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A Prospective Study of the PUSH Tool in Diabetic Foot Ulcers

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Abstract

Purpose—The purpose of this study was to examine the predictive validity of PUSH (Pressure Ulcer Scale for Healing; v. 3.0) in monitoring healing of neuropathic foot ulcers in patients with diabetes mellitus.

Design—This is a 13-week descriptive, prospective study describing the trajectory of change over time and the time-to-heal associated with PUSH scores. The study monitored a convenience sample of 18 subjects with Wagner 2 or greater neuropathic, non-ischemic ulcers on the plantar surface of the foot, which healed completely over a 13-week follow-up period. Every two weeks, the study ulcers were evaluated via PUSH. Healing was defined as complete re-epithelialization.

Results—PUSH scores were modeled using a piecewise linear regression. PUSH values decreased significantly ($p < .0001$) at a rate of 0.6656 per week, until two weeks before healing, and then decreased significantly ($p < .0001$) at a rate of 2.2496 per week for the last two weeks of healing. Conversely, the time-to-heal (in weeks) increased significantly ($p < .0001$), at a rate of 0.6412 per each unit increase in PUSH for PUSH values of 4 or less, then significantly ($p < .0001$) increased at a rate of 1.072 for PUSH values greater than 5. In predicting time-to-heal, the sub-item of length $\times$ width alone ($R^2 = .81$) is comparable to the total PUSH score ($R^2 = 0.76$). Individually, exudate ($R^2 = 0.36$) and tissue type ($R^2 = 0.42$) are not nearly as useful as length $\times$ width.

Conclusion—Our findings indicate that PUSH scores significantly decrease over time in healing neuropathic diabetic foot ulcers (DFU) that have no arterial etiologic component. Findings also suggest that total PUSH scores predict time-to-heal for DFU. We showed that a DFU with a PUSH score of 10 would be expected to heal in 8.8 weeks (95% CI: 7.4 – 10.2) and a DFU with a PUSH score of 4 in 2.6 weeks (95% CI: 1.88 – 3.25). Finally, measurements of size alone predict healing time for neuropathic DFU. This finding could greatly simplify clinical assessments.

Introduction

Diabetic foot ulcers (DFUs) are a common type of chronic wound affecting persons with diabetes mellitus. Approximately 15-20% of persons with diabetes will develop a DFU in

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their lifetime.¹ Since the prevalence of diabetes mellitus is 6.3% in the general population and 8.7% among persons 20 years of age and older,² DFUs constitute a significant health concern. Moreover, DFUs are associated with clinically relevant negative outcomes, with 14 to 24% resulting in an amputation.¹

The treatment of DFUs is multifaceted and good clinical care requires attention to adequate off-loading, frequent debridement, proper wound care, treatment of infection, and revascularization of ischemic limbs.³ Clinicians and researchers must be able to monitor healing in DFUs in order to evaluate the effectiveness of specific interventions and prevent complications; DFU that do not heal expediently may be at a greater risk for developing complications.

Methods to predict DFU healing have been examined, including monitoring the change in wound area.⁴ Although the change in wound area was found to be predictive of healing, an observation period of 4 weeks was required to compute the percent change in wound area. A more immediate and less complicated method for predicting healing would provide timely information in busy clinical environments. In 1997, the National Pressure Ulcer Advisory Panel (NPUAP) developed the Pressure Ulcer Scale for Healing (PUSH),⁵ to provide a clinically useful tool for monitoring pressure ulcer healing. Since then, PUSH has been validated as a useful tool for monitoring healing in venous ulcers⁶ and pressure ulcers.⁷⁻⁹ However, it has not been evaluated for use in evaluating healing of DFUs. Moreover, although previous studies of healing in pressure ulcers showed that the PUSH values significantly decrease over time in healing wounds, the magnitude of that decrease has not been described. As a result, the PUSH tool has not been employed to predict the time-to-heal. Because DFUs can lead to serious complications, use of a tool such as PUSH to predict healing time would enable clinicians to identify ulcers that are not progressing as expected. Such differentiation would provide a rational basis for selecting patients most likely to benefit from more expensive, emerging wound treatments such as growth factors and skin equivalents.

The purpose of this study was to examine the predictive validity of PUSH (v. 3.0) in a sample of patients with neuropathic foot ulcers. We posed three questions: 1) What is the trajectory of PUSH (v. 3.0) scores over time for healing diabetic foot ulcers, 2) Can PUSH (v. 3.0) total score predict the time-to-heal, and 3) Which PUSH (v. 3.0) sub-items (i.e., length $\times$ width, amount of exudate, or tissue type) contribute most to the ability of PUSH to predict healing time?

Methods

We employed a prospective descriptive design using a convenience sample. All subjects had DFU and were enrolled in a larger study designed to identify biophysical determinants of healing (NINR R01 NR07721).

A DFU clinic within a tertiary acute care facility served as the study setting. Subjects included persons who had a Wagner 2 or greater neuropathic ulcer on the plantar surface of the foot and were free of peripheral arterial disease, as determined by ipsilateral toe pressures. If subjects had more than one DFU, a single ulcer was selected for data collection using a random coin toss. The treatment of all DFUs was standardized to include moist dressing, regular debridement. All subjects gave informed consent before data was collected. The Institutional Review Board approved all research protocols. Subjects were enrolled from July 2001 through July 2005.

Instrument

PUSH (v. 3.0) comprises 3 items: length $\times$ width, amount of exudate, and tissue type. The total score equals the sum of the integer score of each item. Changes in the total score over time are used to quantify healing progress. The scale for each item begins with zero and a total score of PUSH ranges from 0 to 17 with a total score of zero representing a healed wound (Appendix).

Length $\times$ width is scored by measuring the greatest length (head to toe) and greatest width (side to side) in centimeters and multiplying these two measures. The item is then scored on a 0 to 10 scale based on the surface area measurement (cm^2). Zero represents a healed wound while a score of 10 characterizes a wound greater than 24 cm^2 . Exudate amount is scored on a 0 to 3 scale as none, light, moderate, or heavy, respectively. Tissue type is scored on a 0 to 4 scale as closed, epithelial tissue, granulation tissue, slough, or necrotic tissue, respectively. A score of 4 represents a wound that contains necrotic tissue (e.g., eschar); a score of 3 a wound that contains slough but no eschar; a score of 2 a wound that contains granulation tissue and no slough or necrotic tissue; a score of 1 a superficial wound healing by re-epithelialization only; and a score of 0 a closed wound.

Study Procedures

A trained member of the research team assessed the study subjects' DFUs with the PUSH (v. 3.0). To assess the inter-rater reliability of PUSH scores, Pearson correlations were used to compare the scores from two different team members at 2, 4, 6, 8, and 10 weeks of followup. Averaged across these five time points, the average correlation was 0.93 for the total PUSH score, 0.92 for the length $\times$ width sub-item, 0.91 for the exudate sub-item, and 0.90 for the tissue-type sub-item. A PUSH assessment of each subject's DFU was completed during visits at 1, 3, 5, 7, 9, 11, and 13 weeks. Subjects were followed for a maximum of 13 weeks or until the DFU healed. An ulcer was defined as healed when visual inspection judged the wound surface as re-epithelialized, based on the definition of Margolis, Berlin, and Strom.¹⁰

Data regarding age, gender, race and type of diabetes were obtained from each subject or their medical record. Data regarding ulcer location was obtained via direct observation. Size of the DFU was determined using VevMD software and a digital image of the ulcer. Because of the small number of subjects in our study, covariates were not included in the analysis models, to avoid possible overfitting of models.

Data Analysis

This study included only subjects whose DFU healed during the maximum 13-week follow-up time. Restricting the analysis to these subjects allowed us to model the trajectory of PUSH scores from the point of entry into the study until complete healing. Analyses for each research question are briefly described below.

To answer research question 1 (What is the trajectory of PUSH scores over time for healing diabetic foot ulcers?), the trajectory of PUSH was modeled using time as the independent variable and the PUSH total score as the dependent variable. The time variable was transformed so that zero represented the time of healing; transformed time ranged between $t = -13$ and $t = 0$. Based on the data, the trajectory was modeled using a piecewise-linear regression model consisting of two simple linear regression lines that intersect at $t = -2$ and pass through the origin (see online description). β_1 is the slope within 2 weeks of healing and $(\beta_1 + \beta_2)$ is the slope more than two weeks from healing.

To answer research question 2 (Is PUSH total score useful for predicting time-to-heal?), we treated the variable time-to-heal, which varied from between 0 and 13 weeks, as the dependent (outcome) variable and PUSH total score as the independent (predictor) variable. We then modeled the variable time-to-heal using a piecewise-linear regression model consisting of two simple linear regression lines that intersect halfway between PUSH scores of 4 and 5, with the initial regression line intersecting the origin (see Supplemental Digital Content).

To answer research question 3 (Which sub-items of the PUSH (v. 3.0) most contribute to the predictive ability of PUSH to determine time-to-heal?), time-to-heal was treated as the dependent variable with sub-item scores as the independent variables using a quadratic linear regression model (see Supplemental Digital Content). The proportion of time-to-heal (R^2), explained by each of the sub-items, was computed separately and for each sum of two of the sub-items. Comparing these models allowed us to make conclusions about the relative usefulness of each item for predicting time-to-heal. For all of the models, within-subject correlation of outcomes was taken into account by allowing the slopes to vary across subjects.

Results

Of the 29 subjects in the larger study with PUSH data, 19 healed during the 13-week follow-up period, 4 did not heal during the data collection period, and 6 were excluded because of an infection ($n=4$), skin breakdown ($n=1$), or heart failure episode ($n=1$). Eighteen out of 19 subjects who healed during data collection are included in this analysis; one subject was excluded because his DFU healed in 1 week. The mean age of our subjects was 54.1 ± 11.1 years (mean $\pm$ SD), all subjects were Caucasian, and 12 (66.6 %) were male. Fourteen subjects (77.8%) had Type 2 diabetes mellitus, and 4 had Type 1 diabetes. Eleven DFU (61.1%) were on the metatarsal heads; 6 (33.3%) were on the midfoot; and 1 (5.6%) was on the heel. The mean size of the DFUs was 4.17 cm^2 ($SD=2.093$). The mean and median follow-up times were 7.44 and 6.0 weeks, respectively. The results of the analyses for each research question are described below.

Research Question 1

Figure 1 displays the scatter plot of individual scores, means, and the predicted scores from the fitted piecewise-linear model versus time. Results from fitting the model are displayed in Table 1. Part (a) of Table 1 shows that PUSH scores decreased at a rate of 0.6656 (slope 1 = -0.6656) per week up until two weeks before healing, and then decreased at a rate of 2.2496 (slope 2 = -2.2496) per week for the last two weeks. Both slope 1 and slope 2 were found to be significantly different from zero ($p < .0001$), and the two slopes differed significantly from one another (slope differential: $p < .0001$). The 95% confidence intervals for both slope 1 and slope 2 are reported in part a of Table 1.

Part b of Table 1 presents the fitted model equation. For example, a DFU observed 2 weeks before it healed ($t = -2$) would have an expected PUSH score of 4.50 (-2.2497×-2); and a DFU observed 10 weeks before healing ($t = -10$) would have an expected PUSH score of 9.82 [$-2.2496 \times -10 + 1.5840 \times (-10 - (-2))$]. The visual fit of the model in Figure 1 and the high R^2 value of 0.83 from part c of Table 1 show that the piecewise linear model we constructed adequately approximates the expected PUSH trajectory. The variances and covariances for the random effects are presented in part d of Table 1. For example, $\text{var}(\beta_{1j})$ is the variance of the subject-specific slope1 parameters across the population of subjects (see Supplemental Digital Content for a more detailed explanation of these effects).

Part e of Table 1 presents, for various values of time-to-heal, the predicted PUSH score, with the corresponding 95% confidence interval and the estimated standard deviation. For example, we see that for a DFU that healed in 8 weeks, the predicted PUSH score is 8.49 (95% CI: 7.57 – 9.41). Furthermore, the estimated standard deviation of PUSH scores for DFUs that heal in 8 weeks is 1.78; thus, based on normal distribution properties, we estimate that 95% of the DFUs will have a PUSH score within 3.49 (= 1.96 standard deviations) of the true mean, and 68% will have a PUSH score within 1.78 (= 1.00 standard deviation) of the true mean.

Research Question 2

Figure 2 displays the scatter plot of individual time-to-heal values, means, and the predicted time-to-heal values from the fitted model versus PUSH score. Results from fitting the model are displayed in Table 2. Part a of Table 2 shows that for PUSH values of 4 or less, time-to-heal (in weeks) increased at a rate of 0.6412 (slope 1) per each unit increase in PUSH; then for PUSH values greater than 5, time-to-heal increased at a rate of 1.072. Both slope 1 and slope 2 are significantly different from zero ($p < .0001$), and the two slopes differ significantly from one another (slope differential: $p = .0132$). The 95% confidence intervals for both slope 1 and slope 2 are reported in Part a of Table 2.

Part b of Table 2 presents the fitted model equation; for example, a DFU with a PUSH score of 4 would be expected to heal in 2.6 weeks (0.6412×4) and a DFU with a PUSH score of 10 would be expected to heal in 8.8 weeks [$0.6412 \times 10 + 0.4309 \times (10 - 4.5)$]. The visual fit of the model in Figure 2 and the high R^2 value of 0.761 from part c of Table 2 show that the piecewise linear model adequately approximates the time-to-heal as a function of PUSH. Variances and covariances for the random effects are presented in part d of Table 2.

Part e of Table 2 presents, for various values of PUSH, the predicted time-to-heal with the corresponding 95% confidence interval and the estimated standard deviation of the time-to-heal values. For example, we see that for a DFU with a PUSH = 10, the predicted time-to-heal is 8.78 (95% CI: 7.40 – 10.16). Furthermore, for DFUs with a PUSH = 10, the estimated standard deviation of time-to-heal is 2.39. Thus, we estimate that time-to-heal will be within 4.78 (= 1.96 standard deviations) of the true mean for 95% of these DFUs, and within 2.39 (= 1.00 standard deviation) of the true mean for 68% of these DFUs.

Research Question 3

Table 3 shows the R^2 values, which are based on the quadratic model for the PUSH total score and sub-item scores as predictors. Similar to the analyses for Research Question 2 (Figure 2 and Table 2), time-to-heal was the dependent variable. Note that $R^2 = 0.76$ for both the quadratic (Table 3) and piecewise linear model (Table 2) with PUSH as the predictor. Thus in terms of variance explained, both the quadratic model and the piecewise linear model fit the data equally well, suggesting it is meaningful to make comparisons using the quadratic model. However, we note that the piecewise model is easier to interpret and appeared to fit the data better. In this analysis, we use the quadratic model mainly because it allows us to easily compare the different models.

The sub-item of length $\times$ width alone ($R^2 = 0.77$) performs as well as the PUSH total score ($R^2 = 0.76$). Individually, neither exudate ($R^2 = 0.36$) nor tissue ($R^2 = 0.42$) are as useful as length $\times$ width, nor is the model with the sum of exudate and tissue ($R^2 = 0.46$). Neither of the two models that use the sum of length $\times$ width and either exudate ($R^2 = 0.73$) or tissue ($R^2 = 0.72$) performed as well as length $\times$ width alone ($R^2 = 0.77$).

The plot of time-to-heal versus length $\times$ width, overlaid with the means for each size value, suggested that a regression model for the sub-item of length $\times$ width could be approximated

by a piecewise linear regression model (see Supplemental Digital Content). Figure 3 displays the scatter plot of individual time-to-heal values, means, and the predicted time-to-heal values from this fitted model versus length $\times$ width. Results from fitting model are displayed in Table 4. Part a of Table 4 shows that time-to-heal increased at an estimated rate of 2.3668 (slope 1) for length $\times$ width values of one, then increased at an estimated rate of 1.4171 (slope 2) for length $\times$ width values greater than one. Both slope1 and slope 2 are significantly different from zero ($p < .0001$) and the two slopes differ significantly from one another (slope differential: $p = .0056$). The 95% confidence intervals for both slope 1 and slope 2 are reported in part a of Table 4.

Part b of Table 4 presents the fitted model equation. For example, a DFU with length $\times$ width = 1 would be expected to heal in 2.4 weeks (2.3668×1); and a DFU with length $\times$ width = 5 would be expected to heal in 8.0 weeks [$2.3668 \times 5 - .9497 \times (5 - 1)$]. The visual fit of the model in Figure 3, and the high R^2 value of 0.81 from part c of Table 4, show that the piecewise linear model adequately approximates time-to-heal as a function of length $\times$ width. The variances and covariances for the random effects are presented in part d of Table 4

Part e of Table 1 summarizes the predicted time-to-heal, with a corresponding 95% confidence interval and the estimated standard deviation of time-to-heal values for values of length $\times$ width. For example, we see that for a DFU with length $\times$ width = 5 the predicted time-to-heal is 8.78 weeks (95% CI: 7.40 – 10.16). Furthermore, for DFU's with length $\times$ width = 5 the estimated standard deviation of time-to-heal is 2.13 weeks; thus, we estimate that the time-to-heal will be within 4.17 weeks (1.96 standard deviations) of the true mean for 95% of these DFUs, and within 2.13 weeks (1.00 standard deviation) of the true mean for 68% of the DFUs.

Discussion

The findings of this study indicate that PUSH scores decrease significantly over time in healing neuropathic DFUs that have no arterial etiologic component. This finding is consistent with PUSH scores in healing pressure ulcers.^{8,9} Unlike those analyses, however, this study also models the trajectory of PUSH scores over time. A piecewise linear model allowed us to approximate the change during the 13-week period with a well fitting model ($R^2 = 0.83$). The rate of decrease is estimated to be 0.67 per week up until 2 weeks before healing, after which the rate accelerates to 2.25 per week. Our model allowed us to predict PUSH scores and their variability for a specified time-to-heal. For example, for DFUs observed 10 weeks before healing, the predicted PUSH value was 9.82 (95% CI: 8.68-10.97) and the estimated standard deviation of the PUSH scores was 1.96.

Our findings also suggest that the PUSH tool can predict how long it should take a specific DFU to heal. The model used to predict time-to-heal from PUSH scores showed a good fit ($R^2 = 0.76$). We showed that a DFU with a PUSH score of 10 would be expected to heal in 8.8 weeks (95% CI: 7.4 – 10.2) and a DFU with a PUSH score of 4 in 2.6 weeks (95% CI: 1.88 – 3.25). Estimated standard deviations for time-to-heal for PUSH scores = 10 and 4, respectively, were 2.39 and 1.61 weeks. For example, if our prediction and standard deviation estimates were equal to the true population values, then 95% of DFUs with a PUSH score of 10 would have corresponding times-to-heal between 4.1 and 13.5 weeks [$8.8 \pm 1.96 (2.39)$], showing a fair amount of variability among the DFUs with respect to healing time.

The ability to estimate time-to-heal based on PUSH scores may be more clinically useful than estimates of PUSH score trajectories, because they provide a means to more clearly

identify the projected time within which healing is expected. DFUs that deviate from the projected time interval can be targeted for more aggressive evaluation and treatment. Moreover, the PUSH tool is more straightforward than other methods such as plotting healing progress using wound planimetry from wound tracings or digital images, or mathematical computations of the percent change in wound area.¹¹

Finally, the results of this study suggest that the measure of length $\times$ width predicts healing time as well or better than any of the other sub-items or the sums of two or three sub-items. Our results suggest that the sub-items exudate and tissue type are not valuable in predicting healing time for DFUs. This is consistent with the findings of PUSH scores in pressure ulcers, where researchers determined that “exudate” and “tissue type” do not significantly decrease over time when pressure ulcers are healing.⁸

The findings of our study suggest that the performance of length $\times$ width as a predictor of time-to-heal ($R^2 = .81$ from Table 4) is comparable to that of the total PUSH score ($R^2 = .76$ from Table 2), based on piecewise linear models. This finding is consistent with another study¹² that examined the predictive validity of percent change in wound area calculated from greatest length $\times$ width measurements. In that study, a 53% decrease in the wound area at 4 weeks predicted the wound would heal by 12 weeks. Therefore, it may be concluded that measurements of size alone can monitor and project the healing time of neuropathic DFUs, use of these variables would simplify assessment for progress in healing significantly. Nevertheless, we acknowledge that assessing exudate and tissue type is relatively quick and easy, and these variables provide additional information that drive treatment decisions. Therefore, the small advantage of removing these sub-items from the PUSH score in predicting time-to-heal may not outweigh their added value in local wound assessment. The advantage of PUSH over calculating percent change in wound size over time is the ease of use and elimination of computations.

Limitations

The major limitations of this study were the small sample size and the lack of a comparison group, such as non-healing DFUs and DFUs caused by arterial or mixed disease. Comparing PUSH trajectories between healing and non-healing DFUs would help substantiate the usefulness of PUSH to differentiate healing from non-healing DFUs. Examining the predictive validity of PUSH in a larger sample would allow more precise estimates of time-to-heal parameters, such as expected time-to-heal and the standard deviation for a given independent variable value, allowing for the creation of clinically useful tools, such as prediction intervals for interpreting PUSH scores. In addition, the DFUs in this sample did not have an arterial component and were relatively small. Therefore, the results of this study should not be extrapolated to DFUs with an arterial component and/or those that are large. Further research is needed using larger samples and a comparison group of non-healing DFUs.

Conclusion

Findings from our study indicate that PUSH scores significantly decrease over time in healing neuropathic diabetic foot ulcers (DFU) that have no arterial etiologic component. Our results also suggest that total PUSH scores predict time-to-heal for DFU. We showed that a DFU with a PUSH score of 10 would be expected to heal in 8.8 weeks (95% CI: 7.4 – 10.2) and a DFU with a PUSH score of 4 in 2.6 weeks (95% CI: 1.88 – 3.25). Finally, measurements of size alone predict healing time for neuropathic DFU. This finding could greatly simplify clinical assessments.

Key Points

1. The PUSH tool has been validated as a method to monitor healing in pressure ulcers and venous ulcers.
2. The use of the PUSH tool to predict time to healing would allow the more immediate identification of DFUs that are not progressing as expected.
3. PUSH values significantly decrease over time among healing neuropathic DFUs.
4. PUSH values can be used to predict time-to-heal in neuropathic DFUs.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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References

1. American Diabetes Association. Consensus development conference on diabetic foot wound care. *Diabetes Care*. 1999; 22:1354–1360. [PubMed: 10480782]
2. Center for Disease Control and Prevention. National diabetes fact sheet, department of health and human services for disease control and prevention. 2003.
3. Brem H, Sheehan P, Rosenberg HJ, Schneider JS, Boulton AJ. Evidence-based protocol for diabetic foot ulcers. *Plast Reconstr Surg*. 2006; 117:193S–209S. discussion 210S–211S. [PubMed: 16799388]
4. Sheehan P. Early change in wound area as a predictor of healing in diabetic foot ulcers: Knowing “when to say when”. *Plast Reconstr Surg*. 2006; 117:245S–247S. [PubMed: 16799392]
5. Thomas DR, Rodeheaver GT, Bartolucci AA, et al. Pressure ulcer scale for healing: Derivation and validation of the PUSH tool. *Advances in Wound Care*. 1997; 10:96–101. [PubMed: 9362591]
6. Ratliff CR, Rodeheaver GT. Use of the PUSH tool to measure venous ulcer healing. *Ostomy/wound management*. 2005;51–58. [serial online].
7. Stotts NA, Rodeheaver GT, Thomas DR, et al. An instrument to measure healing in pressure ulcers: Development and validation of the pressure ulcer scale for healing (PUSH). *Journal of Gerontology: Medical Sciences*. 2001; 56A:M795–M799.
8. Gardner SE, Frantz RA, Bergquist S, Shin CD. A prospective study of the pressure ulcer scale for healing (PUSH). *Journals of Gerontology Series A: Biological Sciences & Medical Sciences*. 2005; 60A:93–97.
9. Gunes UY. A prospective study evaluating the pressure ulcer scale for healing (PUSH tool) to assess stage II, stage III, and stage IV pressure ulcers. *Ostomy Wound Manage*. 2009; 55:48–52. [PubMed: 19471048]
10. Margolis D, Berlin JA, Strom BL. Interobserver agreement, sensitivity, and specificity of a “healed” chronic wound. *Wound Repair and Regeneration*. 1996; 4:335–338. [PubMed: 17177729]
11. Berlowitz DR, Ratliff C, Cuddigan J, Rodeheaver GT. The PUSH tool: A survey to determine its perceived usefulness. *Adv Skin Wound Care*. 2005; 18:480–483. [PubMed: 16365545]

12. Sheehan P, Jones P, Giurini JM, Caselli A, Veves A. Percent change in wound area of diabetic foot ulcers over a 4-week period is a robust predictor of complete healing in a 12-week prospective trial. *Plast Reconstr Surg*. 2006; 117:239S–244S. [PubMed: 16799391]
13. Bickel, R. *Multilevel Analysis of Applied Research: It's just Regression*. The Guilford Press; New York: 2007.

Figure 1.
Individual and Mean PUSH Scores and Predicted Scores from the Piecewise Model (1)
Versus Time. (Jitter has been added to separate points with the same value.)

Figure 2.
Individual and Mean Time-to-heal and Predicted Time-to-heal from the Piecewise Model (3)
Versus PUSH Score. (Jitter has been added to separate points with the same value.)

Figure 3. Individual and Mean Time-to-heal and Predicted Time-to-heal from the Piecewise Model (4) Versus Length $\times$ Width Subscore. (Jitter has been added to separate points with the same value.)

Table 1

Results of Piecewise Linear Regression of PUSH on Time-to-heal

a) Parameter Estimates					
Parameter	estimate	SE	Ddf	t	p-value
Slope 1 ($\beta_1 + \beta_2$)	-0.6656	0.0608	9.35	-10.95	<.0001
Slope 2 (β_1)	-2.2496	0.1462	16.20	-15.39	<.0001
Slope differential (β_2)	1.5840	0.1700	14.50	9.32	<.0001

Notes: LCL and UCL denote the lower and upper 95% confidence interval limits; ddf denotes the denominator degrees of freedom; SE = standard error; t and p-value are for testing the null hypothesis that the parameter is zero.

b) Estimated piecewise linear model equation:

$$\text{PUSH} = \begin{cases} -2.2496t + 1.5840[t - (-2)] & -13 \leq t < -2 \\ -2.2496t & -2 \leq t \leq 0 \end{cases}$$

where t = recoded time (weeks) with $t = 0$ denoting the time of healing

c) $R^2 = 0.827$ computed at mean recoded time = -4.66

d) Covariance-variance estimates for random effects for the piecewise linear model:

$$\begin{aligned} \text{var}(\beta_{1,j}) &= 0.2197, \text{cov}(\beta_{1,j}, \beta_{2,j}) = -0.1936, \text{var}(\beta_{2,j}) = 0.1832, \text{var}(e_{ij}) = 1.1036 \\ \text{var}(\beta_{1,j} + \beta_{2,j}) &= \text{var}(\beta_{ij}) + \text{var}(\beta_{2,j}) + 2\text{cov}(\beta_{1,j}, \beta_{2,j}) = 0.157 \end{aligned}$$

e) Predicted PUSH score with 95% confidence interval and estimated PUSH standard deviation for various time-to-heal values					
time-to-heal (wks)	Predicted	LCL	UCL	SD	
2	4.50	3.88	5.12	1.41	
4	5.83	5.21	6.45	1.50	
6	7.16	6.43	7.89	1.63	
8	8.49	7.57	9.41	1.78	
10	9.82	8.68	10.97	1.96	

Notes: LCL and UCL denote the lower and upper 95% confidence interval limits for the predicted value; SD is the estimated standard deviation for the PUSH scores. For example, for time-to-heal = 10 (thus $t = -10$) the predicted PUSH value 9.82 was computed using $-2.2496t + 1.5840(t - (-2)) = -2.2496(-10) + 1.5840(-8)$, and the SD value 1.96 was computed using

$$\begin{aligned} & \text{var}(\beta_{1j})t^2 \\ & + \text{var}(\beta_{2j})(t - (-2))^2 \\ & + 2 \text{cov}(\beta_{1j}, \beta_{2j})t(t - (-2)) \\ & - (-2) + \text{var}(\varepsilon_{ij}) = 0.2197(-10)^2 + 2(-0.1936)(-10)(-8) + 1.1036 \end{aligned}$$

Note that the recoded time t is the negative of the time-to-heal. LCL and UCL were computed by PROC MIXED.

Table 2

Results for Piecewise Linear Regression of Time-to-heal on PUSH

a) Parameter estimates						
Parameter	estimate	SE	Ddf	t	p-value	LCL UCL
Slope1 (β_1)	0.6412	0.07754	11.00	8.27	<.0001	0.4705 0.8188
Slope2 ($\beta_1 + \beta_2$)	1.0720	0.10970	9.65	9.78	<.0001	0.8265 1.3176
Slope differential (β_2)	0.4309	0.15000	12.90	2.87	0.0132	0.1066 0.7552
Notes: LCL and UCL denote the lower and upper 95% confidence interval limits; ddf denotes the denominator degrees of freedom; SE = standard error; t and p-value are for testing the null hypothesis that the parameter is zero.						
b) Estimated piecewise linear model equation:						
$\text{Time to heal (weeks)} = \begin{cases} 0.6412(\text{PUSH}) & 0 \leq \text{PUSH} \leq 4.5 \\ 0.6412(\text{PUSH}) + 0.4309(\text{PUSH} - 4.5) & 4.5 < \text{PUSH} \end{cases}$						
c) $R^2 = .761$ evaluated at mean PUSH = 5.62						
d) Covariance-variance estimates for random effects for the piecewise linear model:						
$\begin{aligned} \text{var}(\beta_{1,j}) &= 0.04290, \text{var}(\beta_{2,j}) = 0.02417, \text{cov}(\beta_{1,j}, \beta_{2,j}) = -0.01112, \text{var}(e_{ij}) = 1.9210 \\ \text{var}(\beta_{1,j} + \beta_{2,j}) &= \text{var}(\beta_{1,j}) + \text{var}(\beta_{2,j}) + 2 \text{cov}(\beta_{1,j}, \beta_{2,j}) = 0.04483 \end{aligned}$						

e) Predicted time-to-heal with 95% confidence interval and estimated time-to-heal standard deviation for various time-to-heal values				
PUSH	Predicted	LCL	UCL	SD
2	1.28	0.94	1.62	1.45
4	2.56	1.88	3.25	1.61
6	4.49	3.76	5.23	1.82
8	6.64	5.67	7.61	2.08
10	8.78	7.40	10.16	2.39
12	10.93	9.09	12.76	2.73
14	13.07	10.76	15.37	3.09

Notes: LCL and UCL denote the lower and upper 95% confidence interval limits for the predicted value; SD is the estimated standard deviation for the time-to-heal outcomes. For example, denoting PUSH by y , for $y = 10$ the predicted time-to-heal value of 8.78 was computed using $0.6412y + 0.4309$ ($y - (4.5) = 0.6412(10) + 0.4309(5.5)$), and the SD value 2.39 was computed using

$$\begin{aligned} & \text{var}(\beta_{1j})y^2 \\ & + \text{var}(\beta_{2j})(y - (4.5))^2 \\ & + 2 \text{cov}(\beta_{1j}, \beta_{2j})y(y - (4.5)) \\ & - (4.5) + \text{var}(\varepsilon_{ij}) = 0.04290(10)^2 + 0.02417(5.5)^2 + 2(-0.01112(10)(5.5) + 1.9210) \end{aligned}$$

. LCL and UCL were computed by PROC MIXED.

Table 3

R² Values for Quadratic Regression Models with Time-to-heal as a Dependent Variable.

Independent variable	R^2
total score	0.76
length $\times$ width	0.77
Exudate	0.36
Tissue	0.42
(length $\times$ width + exudate) sum	0.73
(length $\times$ width + tissue) sum	0.72
(exudate + tissue) sum	0.47

Note: Each R^2 value is evaluated at the mean of the independent variable.

Table 4
Results of Piecewise Linear Regression of Time-to-heal on Length $\times$ Width Using Model (3)

a) Parameter estimates for the piecewise linear model with time-to-heal as the outcome						
Parameter	estimate	SE	Ddf	t	p-value	LCL UCL
Slope1 (β_1)	2.3668	0.2567	90.9	9.22	<.0001	1.8569 2.8766
Slope2 ($\beta_1 + \beta_2$)	1.4171	0.1404	25.3	10.10	<.0001	1.1282 1.7060
Slope differential (β_2)	-0.9497	0.3346	90.3	-2.84	0.0056	-1.6143 -0.2850
Notes: LCL and UCL denote the lower and upper 95% confidence interval limits; ddf denotes the denominator degrees of freedom; SE = standard error; t and p-value are for testing the null hypothesis that the parameter is zero.						
b) Estimated piecewise linear model equation:						
$\text{Time to heal (weeks)} = \begin{cases} 2.3668(L \times W) & 0 \leq L \times W \leq 1 \\ 2.3668(L \times W) - 0.9497(L \times W - 1) & 1 < L \times W \end{cases}$						
where $L \times W = \text{length} \times \text{width}$						
c) $R^2 = 0.812$, evaluated at mean size = 2.65						
d) Covariance-variance estimates for random effects for the piecewise linear model:						
$\begin{aligned} \text{var}(\beta_{1,j}) &= 0.1125, \text{var}(\beta_{2,j}) = 0.0000, \text{cov}(\beta_{1,j}, \beta_{2,j}) = 0.0000, \text{var}(e_{ij}) = 1.7050 \\ \text{var}(\beta_{1,j} + \beta_{2,j}) &= \text{var}(\beta_{1,j}) + \text{var}(\beta_{2,j}) + 2 \text{cov}(\beta_{1,j}, \beta_{2,j}) = .1125 \end{aligned}$						

e) Predicted time-to-heal with 95% confidence interval and estimated time-to-heal standard deviation for various length $\times$ width values				
Length $\times$ width	Predicted	LCL	UCL	SD
1	2.37	1.86	2.88	1.35
2	3.78	3.29	4.28	1.47
3	5.20	4.55	5.85	1.65
4	6.62	5.74	7.50	1.87
5	8.04	6.90	9.17	2.13
6	9.45	8.05	10.86	2.40
7	10.87	9.19	12.55	2.69

Notes: LCL and UCL denote the lower and upper 95% confidence interval limits for the predicted time-to-heal value; SD is the estimated standard deviation for the time-to-heal outcomes. For example, denoting length $\times$ width by $L \times W$, for $L \times W = 5$, the predicted time-to-heal value of 8.04 was computed using $2.3668(L \times W) - 0.9497(L \times W - 1) = 2.3668(5) - 0.9497(4)$, and the SD value 2.13 was

$$\begin{aligned} &\text{var}(\beta_{1j})(L \times W)^2 \text{var}(\beta_{2j})(L \times W - 1)^2 \\ &\quad + 2 \text{cov}(\beta_{1j}, \beta_{2j})(L \\ &\quad \times W - 1) + \text{var}(\varepsilon_{ij}) \\ &= 0.1125(5)^2 \\ &\quad + 0.0000(4)^2 \\ &\quad + 2(0.0000)(5)(4) + 1.7050 \end{aligned}$$

computed using . LCL and UCL were computed by PROC MIXED.