Shape and Area Measurement Considerations in the Assessment of Diabetic Plantar Ulcers

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Abstract. Ulcer shape is an important determinant of the suitability of simple length (L) by width (W) measurements for the assessment of ulcer area. The present report examines the accuracy of area calculations based on elliptical and rectangular shapes with dimensions based on a consistent measurement rule in which L is the maximum length of the ulcer and W is the maximum dimension perpendicular to L. Accuracies of each calculation model were tested retrospectively using a data set consisting of 83 plantar ulcers in which ulcer tracings were made over a period of up to 16 weeks (1034 individual assessments). Results show overall errors for elliptical and rectangular models as similar, being 7.46 +/- 0.30 percent and 6.90 +/- 0.51 percent with the elliptical model over–estimating and the rectangular model under–estimating actual traced ulcer area. Week–by–week errors did not exceed ten percent for the elliptic model and twelve percent for the rectangular model. Optimization of the calculation models to minimize overall error resulted in a near zero overall error. For the elliptical model, the optimized formula for calculating plantar ulcer area was found to be 0.73LW. Subsequent application of the optimized formula to estimate initial areas of an additional 200 plantar ulcers resulted in an overall error of -0.79 +/- 0.66 percent. In separate analyses, ulcer length and width measurements as obtained via computer image processing were compared with those obtained using a ruler. Results of these comparisons (n = 100) show remarkably small overall differences. There was no significant difference in widths (mean difference -0.49 +/- 1.35 percent), but a small underestimation in length using the direct ruler method was detected (mean difference, 0.96 +/- 0.20 mm, $p < 0.01$ corresponding to an overall error of 4.9 +/- 0.87 percent. The present results (strictly applicable to plantar ulcers) show good week–by–week and overall accuracies in area assessment and also show a good correspondence between computer and ruler measured length and width data. However, the results do not necessarily imply that measurements of L and W are always the method of choice for all wound documentation and tracking purposes. However, the relative simplicity and cost–effectiveness, combined with the demonstrated accuracy of this "old" method when properly done, make it an attractive alternative when more complex methods are not needed, possible or cost–effective.

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Introduction

Wound shape is an interesting, albeit little studied, feature of human skin ulcers.[1–6] The fact that neuropathic plantar ulcers and malleolar ischemic ulcers tend to be "round–like" and venous ulcers tend to be "irregularly" shaped is common knowledge among most clinicians. Beyond this fact, however, there are aspects of wound shape which are of both fundamental and clinical interest. An aspect of concern in this brief

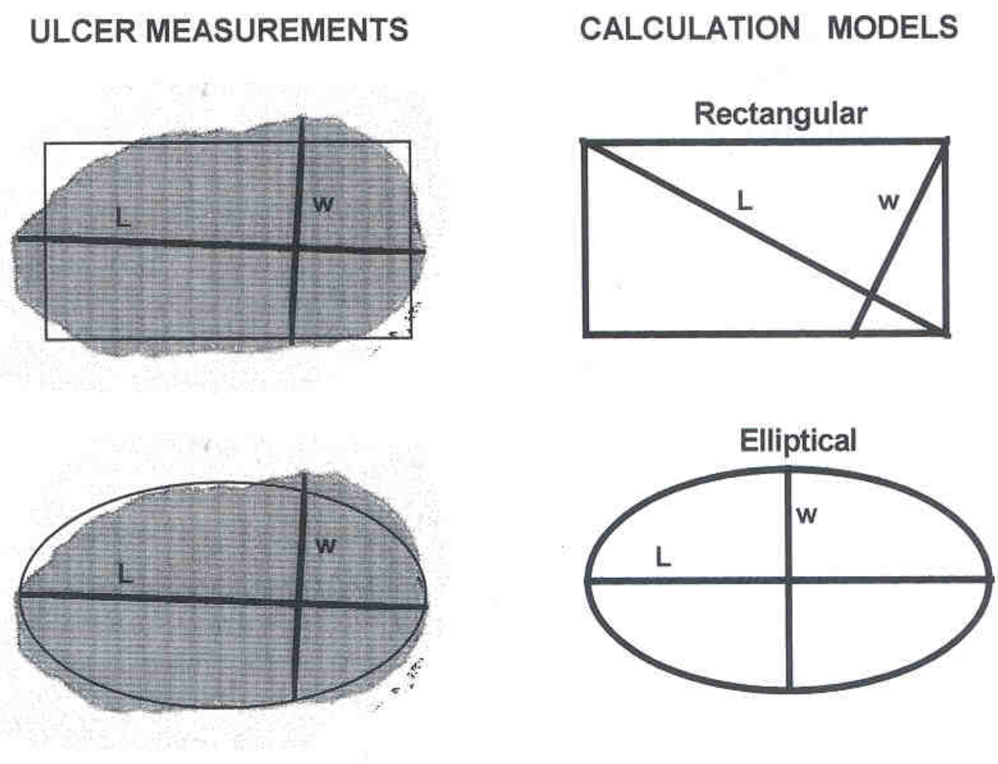

Figure 1. *Illustration of measurements and calculation models. The shaded area is an actual plantar ulcer with a maximum length (L) and perpendicular dimension (W). Superimposed is a rectangle (top) and ellipse (bottom) whose dimensions are as shown on the right part of the figure.*

report is the impact of wound shape on measurement and documentation of ulcer "size" and its progression with treatment.

Although an increasing variety of sophisticated methods have been described and carefully evaluated for wound sizing[7–16] the "old" method of measuring wound length (L) and width (W) is still used, and properly so, by healthcare professionals. In fact, as more ulcers tend to be treated in home healthcare environments, proper application of the length by width method may be more frequently used to help track progression and develop outcome data. It has been noted that this method is easy to use, inexpensive, fast, and has good inter–rater and intra–rater reliability,[17] but perhaps it is deceptively simple. An important aspect is the difficulty of deciding which dimension to initially measure in variously shaped wounds and which follow–up measurements to choose as size and shape progressively change. Here, reference is not being made to inaccuracies in actually performing the measurements, as inaccuracies of various types exist with simple as well as more sophisticated sizing methods.[18] Thus, even if linear measurements, as would be made with a ruler, are assumed accurate, two related questions which impact accuracy face a clinician: 1) how to choose which measurements to make and 2) how well these measurements can be used to estimate ulcer area.

For rectangular wounds there appears to be no issue at all; the measurements to make appear obvious. Measure the "length" and "width" and calculate the area as the product of these two linear measurements. But even in this "simple" case there are still practical problems. Few ulcers are truly rectangular, but even if a reasonable percentage were initially rectangular (or some other regular geometric shape), subsequent choices of "length" and "width" to yield consistent estimates of area change as a result of time and treatment are unclear when there is progressive ulcer shape change over time. One way around this problem may be to define a consistent measurement rule that is independent of the perceived shape of the ulcer. One such rule, as is here put-forward, is to define and measure "length" (L) as the longest line that can be drawn between any two wound edges and "width" (W) as the maximum dimension perpendicular to the line along which the maximum length was measured. Use of such a rule would likely help the clinician choose more consistent and less subjective L and W measurements.

However, because it is not L or W alone that is of exclusive interest, but rather the ulcer area and its progression, an important question remains: How does one best use L and W measurements to adequately characterize wound area and its change? To help provide insight from which one may approach this question, the present brief report focuses on two main issues: ulcer shape and its characterization and ulcer area calculation accuracy based on L and W measurements when applied to diabetic plantar ulcers.

Ulcer Shape Characterization

Length and width. To illustrate some basic concepts via a simple representation, an outline of a traced plantar ulcer is shown on the left part of Figure 1 along with superimposed lines which represent its maximum length (L) and maximum dimension perpendicular to this line (W). Other aspects illustrated in Figure 1 will be dealt with subsequently.

Shape characterization. Most wound shapes, however complex or irregular, can be characterized in terms of a parameter known as a shape factor (SF) which provides a quantitative measure of the degree of "circularity" of the shape. For example, circles have an SF of unity and all other shapes have a value less than unity. The smaller the SF value, the further the shape is from being "circular." A wound SF can be calculated from its actual area (A) and perimeter (p) by the formula:

$$SF = 4\pi(A/p^2).$$

For "regular" geometric shapes such as rectangles, triangles and ellipses, generalized formulae can be derived and used to calculate SFs as a function of L and W, as illustrated in the right part of Figure 1. For these and other shapes, SFs are expressible in terms of a ratio ($R = W/L$) which lies between zero and one. As examples, the SF's for rectangles, ellipses and triangles can be determined from the following formulae (see Appendix 1 for a sample derivation):

Rectangle: $SF = \pi R / (R + 1)^2$
Ellipse: $SF = 2R / (R^2 + 1)$
Triangle: $SF = 2\pi R/\{ 2 + [2(1 - (1 - R^2)^{1/2}]^{1/2} \}^2.$

With the aid of these formulae an examination of some special cases provides further insight. An ellipse with R = 1 has an SF of unity and corresponds to a circle which, as previously noted, has an SF = 1.000. A rectangle with R = 1 has an SF = 0.785 and corresponds to a square. An equilateral triangle (all three sides of equal length) has an R value = 0.867 and a corresponding SF = 0.604. If one imagines a long, skinny area of any shape, the shape factor limit for such an area approaches zero. As a visual aid, Figure 2 shows how the SF varies with R for several shapes.

Area evaluation. If the wound area has a regular geometric shape, then in principle the area is completely determined by the L and W values and is independent of SF. However, precise regular wound geometries are rarely the case in practice and the question arises as to how much error is introduced when an area formula based on a specific geometry is used for wound shapes that deviate from the assumed geometric model. The obvious, albeit subjective, answer is that it depends on the amount of the deviation. To obtain estimates of the error range, consider what error would result if a formula applicable to a rectangular shape were applied to an elliptical or triangular shaped wound. For this estimate it is assumed that L and W of the wounds have been perfectly identified and accurately measured. The result of this simple calculation shows that for the ellipse the error is 21.5 percent and for the triangle 50 percent.

Experimental Methods

Experimental data. To ascertain actual wound shapes and area assessment errors in one class of human wounds, a retrospective analysis of 83 neurotrophic plantar ulcers was done. The raw source material used was kindly supplied to our laboratory for analysis by ProCyte Corporation (Kirkland, WA) and consisted of digitized images

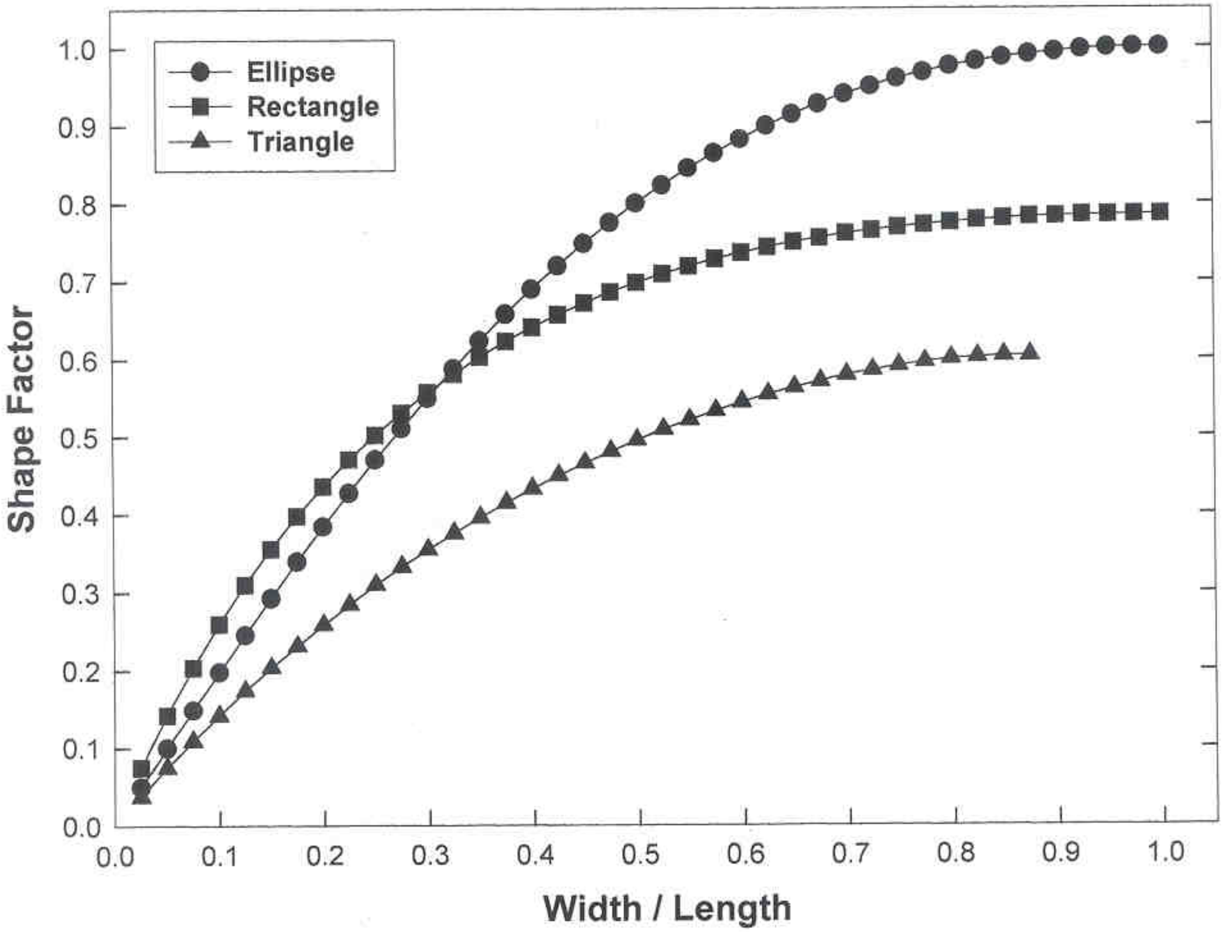

Figure 2. *Shape factor dependence on width/length (W/L) ratio of several regular geometric shapes. Note that for W/L ratios above about 0.3 the elliptical shape has the highest shape factor. If W/L is unity the ellipse is a circle and the rectangle is a square.*

of sequential ulcer tracings for up to 16 sequential weeks. The images were originally obtained as part of a multi–center study. To obtain the necessary metric and shape data for the present study, each image was analyzed as follows. Using imaging processing software (SigmaScan®, Jandel Scientific, San Rafael, CA), four parameters of the ulcer were determined: the perimeter (p), the area contained within the perimeter (A), the maximum length of the area (L), and the maximum width measured perpendicular to the line of maximum length (W). From the measured A and p the shape factor (SF) of the ulcer was determined from the formula $SF = 4(\pi)A/p^2$. The measured L and W values were then used to compute "fictitious" ulcer areas using elliptical and rectangular calculation models to represent the ulcer shape as shown in the right hand part of Figure 1.

For the elliptical shaped model, an area, A_e, was determined by the formula:

$A_e = K_e (\pi/4) LW$ in which the coefficient K_e is unity for a pure ellipse.

The corresponding shape factor of the ellipse was also determined. It should be noted that for an elliptical shape the maximum length and perpendicular width correspond to the principal axes. This is generally not true for a rectangle since L corresponds to the diagonal and W to the maximum length perpendicular to the diagonal. Thus, for the rectangular calculation model, the area, A_r, is not simply LW as it would be if the length and width were chosen as the "horizontal" and "vertical" dimensions of a rectangle. In terms of the maximum measured L and W, which arise from the application of the measurement rule to the ulcer, the area is calculated based on the derived formula:

Table 1
Summary of Pertinent Baseline Geometric Features of the Studied Ulcers

	Area (mm^2)	Perimeter (mm^2)	L (mm)	W (mm)	W/L	SF
Median	186.1	59.3	18.5	14.3	0.78	0.736
Mean	299.3	68.2	21.8	15.3	0.75	0.690
sem	40.5	4.1	1.4	0.8	0.02	0.016

L and W = maximum length and width
SF = shape factor
N = 83

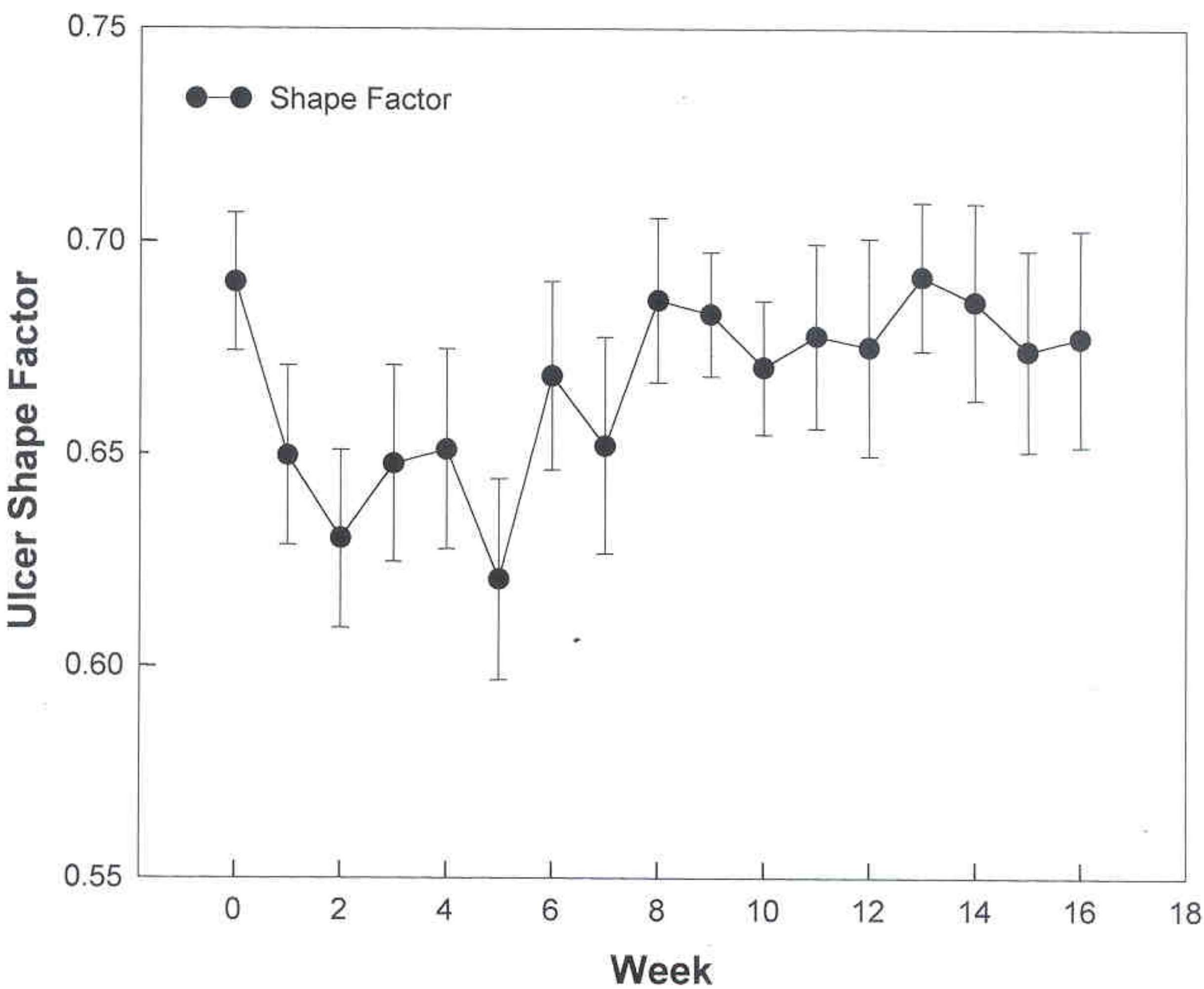

Figure 3. *Plantar ulcer sequential shape factors. Shape factor is proportional to the ratio of actual ulcer area to the square of the perimeter. Solid circles are mean and bars are sem. Data are from 83 patients (ulcers) with a total of 1034 separate measurements.*

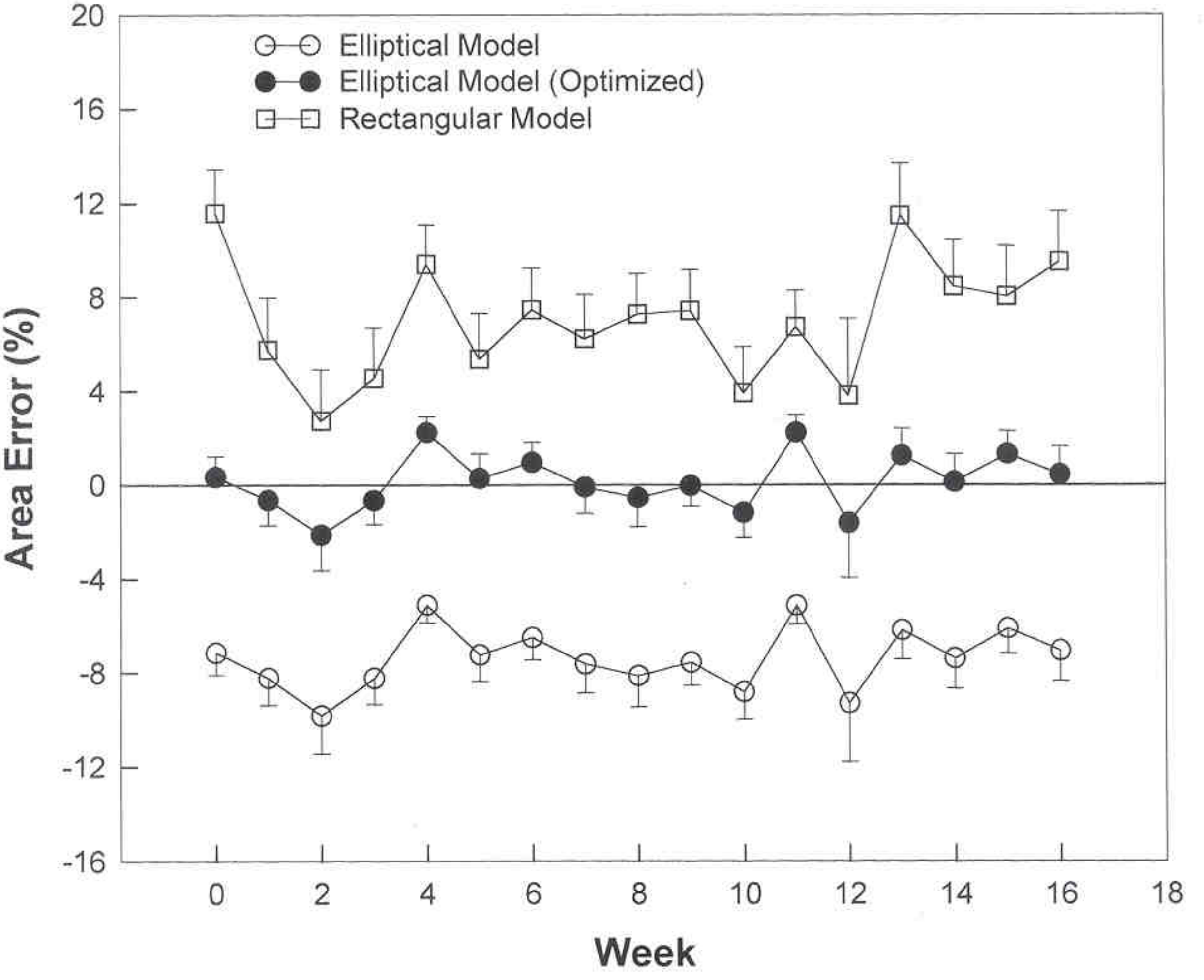

Figure 4. *Week–by–week percentage error in calculated plantar ulcer area. Area errors are calculated as the difference in area between actual area and that calculated by the different geometric models. The optimized model uses a multiplying constant to minimize overall week–by–week error. Data are from 83 patients (ulcers) with a total of 1034 separate error calculations.*

$A_r = (K_r\ LW/2)\ (1 + \cos 2X)$ in which X is the angle whose tangent is W/L .

To test the accuracy of using L and W measurements to determine actual ulcer area, the area as determined by computer–aided planimetry (A) was compared with that computed using the elliptical and rectangular calculation models. This was done by computing the percentage error in area at each visit, calculated as follows:

$A_{er\,r} = 100(A - A_e)/A$ for the ellipse;

$A_{er\,r} = 100(A - A_r)/A$ for the rectangular model.

Negative values for errors represent an overestimation and positive values an underestimation of actual area. Errors were determined for each week (0 through 16) separately and overall using the pure geometric models (K = 1.00). Only patients seen for at least 10 weeks were initially included (N = 83). Subsequently, the value of K (K_e and K_r) which minimized the overall error for the aggregate of 1034 measurements was determined for both the elliptical and rectangular models. Afterwards, the optimized formula obtained from the sequential analysis was used to estimate initial areas of an additional 200 plantar ulcers. In separate analyses, the length and width measurements as obtained on 100 ulcers via computer image processing were compared with those obtained using a ruler.

Results

Ulcer parameters and shape factor. Pertinent geometric characteristics of the studied ulcers as determined at week 0 are summarized in Table 1. As shown in Figure 3, except for an apparent decrease in shape factor during the early weeks of treatment, the ulcer shape factor showed no systematic change over the course of 16 weeks.

Area errors. Elliptic model. The week–by–week error in area assessment using both the pure and modified ellipse models is shown in Figure 4. Modeling the ulcer shape as a pure ellipse results in consistent over–estimation of the true area, but the mean weekly error did not exceed 10 percent. Overall error (weeks 0 to 16, n = 1034) was 7.46 +/- 0.30 percent. The modified (optimized) model which minimized overall error over weeks 0 to 16 required a value of K = 0.93 and resulted in an overall error of 0.06 +/- 0.28 percent with a weekly error less than 2.5 percent. Based on this finding, the optimized formula for the calculation of ulcer area would be A = 0.73 LW. Application of this formula to the additional 200 plantar ulcers resulted in an overall error of -0.79 +/- 0.66 percent. Results of the comparison between computer and ruler measured ulcer length and width showed small overall differences between the two methods. There was no significant difference in widths (mean difference, -0.49 +/-1.35 percent), but a small underestimation in length using the direct ruler method was detected (mean difference, 0.96 +/- 0.20 mm, $p < 0.01$ corresponding to an overall error of 4.9 +/- 0.87 percent.

Rectangular model. The week–by–week error in area assessment using the pure rectangular models ($K_r = 1$) is also shown in Figure 4. It is seen that modeling the ulcer shape as a rectangle results in consistent under–estimation of its area with a mean weekly error not exceeding 12 percent. Overall error (weeks 0 to 16, n = 1034) was 6.90 +/- 0.51 percent. The modified model which minimized overall error required a value of K = 1.07 and resulted in an overall error of 0.38 +/- 0.54 percent with a weekly error less than 5.5 percent (graphic not shown). The fact that the rectangular model under–estimates area (rather than over–estimates as might be expected) is a consequence (and benefit) of the measurement rule used. If one had chosen the measured L and W to correspond to the horizontal and vertical dimension of the rectangular model, a significant and unacceptable over–estimation would result.

Discussion

One goal of the present study was to determine the likely errors in wound area assessment when using a particular measurement method and calculation model. The advocated measurement method consists of measuring the wound maximum length (L) and then locating and measuring the maximum width (W) perpendicular to the line of maximum length. This procedure is applicable to any wound shape as a uniform and consistent method. However, the experimental results here reported with regard to area assessment errors apply only to plantar ulcers. Further, the calculated wound area errors do not include errors associated with initial tracings nor potential errors in the actual measurement of wound L and W. Thus, whereas the selection and measurement of L and W from traced areas using computer image processing software are accurate and consistent, the accuracy and consistency of such measurements (L and W) when done directly on the ulcer would be expected to be more variable. However, based on the analyses of the small deviations between computer and directly measured lengths and widths herein reported, one may reasonably expect good accuaracy in ulcer area calculation using the measurement rule and formula herein developed. The degree to which such accuracy can be achieved by direct wound measurements, as routinely made by wound caregivers in various settings including home healthcare, is currently being evaluated. This issue should be clarified in due course. At this time, however, the error estimates herein obtained may be viewed as a lower bound.

The present results show that both the elliptical and rectangular calculation models provide similar area accuracies when applied to plantar ulcers. The unmodified models yield similar week–by–week errors, with the elliptic model over–estimating and the rectangular model under–estimating the actual area by less than 10 percent and 12 percent respectively. Modification of the calculation models to minimize overall error using an empirical multiplier reduces overall errors for elliptic and rectangular shaped wounds to near zero. Because the correspondence between measured L and W are more readily understandable with the elliptic model, representing their major and minor axes, this author would choose it as the area calculation model and determine plantar ulcer area on the basis of the modified formula:

$$A = K(\pi/4)LW \text{ where } K = 0.93.$$

The present results do not necessarily imply that measuring L and W as here indicated is the method of choice for all wound documentation and tracking purposes. The relative simplicity, cost–effectiveness and the now clearly demonstrated "reasonable" accuracy of this "old" method when properly done should encourage this method of wound measurement when more complex methods are not indicated, needed, possible or cost–effective.

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Appendix 1

Example of Shape Factor (SF) Derivation

Consider an ellipse with a major axis L, a minor axis A and perimeter p (illustrated in Figure 1). The SF, defined by $4\pi A/p^2$, can be represented in terms of L and W by expressing the elliptic area as $\pi/4$ (LW) and perimeter as $\pi[L^2 + W^2/2]^{1/2}$. Substituting these expressions for A and p in the defining shape factor equation and expressing the ratio W/L as R yields, after some manipulation the elliptical shape factor formula shown in the text is obtained. A similar approach can be used to obtain shape factors for other regular geometric shapes.