A New Piece of the Puzzle to Understand Cervical Sagittal Alignment: Utilizing a Novel Angle $\delta$ to Describe the Relationship among T1 Vertebral Body Slope, Cervical Lordosis, and Cervical Sagittal Alignment

Cervical alignment has become increasingly important in the planning of spine surgery. A relationship between the slope of T1 ($T_{1S}$), the cervical lordosis ($CL$), and the overall cervical sagittal vertical axis ($cSVA$) has previously been demonstrated, but the exact nature of this relationship is poorly understood. In this study, we derive theoretical and empirical equations to better understand how $T_{1S}$ and $CL$ affect $cSVA$. The first equation was developed on a theoretical basis using inherent trigonometric relationships of the cervical spine. By treating the cervical spine as the arc of a circumference, and by taking into account the cervical height ($CH$), the geometric relationship between the $T_{1S}$, $CL$, and $cSVA$ was developed via a trigonometric identity utilizing a novel angle $\delta$ subtended by the $CH$ and $cSVA$ ($\delta = T_{1S} - CL/2$). The second equation was developed on an empirical basis by performing a multiple linear regression on data obtained from a retrospective review of a large multicenter deformity database. The theoretical equation determined that the value of $cSVA$ could be expressed as: $cSVA = CH \times \tan(\pi/180 \times (T_{1S} - CL/2))$. The empirical equation determined that value of $cSVA$ could be expressed as: $cSVA = (1.1 \times T_{1S}) - (0.43 \times CL) + 6.69$. In both, the sagittal alignment of the head over the shoulders is directly proportional to the $T_{1S}$ and inversely proportional to $CL/2$. These 2 equations may allow surgeons to better understand how the $CL$ compensates for the $T_{1S}$, to accurately predict the postoperative $cSVA$, and to customize cervical interbody grafts by taking into consideration each individual patient’s specific cervical spine parameters.

**KEY WORDS:** Spinal deformity, Postural balance, Cervical vertebrae, Cervical lordosis, Sagittal alignment

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The reconstruction of the thoracolumbar sagittal alignment is the single most important factor affecting outcome after deformity surgery. However, the extent to which clinical outcomes are affected by cervical malalignment is less established. Nevertheless, an increase in the C2-C7 vertical axis ($C2-C7$), the horizontal distance between the C2 plumb line and superior aspect of C7, whereby the head’s center of gravity lies anterior with respect to C7, has been associated with worse surgical outcomes. Both the C7 and the T1 slopes ($T_{1S}$ – the angle between the superior endplate of the vertebral body and a line horizontal to the floor) correlate with the cervical sagittal vertical axis ($cSVA$). A large “take-off angle” (ie, $T_{1S}$) will induce the cervical spine to lean forward, thus increasing the relative sagittal distance between C2 and C7. The cervical lordosis ($CL$ – the curvature of the cervical spine between C2 and C7 as measured by the Cobb method) buffers this effect; therefore, given two patients with similar T1 slopes, the patient with greater CL will have a correspondingly smaller $cSVA$. Thus, the $cSVA$ has a direct relationship with the $T_{1S}$ and an inverse one with the CL. Accordingly, in order to preserve alignment...
and as previously reported, T1S and CL have a direct correlation.6,8

Several reports have described a correlation among the T1S, CL, and the cSVA; however, the exact relationship is currently unknown. At present, there is no established method to calculate the cSVA solely from the T1S and the CL. Understanding the interactions between these parameters would allow surgeons to calculate the CL necessary to achieve a desired cSVA, to assess if a patient is overcompensating for an abnormal T1S, and to better understand the physiological principles behind the structure of the cervical spine.

In order to address this problem, we designed an equation based on trigonometric relationships to calculate the cSVA in terms of the T1S and the CL. We then compared the results obtained using this method to a new empirical equation derived from a large multicenter deformity database.

**METHODS**

**Theoretical Relationship**

When the aforementioned spinal parameters are considered in the context of the geometry of the cervical spine, they can be defined as follows: using the right triangle shown in Figure 1, the opposite and adjacent sides represent the cSVA and the cervical height (CH – the vertical distance between the anterior aspect of T1 up to the upper endplate of C2) respectively. The angle δ formed between the hypotenuse and CH is such that δ will be larger if the T1S increases and smaller if the cervical spine becomes more lordotic. Thus, the angle δ responds to changes in the T1S and CL in the same way as does the overall cervical sagittal alignment. Herein, we describe potential applications of that knowledge.

To construct a mathematical relationship between the angles δ, T1S, and CL, we assume that the spine section is well approximated by the arc subtended by CL, as displayed in Figure 2, which also depicts 3 important
geometric relationships used to derive the final theoretical formula. First, that \( \beta + \delta = T1S \) (Figure 2), since both are angles between lines that are rigidly rotated by 90 degrees. Second, that the angle \( \beta \) between a chord and the tangent of a circle is half the arc \( CL \) belonging to that chord, i.e., \( \beta = \frac{CL}{2} \) (Figure 2). Third, that the trigonometric identity \( \tan(\delta) = \frac{cSVA}{CH} \) can be used to calculate the \( cSVA \) from measurements of the angle \( \delta \) alongside the \( CH \). Thus, from these derivations it can be seen that:

\[
\delta = T1S - \frac{CL}{2} \\
\tan(\delta) = \frac{cSVA}{CH} \\
cSVA = CH \cdot \tan \left( T1S - \frac{CL}{2} \right).
\]

**Empirical Relationship, Study Design, and Population and Statistical Analysis**

A retrospective review of a prospectively maintained multicenter adult spinal deformity database between 2009 and 2014 was undertaken. The database is composed of consecutive enrolled patients with adult spinal deformity (defined by age >18 yr and one of the following: scoliosis Cobb angle >20 degrees, SVA >50 mm, pelvic tilt (PT) >25 degrees, or thoracic kyphosis >60 degrees). This study was conducted in accordance with the amended Declaration of Helsinki. The database contains de-identified baseline information regarding the demographics, medical comorbidities, clinical examinations, and diagnostic study results of 1053 adult patients with spinal deformity. All 1053 patients within the database were used to derive the following empirical formula. Only data collected at baseline was used for the analysis. All study subjects provided informed consent.

To compare clinical radiographic findings with the theoretical underpinnings of the relationship between SVA, CL, and T1S described previously, we fit a multiple linear regression to predict the average change in \( cSVA \) based on both CL and T1S. The relationship between these two covariates and the \( cSVA \) was assumed to be additive and linear. Mean predicted response (\( cSVA \)) for specific values of CL and T1S were obtained as well as 95% confidence intervals. All analyses were performed in STATA v. 14.1 (StataCorp LP, College Station, Texas).

A sensitivity analysis was then performed to evaluate the diagnostic characteristics of our model to predict an SVA larger than 40 mm in the patients included in our sample.

**RESULTS**

**Geometrical Paradigm**

Analytically, the cervical SVA can be calculated as follows:

\[
cSVA = CH \cdot \tan \left( \frac{\pi}{180} \cdot \left( T1S - \frac{CL}{2} \right) \right).
\]

where \( \pi/180 \) is an expression to transform degrees into radians. This equation agrees with previous findings, which hold that the \( cSVA \) correlates directly with the slope of \( T1 \) and inversely with \( CH \). The relationship between these two variables and the \( cSVA \) was assumed to be additive and linear. Mean predicted response (\( cSVA \)) for specific values of CL and T1S were obtained as well as 95% confidence intervals. All analyses were performed in STATA v. 14.1 (StataCorp LP, College Station, Texas).

**Empirical Paradigm**

A regression analysis on patient data collected from the ISSG database was performed using the method of least squares estimation. This analysis, which was carried out with the intent of deriving a relationship between SVA, T1S, and CL using “real world” patient data, resulted in the equation: \( \text{SVA} = (1.1 \cdot T1S) - (0.43 \cdot CL) + 6.69 \) (R-squared = 0.32, adjusted R-squared = 0.32). In a similar fashion to that of the previous equation, \( cSVA \) is directly proportional to the \( T1S \) and inversely proportional to the \( CL \). Specifically, for a change of one degree in the \( T1S \) the mean estimated change in \( SVA \) is 1.1 mm with \( CL \) as a constant. Conversely, for a 1-degree change in \( CL \), the estimated mean change (point estimate) in \( SVA \) is a decrease in 0.43 mm with \( T1S \) slope as a constant. The estimated confidence intervals for the mean prediction are reported in Table.

**Comparing the Two Approaches**

When compared side-by-side, the empirically derived equation and theoretically derived equation show near identical relationships between \( cSVA \), \( T1S \), and \( CL \), especially for small (and hence physiologic) angles of \( \delta \). As demonstrated below, for small angles...
of $\delta$ the tangent of a given angle is well approximated by the angle itself. Therefore,

$$SVA = CH \times \tan \left( \frac{\pi}{180} \times \left( T1S - \frac{CL}{2} \right) \right)$$

can be simplified to:

$$cSVA \approx CH \times \left( \frac{\pi}{180} \times (T1S - \frac{CL}{2}) \right)$$

or,

$$cSVA \approx CH \times \left( \frac{\pi}{180} \times (T1S - 0.5 \times CL) \right).$$

Because CH and $\frac{\pi}{180}$ remain constant (k)

$$cSVA = k \times (T1S - 0.5\times CL)$$

is similar to

$$cSVA = (1.1 \times T1S) - (0.43 \times CL) + 6.69.$$
DISCUSSION

Cervical sagittal alignment influences outcomes after cervical deformity surgery and cervical fusions in general; correction of the cSVA and restoration of CL correlates with improved postoperative outcomes, higher quality of life, and prevention of disability.4,7,9 Ames et al13 previously described that the T1S determines the amount of CL needed in order to maintain proper alignment of the head center of gravity. Bossierre et al10 found a strong correlation between the CL, the C7 slope, and the cSVA, concluding that the first two somehow determine the latter. Lee et al11 concluded that the T1S was key in determining the cSVA and that a large value would require a great amount of CL in order to preserve a physiological cervical sagittal alignment. In this paper, we have expanded on the aforementioned concepts, describing a precise relation between these parameters. We have derived two simple equations using 2 distinct methods that provide insight into the relationship among cSVA, CL, and T1S.

The first equation, derived using the trigonometric relations inherent to the cervical spine, utilizes the close relationship between the angle $\delta$ and the cSVA. This angle is closely analogous to the angle proposed by Yang and Ondra12 to estimate the angle of resection for a thoracolumbar pedicle subtraction osteotomy. The second equation was derived empirically by retrospectively analyzing cervical spine parameters gathered from a patient database. Per these equations, the cSVA will vary as a direct function of the T1S (a variable that changes after thoracolumbar deformity surgery), and as an inverse function of the CL.

The coincidence of the empirical and the theoretical equations largely depends on how much the CL resembles the arc of a circumference. Although it approximates to one, the lower cervical segments have a larger proportion of the curve in the subaxial cervical spine. In patients with spinal pathology, this becomes more of a problem. The 2 equations will not yield the exact same result. Nevertheless, the theoretical equation does explain the relative contribution of the CL and T1S to the cSVA and also coincides with other empirical formulas published before.11,12 Regardless, if the segment considered is relatively short, as the cervical spine arc is, the two equations will approach to each other because the harmony of the curvature will be less important than in a long arc. A direct application to assess or predict the cSVA should therefore be based on the empirical equation.

The clinical utility of the equations described in this paper is apparent when considering prior literature on the subject of cSVA. For instance, a previous manuscript by Protopsaltis et al13 described improvements in the cSVA after thoracolumbar deformity correction. As expected, diminishing the T1S during thoracolumbar deformity correction proportionally decreased the cervical sagittal malalignment.8 Additionally, patients with preoperative cervical hyperlordosis also experienced compensatory correction of the CL after the T1S was corrected to a more physiologic level.7 These changes are in agreement with the equations described here. Thus, the empirical equation presented here may be used by surgeons planning thoracolumbar deformity correction procedures to estimate the amount of correction achievable in the cSVA and CL following surgical correction of the T1S. The findings presented in this study can also be generalized to other spine surgeries. For instance, a number of cervical spine procedures ranging from simple anterior cervical discectomies to more complex cervical fusions have the potential to alter CL.2 Awareness of preserving or improving the CL is important in the planning of any cervical fusion.

LIMITATIONS

The generalizability of the study is limited by several factors inherent to the study design. Notably, the empirical equation was derived using data from the ISSG database, which is comprised of patients with significant spinal deformities. Even though many of these patients did not have cervical deformity, thoracolumbar abnormalities such as total SVA $>50$ mm, thoracic kyphosis $>60$ degrees, or pelvic tilt $>25$ degrees have the potential to influence the T1S and overall cervical alignment.

Overall, the relationship described here confirms the findings previously described by others: CL compensates for the T1S, and in order to achieve a neutral cSVA the CL needs to be double the T1S. Future research should include validation of this hypothesis on healthy patients and evaluation of its utility to predict the cSVA after thoracolumbar deformity correction.

CONCLUSION

In the present study, we derive two different equations to illustrate the effect of T1 slope and CL on the overall cervical sagittal vertical alignment. One equation was derived on a theoretical basis using purely trigonometric principles; this basis of this equation being the novel angle $\delta$, which responds to changes in T1S and CL in the same way as overall cervical sagittal alignment. The other equation was derived empirically using data from a retrospective analysis of a patient database. The fact that these two equations yield very similar results is testament to the existence of a robust underlying relationship between these three cervical spine parameters. Improving upon these methods by using prospective data from normal patients may allow for a better understanding of spine morphology. This, in turn, will enable more accurate derivations of the cSVA, and potentially yield customized cervical interbody grafts that take into consideration each individual patient’s specific requirements.

DISCLOSURES

The authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article.

REFERENCES


