in Figs. 1 and 2 have been averaged and combined in Fig. 3. There were no clear differences in flexion. A slight difference existed in extension, although there was relatively high variability in the anterior studies. In axial rotation and lateral bending, there was substantially more motion in the posterior approaches compared to the anterior. Note that none of these comparisons are statistical.

Other factors

In Bagby's original treatise on interbody cage stabilization, he described the distraction-compression theory of intervertebral stabilization [3]. The concept is that intervertebral stabilization will be enhanced with increasing distraction of the annulus fibrosus. Various clinical and laboratory studies have shown that distraction of the disc space does occur with interbody cages [5, 9, 24, 31], and a recent biomechanical study showed that the degree of stabilization is related to the amount of distraction [24]. Animal models demonstrated that some distraction is lost postoperatively, primarily in the first 6 weeks [13, 31]. This loss of distraction will result in decreased immediate stabilization, particularly in flexion-extension and lateral bending [16].

Another factor which affects the stabilization of cages is the vertebral body bone density. It was shown that for various cage types, increased bone density enhances stabilization in flexion-extension and lateral bending, but not axial rotation [26].

Effect of supplementary posterior fixation

Many authors have recommended that posterior fixation be added to interbody cage constructs to enhance their stabilization. This has been studied extensively, and it is well documented that pedicle screw fixation, translaminar screw fixation, and transfacet screw fixation all substantially improve the stabilization. A summary of three studies including cages from an anterior or posterior approach with pedicle screws and an anterior cage with translaminar screw fixation demonstrates this point (Fig. 4).

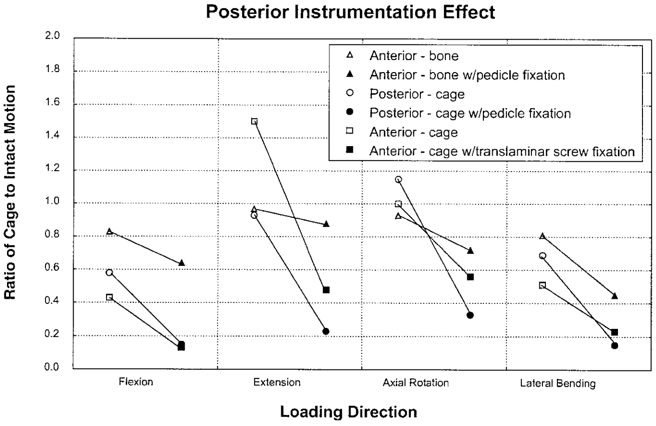

Fig. 4 Effect of supplementary posterior instrumentation on cage stabilization as shown in three representative studies. The anterior approach with interbody bone graft was conducted by Glazer et al. [12]. The posterior approach with cages was conducted by Lund et al. [22] and the anterior approach with cages was performed by Rathonyi et al. [29]

Cage-vertebra interface strength

Fewer studies have been conducted on the strength of the cage-vertebra interface. Again, only those investigations which used a human cadaveric model will be reviewed.

From an engineering perspective, the load at which a cage will subside into a vertebral body is dependent upon the strength of the vertebral bone and the surface area of the interface. The complicating factor is that the strength of the vertebral bone varies greatly between individuals and also within the same individual. Other factors such as surgical preparation of the vertebral body (e.g. end-plate preservation) complicate the situation. Current studies have enhanced our understanding of some of these factors and these will be reviewed.

Effect of bone density

It is well known that the compressive strength of cancellous bone is tied directly to its apparent density. Therefore, it seems obvious that the strength of the cage-vertebra interface should be dependent upon the bone density of the vertebral body. Recent laboratory studies have verified that this is the case [20, 32]. One of these studies addressed the strength of three different cage designs, while the other study looked at two similar but slightly different designs. The bone density, determined by dual energy X-ray absorptiometry, was clearly related to compressive strength of the interface in both studies.

Effect of end-plate preparation

The two studies referenced above and one earlier experiment [17] investigated the role of the vertebral end-plate on the strength of the cage-vertebra interface. None of the three studies found a significant difference between cages which preserve the subchondral end-plate and those which penetrate it when inserted according to the guidelines from the manufacturer.

Effect of cage design

The study by Jost et al. [20] compared the cage-vertebra interface strength for three different cage designs. They detected no significant differences between the threaded Ray cage, the rectangular Brantigan cage, and the porous Contact Fusion cage. Steffen et al. [32] concluded that a cage which rests peripherally on the end-plate may be better to resist settling into the vertebral body.

Effect of supplementary posterior fixation

The study by Jost et al. [20] investigated the effect of pedicle screw fixation on the compressive strength of the cage-vertebra interface. They found that the compressive strength did not change with supplementary pedicle screw fixation.

Discussion

This literature review addresses the basic mechanics of interbody cage fixation in the lumbar spine. It focusses on two important aspects of cage performance: three-dimensional stabilization and the compressive strength of the cage-vertebra interface.

Biomechanical models for interbody cages

The scope of the literature review includes only studies conducted with a human cadaveric model. Many studies on interbody cages, particularly some of the initial investigations, were conducted on a variety of animal models including porcine, bovine, and baboon [7, 8, 35]. It is well known that there are substantial anatomic differences between these animal models and the human spine, including different articular facet morphology and immature growth plates. However, if these studies produced similar results to those of the human cadaveric model, then they may prove useful in biomechanical experiments. Unfortunately, substantial differences do exist between the results of these early studies and the most recent biomechanical findings in human models. To demonstrate this point, we have combined the anterior and posterior cage stabilization results from Fig. 3 with results from these animal experiments (Fig. 5). Note that in loading directions other than flexion, the results from the animal models are dra-

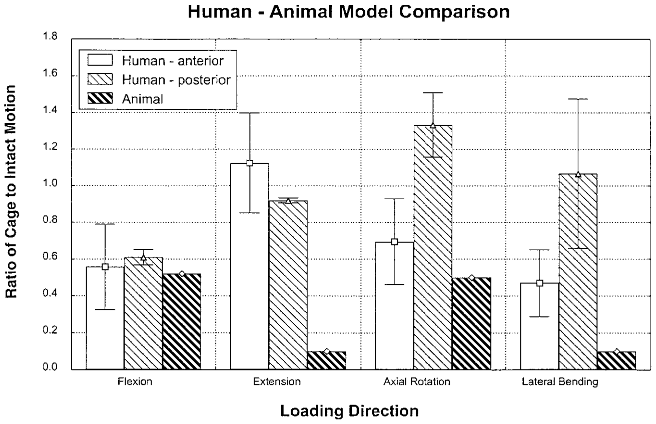

Fig. 5 Results of anterior and posterior approaches for cage insertion in human cadaveric models compared with some early animal results. The human data are as plotted in Fig. 3. The flexion and extension animal data are from Wilder et al. [35]. The axial rotation animal data are from Brodke et al. [7] while the lateral bending animal data are from Butts et al. [8]

matically different from the average results of several studies in a human model. These findings make us question the use of these animal models in characterizing interbody cage mechanics and are the reason for our exclusive focus on human cadaveric models in this paper.

Three-dimensional stabilization

The results of different studies on anterior and posterior cage stabilization are remarkably similar. It seems that a cage inserted from either direction provides good stabilization in flexion but does not provide stabilization in extension. It is interesting that the anterior approach, which destroys much of the anterior annulus and longitudinal ligament, does not result in dramatically poorer stabilization than the posterior approach. The lack of a difference could be due to the facet destruction which occurs in the posterior approach. The anterior approach produces better stabilization than the posterior in axial rotation and lateral bending. The primary difference between the anterior and posterior surgical approach is that a medial facetectomy is required in the posterior procedure. Since the facets play such a vital role in axial rotation [1], this may explain the better results with an anterior approach in this direction. The role of a medial facetectomy is not as significant in lateral bending, but could still be a factor. Another possibility is that the cages from a posterior approach are placed more centrally in an effort to avoid excessive facet removal. This would presumably result in poorer lateral bending stabilization. In summary, the anterior approach seems to produce better immediate stabilization than does the posterior approach.

Of note in both anterior and posterior approaches is the absence of stabilization in extension after cage insertion. It is not clear whether this is a clinical problem which requires supplementary fixation. Extension motion in the lumbar spine is small, approximately 3 degrees per level. It seems reasonable that postoperative rehabilitation which avoids any extension movement may be one way of avoiding this direction. However, supplementary fixation is another potential solution.

Clearly, adding posterior fixation to an interbody cage construct creates the most stable construct. Pedicle screw fixation, translaminar screws, and transfacet screws all produce excellent biomechanical stabilization. It is possible that simpler techniques which focus on the extension direction may be a better solution. For example, Fidler [11] described the clinical use of a H-graft between the spinous processes to supplement interbody bone graft, with excellent results. The inevitable question lies in what degree of immediate stabilization is required to create significant bone growth into the cage and eventual fusion. This question will be answered only by well-controlled prospective clinical investigation.

Implant-vertebra interface strength

The compression strength of the cage-vertebra interface is becoming better understood. It is clear that vertebral bone density plays a very important role in preventing the cage from penetrating into the vertebral body. However, a recent clinical study addressing cage settling did not find a significant correlation between settling and bone density [2]. This suggests that there are other factors which are also of importance to prevent significant cage settling.

Many surgeons emphasize the role of the vertebral end-plate in preventing cage settling. After removal of the cartilaginous end-plate, the subchondral end-plate is often retained to prevent subsidence. However, the biomechanical evidence suggests that the subchondral end-plate does not have a significant role in the strength of the cage-vertebra interface. It is possible that removal of the end-plate will have a small weakening effect of the cage-vertebra interface, but it does not appear to be as significant as once believed. This is perfectly understandable given that the end-plate is dense subchondral bone that is only about 0.25 mm thick [34].

The location of the cage on the end-plate probably has a role in the potential for settling. Steffen et al. [32] suggested that more peripheral contact is probably best from a mechanical and a biological perspective. Additional work in this area would be beneficial.

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