The principles and planning of deformity correction have been well described.\textsuperscript{1-4} The nomenclature and abbreviations presented herein are adopted from the glossary by Paley.\textsuperscript{1,5} The center of rotation of angulation (CORA) is the point of intersection of the proximal and distal axis lines of an angulated bone. The crossing of the axis lines produces a transverse angle and a longitudinal angle. A line dividing an angle in half is called a bisector line. Each angulation has a transverse bisector line (tBL) and a longitudinal bisector line (lBL). All points on the tBL are also considered CORA.

The neutral CORA is located at the point of intersection of the proximal and distal axis lines of the bone. The axis of correction of angulation (ACA) is the imaginary axis line around which an angular deformity is corrected. It has been shown that when the ACA passes through a CORA, complete colinear realignment of the proximal and distal axis lines occurs.\textsuperscript{1,2,4} When the ACA passes through a CORA concave or convex to the neutral CORA, secondary shortening or lengthening of the bone occurs. When the ACA passes proximal or distal to the bisector line, a secondary translation deformity is produced.\textsuperscript{1,2,4} When the ACA lies on the lBL, no secondary lengthening or shortening occurs. When the ACA lies on the tBL, no secondary translation occurs.

The use of external fixation for limb realignment is well accepted. Principles of deformity correction with circular external fixation have been described based on the fundamental work of Ilizarov.\textsuperscript{5} To achieve realignment of an angular deformity without creating a secondary translation deformity, the axis of the hinges of the Ilizarov apparatus is centered over a CORA on the tBL of the angular deformity. The circular Ilizarov fixator allows hinge placement at any level, including proximal or distal to any ring in a longitudinal direction and concave or convex to the bone in a transverse direction. If the hinge axis is placed at the tBL convex to the neutral CORA, shortening of the bone occurs. If the hinge axis is placed at the tBL concave to the neutral CORA, lengthening of the bone occurs. If the hinge axis is placed proximal or distal to the tBL, secondary translation of the bone occurs. If the hinge axis is located proximal or distal to the tBL and concave or convex to the lBL, secondary length change and secondary translation result.

Unilateral external fixators are more limited regarding hinge or angulator axis placement. Uniplanar fixators use hinges and angulators to correct deformities. Uniplanar hinges are passive devices that require a change in length of the fixator axis. The level of the hinge/angulator is not easily controlled. Axis of correction of angulation can be plotted graphically and secondary deformities calculated trigonometrically. Location of the hinge/angulator can be accurately planned and adjustments incorporated to compensate for expected secondary deformities.

**Calculation and Correction of Secondary Translation Deformities and Secondary Length Deformities**

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body to change their angle. The ACA usually is one cortex of the bone rather than the axis of the hinge. Angulators are active devices that can be directly adjusted to change their angles. The ACA is the axis of rotation of the angulator. Hinges usually are used on the concave side of the deformity, whereas angulators can be used on the concave or convex side. It is difficult to align the hinge or angulator axis exactly on the tBL. When the unilateral fixator hinge or angulator axis is not on the tBL, a secondary translation deformity results. The secondary translation needs to be corrected with translation adjustments of the unilateral external fixator to avoid a fixed translation deformity of the bone axes. Even when the hinge or angulator axis of a unilateral fixator can be initially aligned on the tBL, it is difficult to maintain its level along the tBL.

To achieve realignment of an angular deformity without creating a secondary translation deformity, the axis of the hinges of the Ilizarov apparatus is centered over a CORA on the tBL of the angular deformity.

Figure 1: Calculation of secondary length and secondary translation. Tibial angulation of magnitude $\alpha$ (A). The proximal and distal axis lines of the tibia intersect at the neutral CORA. The tBL and IBL are marked. The Heidelberg external fixator (Smith & Nephew Inc, Memphis, Tenn) with an angulator is templated on the convex side of the varus deformity. The axis of the fixator is the ACA. The [tBL] and [IBL] are measured as the perpendicular distance of the neutral CORA to the BL and tBL, respectively (B). These distances are used in the trigonometric formulae to calculate the amount of secondary translation and secondary length, respectively. Abbreviations: ACA=axis of correction of angulation, IBL=longitudinal bisecting line, n-CORA=neutral central of rotation of angulation, and tBL=transverse bisecting line. (Reprinted with permission from Paley D. Principles of Deformity Correction. Berlin, Germany: Springer-Verlag; 2002. Copyright © 2002.)

Figure 2: Graphic method to determine secondary length and secondary translation. Secondary translation is measured as the distance along the tBL between the arms of the angle $\alpha$. Secondary length is measured by drawing an angle, $\alpha'$ (angle $\alpha$ rotated 90°), centered on the IBL. The secondary length is measured as the distance between the arms of angle $\alpha'$ along the IBL. Abbreviations: IBL=longitudinal bisecting line, SL=secondary length, ST=secondary translation, and tBL=transverse bisecting line. (Reprinted with permission from Paley D. Principles of Deformity Correction. Berlin, Germany: Springer-Verlag; 2002. Copyright © 2002.)

To achieve realignment of an angular deformity without creating a secondary translation deformity, the axis of the hinges of the Ilizarov apparatus is centered over a CORA on the tBL of the angular deformity.

This article presents a simple method to determine the amount of secondary translation or secondary length change that results from different levels and locations of hinge or angulator placement.

Materials and Methods
Bisector Coordinate System
The tBL is perpendicular to the IBL. The neutral CORA is taken as the origin of the reference system. The neutral CORA also is the intersection of the neutral tBL and IBL, which is used as the reference lines for the x,y graphic coordinate system.

With angulators used on the convex side, the ACA corresponds to the central axis of the angulator. With hinges used on the concave side, the ACA is the convex
cortex of the bone. Any ACA can be marked as a point on this graph. The coordinates of this ACA can be defined by two vectors, $t_{BL}$ and $l_{BL}$. The plane of this two-dimensional graph represents the plane of the angular deformity. This corresponds to the radiograph obtained with the x-ray beam perpendicular to the true plane of angulation. The graph can be drawn directly on the radiograph (Figure 1).

Using the $t_{BL}$ and $l_{BL}$ determined graphically, the secondary translation (ST) and secondary length (SL) can be calculated using trigonometric formulae modified from those presented by Ilizarov.

$$SL = 2 \times |t_{BL}| \times \sin(\alpha/2)$$
$$ST = 2 \times |l_{BL}| \times \sin(\alpha/2)$$

Using these formulae, it is possible to calculate every secondary translation and length for every ACA relative to the neutral CORA. The amount of secondary translation and length also can be determined graphically (Figure 2). The perpendicular lines from the ACA to the $l_{BL}$ and $t_{BL}$ are the $t_{BL}$ and $l_{BL}$ of the angulation, respectively ($t_{BL}'$ and $l_{BL}'$, respectively), measured at the ACA (hinge axis). The distance between the central arms of a goniometer opened to the magnitude of angulation $\alpha$ measured along the $t_{BL}$ at its intersection with the hinge $l_{BL}'$ is the amount of secondary length. Similarly, the distance between the arms of a goniometer opened to the magnitude of angulation $\alpha$ measured along the $l_{BL}$ at the intersection with the hinge $t_{BL}'$ is the amount of secondary translation.

**Angulator Placement for Angular Deformity Correction**

Angulators can be used in any location convex to, concave to, or overlying the CORA. The axis of rotation of the angulator becomes the ACA for the bone deformity. The alignment achievable by this mechanism may need to be adjusted for secondary length and translation based on the preoperative planning. Standing long frontal and sagittal plane radiographs are obtained, and the malalignment test and CORA method are performed as pre-
When both frontal and sagittal plane angulations are present, oblique plane analysis is conducted, using trigonometric formulae or the graphic method. The neutral CORA is identified as the intersection point of the proximal and distal anatomic or mechanical axis lines.

The magnitude of the angulation (longitudinal angle) and its complement, the transverse angle (180° minus the magnitude), are measured. The tBL and IBL of these angles are drawn passing through the neutral CORA. They should be perpendicular to each other.

The Heidelberg external fixation system templates (Smith & Nephew Inc, Memphis, Tenn) (or, if another monolateral external fixator is used, the specific templates of that system are used) are used to draw the planned position of the external fixator and pins on the radiograph. The angulator is placed as close as possible to the tBL.

Secondary length and translation can be determined by graphic or trigonometric analysis. For both analyses, the neutral CORA is considered the origin of the graph (0,0) and the perpendicular distance between the ACA and the tBL (|IBL|) and between the ACA and the IBL (|tBL|) are measured (Figure 1). The measurements |IBL| and |tBL| are used to calculate secondary length and translation using the trigonometric formulae.

The circular Ilizarov fixator allows hinge placement at any level, including proximal or distal to any ring in a longitudinal direction and concave or convex to the bone in a transverse direction.

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trigonometric formulae. To determine secondary length and translation from the graph, the base of the angles created by extending the arms of a goniometer from the neutral CORA to the IBL and tBL, respectively, are measured (Figure 2).

Using the Heidelberg external fixation system, expected secondary translation in the plane of the pins can be corrected acutely or gradually using a second pin clamp secured to the pins (Figure 3). This correction can be performed after the secondary translation occurs (usually as an acute correction) or simultaneously with the angular correction (usually with gradual correction). In the latter situation, unwanted translation of the bone ends never occurs because it is corrected by the double clamp mechanism at the same rate as that at which it is produced by the angulator.

Secondary length deformity correction must be combined with the angular correction. This length adjustment is accomplished by lengthening or shortening the telescopic body of the Heidelberg fixator (Figure 3). The amount of length adjustment required with the angular correction to maintain a neutral correction is equal to the secondary length calculation.

Secondary translation also can be corrected using two angulators, making use of the geometric principle that two equal and opposite angulations have the net effect of translation (Figure 4). This method of translation correction can be used in any plane, including the plane of the pins. The amount of angulation and counterangulation ($\tau$) at the two angulators can be determined graphically, or can be calculated trigonometrically knowing only the amount of translation required (ST) and the distance between the two angulators (D).

$$\tau = \tan^{-1}(ST/D)$$

**Hinge Placement for Deformity Correction**

Hinges are used for deformity correction from the concave side. As the fixator body is distracted, a gradual opening wedge correction occurs, pivoting on the convex cortex. Therefore, the convex cortex is the ACA. If the hinge is placed off the bisector line, translation deformity is produced (Figure 5). Because of the translation, the convex cortex does not act as the ACA. The ACA is the hinge axis. If the hinge is placed on the tBL initially, the osteotomy remains aligned without translation by the end of correction. Between the beginning of correction and the end, the bisector line changes its position. At the end of correction, the bisector line is the bisector of the opening wedge angle. It has therefore moved up by an amount that is half the angle of correction. Relative to the final level of the bisector line, the hinge is as far away initially as it is at the end. This causes the bone ends to translate back and forth by the same amount, canceling out any translation deformity produced (Figure 6).

**RESULTS**

This study was conducted to find a simple objective method to predetermine the amounts of secondary translation and length that need to be corrected for different hinge locations. The trigonometric...
and graphic methods described in this study accurately determined the best hinge location and amount of compensatory length and translation correction. Furthermore, with the methods developed by Gladbach et al.,13 Heijens et al.,14 and Pfeil et al.,15 and as illustrated in this study, it is possible to accurately plan and perform gradual deformity correction using monolateral external fixation. This accuracy is similar to that achieved previously with circular external fixation.

The calculation and techniques reported in this study were clinically applied for 2 years and will be the subject of a future comparison with circular external fixation. Although the methodologies reported herein are specifically described for the Heidelberg external fixator, they are generic and can be modified for application with other monolateral external fixators that have hinge or angulator components (eg, Orthofix [Orthofix Inc, Bussellongo, Italy] and DynaFix [EBI Medical Systems, Parsippany, NJ]).

**DISCUSSION**

The CORA method of planning has revealed the relationships between the ACA, CORA, and osteotomy level. These are summarized as osteotomy rules 1 and 2 and a corollary to these rules.1-4 Osteotomy rule 1 states that angular correction with the ACA and the osteotomy passing through the CORA leads to complete colinear realignment of the proximal and distal axes of the bone, without displacement of the bone ends. Osteotomy rule 2 states that when the ACA passes through the CORA but the osteotomy is at a different level, complete colinear realignment of the proximal and distal axis lines occurs, with displacement of the bone ends. Finally, the corollary to these osteotomy rules is that when the ACA and osteotomy do not pass through a CORA, a secondary translation deformity of the proximal and distal axis lines results. These geometric principles apply to osteotomy deformity correction irrespective of the hardware used. These principles have been applied to circular external fixation, and the technical details and consequences of hinge placement have been previously described.1-4,16 Using these techniques, deformity correction with circular external fixation has been shown to be controllable.17

Angular correction using monolateral fixators has also been previously described.9,15,18 Price et al18 recommend acute angular correction following the osteotomy rules. Acute correction with angulation alone or acute translation and angulation yielded excellent results. The limiting factor is the soft-tissue structure at risk.19,20 Gradual deformity correction is less limited by the soft tissues and is therefore safer in many situations.

Gradual deformity correction using monolateral external fixation has been reported.21 Because of lack of consideration of the hinge level, in many cases, secondary translation deformity resulted. Pfeil et al.15 designed an external fixator that could perform gradual angular cor-

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**Figure 6:** To have the convex cortex and not the hinge act as the ACA, the hinge should be placed with the initial start position (hingei) on the initial tBL (tBLi). During deformity correction, the hinge follows the telescopic axis. The hinge migrates proximally by the distance L, which is the length adjustment along the telescopic axis (A). A short translation occurs during hinge migration, caused by the straight path of the ACA migration along the telescopic axis (B). After half the correction, the secondary translation reaches its maximum; by the end of correction, which is half the corrective angle again, the secondary translation is completely corrected. The tBL migrates half the corrective angle to be the final tBL of the resulting opening wedge (C). This translation would not occur if the hinge followed the path of a circle drawn around the ACA instead of the path of a chord across the circle (D). Abbreviations: ACA=axis of correction of angulation, hingei=final hinge, hingei=initial hinge, n-CORA=neutral center of rotation of angulation, and tBL=transverse bisecting line. (Reprinted with permission from Paley D. Principles of Deformity Correction. Berlin, Germany: Springer-Verlag; 2002. Copyright © 2002.)
rection. Pfeil et al 15 and Leyes et al 21 had the same early experience with secondary translation deformity caused by the hinge placement not coinciding with the tBL. To improve the alignment results, Pfeil et al 15 presented methods to compensate for secondary translation and length deformities. Although these methods permit correction of secondary deformities, they do not determine the amount of correction required.

REFERENCES