Since the first scoliosis surgery, performed in 1914 by Dr Russell Hibbs, there have been rapid changes and developments in spinal deformity surgery, such as the use of electrocautery, segmental spinal fixation including pedicle screw fixation, and the development of intraoperative neuromonitoring. The development of vertebral osteotomies has certainly contributed a great deal to the advancement of deformity surgery, allowing the deformity surgeon to obtain more correction in rigid deformities.

When surgeons try to decide whether they should correct a deformity, they consider various factors, such as the patient’s chief complaint, neurological status, and medical comorbidities, and the natural course of the deformity. For example, if the main goal of surgery is to relieve leg pain, decompression is the main focus. Careful consideration should be made for older patients due to the high incidence of pseudarthrosis and complications.1

If deformity correction is indicated, the surgeon needs to decide whether a vertebral osteotomy will be required as well. Vertebral osteotomies are necessary if the deformity is too rigid to be corrected with instrumentation alone or with the addition of a posterior ligament release. There are various osteotomy options for correcting deformities, including the Smith-Petersen osteotomy (SPO), pedicle subtraction osteotomy (PSO), and vertebral column resection (VCR). Each osteotomy has different potential in terms of the amount of correction produced. Therefore, each osteotomy is indicated in different situations.

When we consider the indication for each osteotomy, the most important factor is which surgical approach will be performed. There are three options: anterior-only, circumferential, and posterior-only. Recently, more and more scientific articles have been published supporting the safety and efficacy of a posterior-only approach for the treatment of all spinal deformities. Many articles support that this approach is enough even with very rigid or sometimes even fixed deformities.2–4 Therefore, in this article all osteotomies and their indications are based on a posterior-only procedure, which has been our practice for the past 10 years.

Even after deciding which surgical approach will be used, determining the type and extent of the osteotomy is complex and somewhat idiosyncratic.

Abstract
Treatment of patients with deformities should be tailored to their primary complaint. Once correction is indicated, surgeons should choose the surgical approach and the type of corrective methods based on the type of deformity, curve magnitude, stiffness, bone density, operative goals, and surgeon’s experience and comfort level. Current vertebral osteotomy options include Smith-Petersen osteotomy (SPO), pedicle subtraction osteotomy (PSO), and vertebral column resection (VCR), providing correction of both primary sagittal and multiplanar deformity with coronal and sagittal imbalance. It is important to understand sagittal imbalance when determining who is an appropriate candidate for a vertebral osteotomy for deformity correction. Surgeons should determine the amount of angular correction, the amount of bony resection, and fusion levels after careful analysis of pre-operative X-rays. Asymmetrical bony resection and closure of the osteotomy site allows the correction of coronal imbalance. A vertebral osteotomy, especially with a posterior-only approach, is a challenging but safe procedure and can provide excellent correction for severe spinal deformity.

Keywords
Vertebral osteotomy, posterior-only approach, Smith-Petersen osteotomy, pedicle subtraction osteotomy, vertebral column resection, sagittal imbalance, kyphotic angle, fusion level, results, complications, coronal and sagittal imbalance

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and amount of correction. The type of deformity can be classified into one of two categories: predominantly sagittal imbalance or multiplanar deformity with coronal and sagittal imbalance.

**Predominantly Sagittal Imbalance**

*Normal Sagittal Curvature*

What is considered normal sagittal alignment of the thoracic and lumbar regions of the spine varies greatly. Typically, lumbar lordosis is at least 30° greater than thoracic kyphosis. Because of this wide variation, overall sagittal balance is considered more important. The Scoliosis Research Society (SRS) defines sagittal balance as (+) if the C7 plumbline is anterior to the posterosuperior corner of S1 and (-) if posterior. One study showed that the C7 plumbline is within 2.5cm in two-thirds of asymptomatic adults. From another study, we have documented that as patients get older their sagittal plumbline seems to move forward, but more studies are needed to define normal sagittal balance in all age ranges. Another factor to be considered in a normal sagittal curvature is pelvic incidence. Pelvic incidence is defined as “the angle between the line perpendicular to the sacral plate at its midpoint and the line connecting this point to the middle axis of the femoral heads.” Pelvic incidence appears to help to determine the unique lumbar lordosis needed to maintain normal spinal balance.

**Compensated Balance**

Abnormal sagittal alignment or abnormal pelvic incidence can result in normal sagittal balance if compensation can occur. According to the position of the pelvis, two possibilities exist: anteverted or retroverted compensation. Hip extensor muscle weakness or flexion contracture can cause anteversion of the pelvis. In this case, increased lumbar lordosis can compensate for the anteverted pelvis. Flat back syndrome or degenerative lumbar kyphosis can result in a retroverted pelvis. Here, hip and knee flexion can compensate for the retroverted pelvis. However, in the presence of both decreased lumbar lordosis and weakened hip extensors, patients will have decompensation and may be contraindicated for corrective surgery.

**Sagittal Imbalance**

Sagittal imbalance can be caused by one or more of the three factors mentioned above. When we correct sagittal imbalance, all three factors should be considered as much as possible. The severity of symptoms appears to correlate with the amount of sagittal imbalance. Sagittal imbalance can be classified into two types: type 1 (segmental) and type 2 (global). This type of classification is important for determining which osteotomy to perform: SPO versus PSO versus VCR. A third type of combined coronal and sagittal imbalance is also noted.

**Literature Review and Surgical Techniques for Each Osteotomy**

A brief literature review and definition of each osteotomy is necessary to clarify the terminology utilized.

**Smith-Petersen Osteotomy**

The first description of an SPO was in 1945 by Smith-Petersen as a one- or two-level osteotomy for ankylosing spondylitis. Subsequently, multilevel SPO was advocated by many authors for kyphosis correction due to ankylosing spondylitis as well as other pathologies, and currently a multilevel SPO is frequently performed. A multilevel SPO is sometimes referred to as a Ponté osteotomy to give credit to Alberto Ponté, who first described the modern concept of multiple chevron osteotomies with spinal instrumentation on non-fused segments predominately in Scheuermann’s kyphosis. In this manuscript, however, SPO refers to multiple variants of the original SPO instead of referring to it as a Ponté osteotomy. An SPO refers to a posterior column osteotomy in which the posterior ligaments and facet joints are removed and a mobile anterior disc is required for correction (see Figure 1).

**Pedicle Subtraction Osteotomy**

A PSO is referred to as a transpedicular wedge osteotomy, which was first described by Thomasen in 1985. An eggshell osteotomy is a variant of the PSO, which is a transpedicular decancellation closed wedge osteotomy. Both were described in the same year. In this article, a PSO refers to both the wedge osteotomy and eggshell osteotomy. A PSO is performed by removing the posterior elements and pedicles and decancelating the vertebral body, hinging on the anterior cortex. Thus, it involves all three columns (posterior, middle, anterior) of the spine.

**Vertebral Column Resection**

Among the various osteotomy options, a VCR can obtain the largest correction. The VCR was initially described as a combined...
anterior/posterior procedure.\textsuperscript{77} Recently, however, VCR through a posterior-only approach has been advocated for the correction of severe rigid spinal deformities while preventing complications that can result from an anterior approach.\textsuperscript{80} More recently, the posterior VCR was shown to be safe and effective in a large series of patients.\textsuperscript{4} Figure 2 illustrates the step-by-step performance of a posterior VCR, which is removal of the entire vertebra(e), including the discs above and below.

Which Type of Osteotomy Is Required?

Determining which osteotomy should be performed is not easy. To aid in this determination it is helpful to separate sagittal imbalance into two types: type 1 (segmental) and type 2 (global).\textsuperscript{21} Bridwell described general guidelines based on this classification.\textsuperscript{21} Many authors have supported this concept.\textsuperscript{22,23} More recently, spinal deformity was classified according to curve flexibility on pre-operative radiographs, thus leading to a simple decision-making process regarding osteotomy options: type A—flexible (completely correctable); type B—stiff (incompletely correctable); or type C—fixed/stuck (not correctable).\textsuperscript{24} This classification is for sagittal imbalance as well as coronal imbalance, but is described here under sagittal imbalance. In type A, most are primary cases, thus no autofusion is present. These are almost completely correctable and will not need osteotomies for realignment; however, a ligament release and/or facet loosening usually helps. In type B, surgeries are for either primary or revision cases. These curves demonstrate approximately 30–50\% or less flexibility. They incompletely rebalance the C7 plumbline and trunk shift on pre-operative flexibility films, but are certainly correctable to some degree. They may need SPOs to rebalance and/or a PSO for more sagittal plane rebalancing. In type C, most surgeries are revisions except apical autofusions. These curves do not correct on pre-operative radiographs. For revision surgery, previous implants should be removed. These patients will definitely need osteotomies (multilevel SPO, PSO, and/or VCR) to correct their fixed deformity.

How Much Correction Is Required to Obtain Proper Sagittal Balance?

The surgical outcome can be accurately predicted with the formula of thoracic kyphosis (TK), lumbar lordosis (LL), and pelvic incidence (PI) (TK + LL + PI ≤45\%), which shows more than 90\% sensitivity for predicting success at two years after corrective surgery.\textsuperscript{25} Ondra et al. described the mathematical approximation of PSO size based on the C7 plumbline and sagittal balance.\textsuperscript{26}

Correction Obtained with Vertebral Column Shortening—Vertebral Column Shortening versus Angular Correction

Studies have shown that an SPO can achieve approximately 10\% of correction in the sagittal plane at each osteotomy level. A PSO can correct approximately 30–40\% of kyphosis at a level after the osteotomy is closed.\textsuperscript{27} Usually, 1mm of resected posterior bone will equate to approximately 1\% of lordosis once the osteotomy is closed.

Recently, Cho et al. invented two formulas to determine how much angular correction can be obtained in correlation with the amount of vertebral column shortening with a posterior VCR: geometrical and rough approximation (see Figure 3).\textsuperscript{28} With both approximations, the amount of kyphosis correction was estimated precisely. Pre-operative planning can be undertaken with the formula for the geometrical approximation (G),
3. Suk SI, et al., degeneration below the fusion levels. More recently, Chang et al. added
associated with patient comorbidity, pseudarthrosis, and subsequent
Bridwell and colleagues pointed out that poor clinical outcomes are
osteotomies, which is a variant of the PSO. Long-term follow-up of PSOs
PJK as a negative clinical outcome factor of closing–opening wedge
1. Kim YJ, et al., Many authors have reported good results with relatively low complication
Results and Complications

Distal and Proximal Fusion Levels
In the selection of instrumentation and fusion levels for each
osteotomy, there is no golden rule. Generally, both end-instrumented
vertebrae should not be the apex of the kyphotic curve. Also, fusing a
symmetrical number of levels from the apex is important. The sagittal
stable vertebra should be included in the distal fusion level, according to
Cho et al. The proximal fusion level is more difficult to determine.
Proximal junctional kyphosis (PJK) is more common after lower thoracic fusion versus upper thoracic fusion. Surgeons should include the first
lordotic segment if PJK needs to be surgically treated.
From our experience, the four most common causes of failure in
kyphosis correction are: hypercorrection; selecting incorrect proximal and/or distal fusion levels (e.g. failure of including the sagittal stable vertebra or asymmetrical levels fused from the apex); not considering regional kyphotic alignment because the proximal curve is usually larger than the mid-thoracic curve; and screw pull-out due to failure of secure pedicle screws. Especially for SPO correction, good bone quality and solid screw purchase are important.

Results and Complications
Many authors have reported good results with relatively low complication rates after vertebral osteotomies. Reporting good results of PSOs, Bridwell and colleagues pointed out that poor clinical outcomes are associated with patient comorbidity, pseudarthrosis, and subsequent degeneration below the fusion levels. More recently, Chang et al. added PJK as a negative clinical outcome factor of closing–opening wedge osteotomies, which is a variant of the PSO. Long-term follow-up of PSOs
also provided satisfactory clinical and radiographic outcomes despite pseudarthrosis revisions and sagittal decompensations. Complications of PSOs are not different from complications of other spinal surgeries. Regarding neurological complications of PSOs, Buchowski et al. showed an intraoperative or post-operative neurological deficit rate of 11.1%, but only a small number of deficits were permanent (2.8%). Intraoperative hypotension was reported as one of the causes of loss of intraoperative neuromonitoring data during SPO for Scheuermann kyphosis. More recently, Lenke et al. reported relatively low neurological complication rates after posterior-only VCR in 91 patients. In that study, only one patient had a spinal-cord-related neurological deficit, and two patients had transient lumbar root palsies.

Multiplanar Deformity with Coronal and Sagittal Imbalance
Failed deformity surgery or a congenital disorder can result in rigid coronal imbalance, requiring an osteotomy if a revision is necessary. Usually, coronal imbalance is accompanied by sagittal imbalance. Every osteotomy can be utilized in every spectrum of these deformities. Furthermore, the decision-making process is similar to that for pure sagittal imbalance; the only technical difference from pure sagittal imbalance correction is asymmetry of the osteotomy and closure.
In SPOs, the amount of osteotomy and closing force with instrumentation can be asymmetrical to correct coronal imbalance as well as sagittal imbalance. In PSOs, when closing a wedge osteotomy the superior and inferior aspects of the osteotomy can be non-parallel according to the direction of the coronal imbalance: right versus left (see Figure 4). A VCR can also be utilized in severe coronal deformities. Recently, posterior-only VCRs have been performed for severe rigid scoliosis. A hemivertebrectomy is a variant of the VCR and can also be performed through a posterior-only approach (see Figure 5).

Conclusion
It is important to understand sagittal imbalance when determining who is an appropriate candidate for a vertebral osteotomy for deformity correction. Once an osteotomy (or osteotomies) is indicated, careful preoperative assessment of the curve(s) can help to determine which osteotomy is best suited, how much angular correction is needed, how much vertebral column shortening is required, and how many levels should be fused. A vertebral osteotomy, especially with a posterior-only approach, is a challenging but safe procedure and can provide dramatic radiographic and clinical correction for severe spinal deformity.