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Improving the accuracy of skin elasticity measurement by using Q-parameters in Cutometer

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Synopsis

The skin elasticity parameters (Ue, Uv, Uf, Ur, Ua, and R0 through R9) in the Cutometer are widely used for *in vivo* measurement of skin elasticity. Their accuracy, however, is impaired by the inadequacy of the definition of a key parameter, the time point of 0.1 s, which separates the elastic and viscoelastic responses of human skin. This study shows why an inflection point (t_{IP}) should be calculated from each individual response curve to define skin elasticity, and how the *Q*-parameters are defined in the Cutometer. By analyzing the strain versus time curves of some pure elastic standards and of a population of 746 human volunteers, a method of determining the t_{IP} from each mode 1 response curve was established. The results showed a wide distribution of this parameter ranging from 0.11 to 0.19 s, demonstrating that the current single-valued empirical parameter of 0.1 s was not adequate to represent this property of skin. A set of area-based skin viscoelastic parameters were also defined. The biological elasticity thus obtained correlated well with the study volunteers' chronological age which was statistically significant. We conclude that the *Q*-parameters are more accurate than the *U* and *R* parameters and should be used to improve measurement accuracy of human skin elasticity.

INTRODUCTION

Skin elasticity is an important biomechanical property of human skin, and the Cutometer® (Courage + Khazaka Electronic GmbH, Cologne, Germany) is the most widely used instrument for noninvasive measurement of skin elasticity. Extensive studies have been reported using the Cutometer to understand skin elastic properties in relation to age, gender, and race (1–6), to correlate elasticity with skin hydration state (7–8), and to detect changes in diseased skin and quantify treatment effects (9–13).

Of the elasticity studies using the Cutometer, the vast majority used the *U* parameters (Ue, Uv, Uf, Ur, and Ua) under mode 1 conditions as described by Barel *et al.* (14). In a typical elasticity measurement, a constant negative pressure is applied to the skin and a response curve is generated showing the deformation or elongation of the skin versus time in both the suction and relaxation phases. Based on the curve, the *U* parameters are determined and used to calculate various skin elasticity parameters (R0 through R9) (15). Among the R parameters, *R*7 (*Ur*/*Uf*), which is often referred to as the "biological elasticity" since it measures the skin's ability to return to its initial position following deformation (3), has been found to decrease with age in several studies (2,4,5).

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Despite the numerous statistically significant correlations reported in the literature, researchers feel that the Cutometer is not accurate enough to measure relatively small magnitude changes in skin elasticity. Murray and Wickett compared the elasticity of dry and moisturized skin, but observed no significant changes in the elastic parameters Ur/Ue and Ur/Uf (16). Neto *et al.* noted the complex and inconsistent use of the U parameters reported in the literature, and argue that the current analysis of multiple U parameters does not seem to add relevant data for the study of skin elasticity (17), pointing to the confusion and limitations of this method.

In an attempt to improve accuracy, we reviewed the definition of the current U-parameters and identified one critical parameter that might have contributed to the perceived inaccuracy in Cutometer skin elasticity measurement. The parameter was the time during which the immediate elastic deformation in the suction phase, or the elastic return in the relaxation phase, took place. Currently, this time is defined by an empirical value of 0.1 s in the Cutometer mode 1 computational algorithms. It is then used to calculate the viscoelastic parameters of Ue, Uv, Ur, and the R parameters $R5$, $R6$, and $R7$, through the following definitions (15):

$$Ue = e(0.1), \qquad Uv = e(a) - e(0.1), \qquad Ur = e(a) - e(a + 0.1)$$

$$R5 = Ur/Ue, \qquad R6 = Uv/Ue, \qquad R7 = Ur/Uf$$

where, e is the elongation or deformation measured at a given time point, the number 0.1 is the time in seconds after the start of the suction or relaxation phase, and a is the measuring time of the suction phase.

When we examined the properties of this critical parameter, we asked a basic question: how closely would the use of this empirical, single-value parameter represent individual skin properties knowing that there exists a wide variation in skin properties among the general population? Therefore, the aim of this study was to show why and how this parameter should be redefined in order to improve the accuracy of skin elasticity measurements. Since 2009, the algorithms and the new skin elasticity parameters thus defined have been adopted in the Cutometer analysis software as the Q-parameters. The technical details of these parameters, however, have not been reported until now.

MATERIAL AND METHODS

CUTOMETER SETTINGS

The elasticity of skin and other materials were evaluated using a Cutometer MPA 580 (Courage + Khazaka Electronic GmbH, Cologne, Germany) with a 2-mm aperture probe. The negative pressure (vacuum) was set at 450 mbar and a single cycle mode 1 measurement performed. The duration of the suction and relaxation phases was 2 s each.

PURE ELASTIC MATERIAL

Cured super-soft silicone rubber pieces, Ecoflex 5 and Ecoflex 0–10 (Smooth-On, Inc., Easton, PA), were used as pure elastic standards for the elasticity measurements.

The pieces had a flat and smooth surface with hardness scores of Shore 5A and Shore 0–10, respectively.

IN VIVO HUMAN SKIN ELASTICITY MEASUREMENT

The strain versus time curves of mode 1 measurement were collected from the database of our laboratory, in which numerous previously conducted clinical studies were archived. The studies were carried out in West Michigan of the United States and followed the guidelines of human clinical study on skin property testing. Volunteers of both genders in the age range of 18–82 years old and of various ethnicities (Caucasian, Asian, Hispanic, and African American) living in the United States participated those studies. In each study, the participants were asked to remove their facial makeup and cleanse the skin sites. Following acclimation to room temperature for 15 min, skin elasticity was measured in triplicate on each test site (the cheek or the inner forearm). The individual response curves of strain versus time were saved for calculation of the inflection points (t_{IP}s) and other skin elasticity parameters.

DETERMINATION OF INFLECTION POINT

A computational algorithm was developed to calculate the t_{IP} from each of the mode 1 response curves. Since the elastic property of a material is represented by the linear region of the response curve, the t_{IP} in a mode 1 response curve is defined as the point at which the curve begins to deviate from the linear region to a nonlinear viscoelastic region, as shown by t_{IP} on the time scale in Figure 1. The algorithm was written in Visual Basic and the calculations carried out using Microsoft Excel (Microsoft Corporation, Redmond, WA) to process multiple response curves in a batch mode.

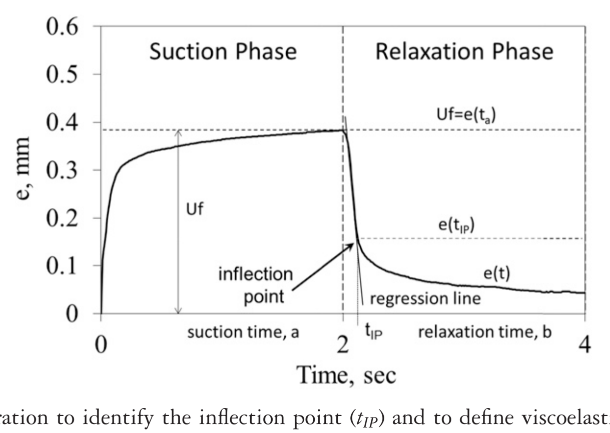

Figure 1. An illustration to identify the inflection point (t_{IP}) and to define viscoelastic parameters from a typical mode 1 strain versus time response curve of human skin. In the diagram, $e(t)$ is the mathematical function of the response curve. The t_{IP} is defined as the time in the relaxation phase when $e(t)$ begins to deviate from the linear regression line of the elastic recovery region. The right-angled trapezoid bordered by $e(t_a)$, $e(t_{IP})$, and the regression line is hence the elastic recovery area, and the remaining area bordered by $e(t_{IP})$ and $e(t)$ is that of the viscoelastic recovery.

RESULTS AND DISCUSSION

RESPONSE CURVE OF PURE ELASTIC MATERIAL

Under the current theory, the Cutometer elasticity measurement for an ideal elastic material should produce a linear response in the strain versus time curve under the mode 1 testing conditions. In our study, we first examined the linearity of the response curves using silicone rubber slabs as pure elastic standard. That test produced near perfect linear response curves (the elastic deformation region before reaching the plateau) in the relaxation phase when tested under various negative pressure settings (Figure 2). However, the response was not as linear in the suction phase. The coefficient of determination values (r^2) for the relaxation and suction phases were 0.991 ± 0.006 and 0.956 ± 0.029, respectively. These results suggest that the relaxation phase reflects the ideal elastic property more accurately than the suction phase, and should be the region used for skin elasticity measurements.

INFLECTION POINT

For the combined study populations in the database, we calculated the individual t_{IP}s in the relaxation phase from the 4234 response curves of the cheek and forearm sites. The t_{IP} values thus obtained had a distribution ranging from 0.11 to 0.19 s, with a mean value of 0.14 s, as shown by the histogram in Figure 3. Comparing these actual values to the single empirical value of 0.1 s, we can see how much error in elasticity measurements could have been introduced to the calculation of *U* and *R* parameters. Calculating the values of parameter *R*7 (*Ur*/*Uf*) using their corresponding t_{IP}s and compare them with the *R*7 values based on the single empirical value of 0.1 s, we found that the new method produced higher values of *Ur*/*Uf* by an average of 0.184 unit, which is a 46.3% increase in skin biological elasticity. Since the t_{IP} was calculated from each individual response curve, we believe the skin elasticity thus obtained is more accurate than the previous empirical approximation method.

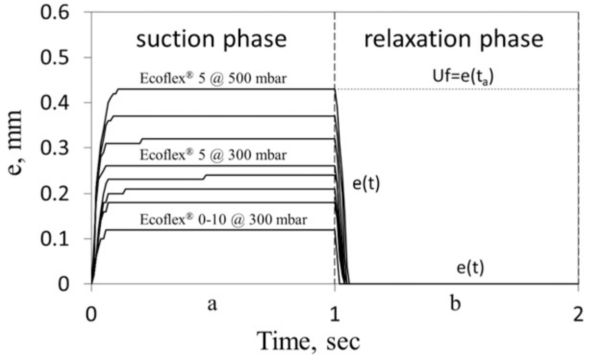

Figure 2. The response curves of pure elastic standards (silicone rubber, Ecoflex 5, and Ecoflex 0–10) at various negative pressure settings. Ideal elastic recovery (E_R) is seen in the relaxation phase on the right side of the chart. The E_R of Ecoflex 5 at 500 mbar is represented by the right-angled trapezoid bordered by lines of $e(t_a)$ and $e(t)$.

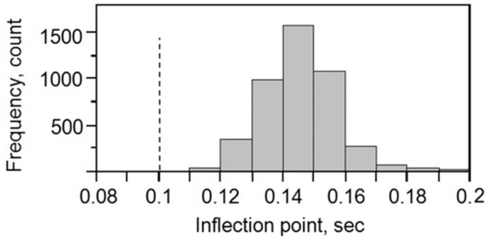

Figure 3. Distribution of the inflection points (t_{IP}) determined from 4234 response curves of people of different age, gender, and ethnicity. The parameter was determined in the relaxation phase of response curves of cheek and forearm skin sites. Grey bars = frequency distribution of t_{IP} values; Dashed line = the single-valued empirical parameter of 0.1 s.

DEFINING NEW VISCOELASTIC PARAMETERS OF SKIN

Using the individually determined t_{IP}s, we could calculate the elastic and viscoelastic properties from each individual response curve. For the pure elastic standard material, its deformation completely recovers in the relaxation phase. Using the areas above the curve to represent this recovery, we defined the ideal elastic recovery (E_R) as the area bordered by the relaxation curve and the maximum amplitude, *Uf*. As illustrated in Figure 2, the area for the response curve of Ecoflex 5 at 500 mbar is the right-angled trapezoid in the relaxation phase, and its corresponding mathematical representation (R_E) is given in equation (1). Comparing R_E to the total area of the relaxation phase, $R0$ [equation (2)], we obtained the elastic recovery of the pure elastic material, E_R, as the ratio of R_E and $R0$ [equation (3)].

$$R_E = \int_0^b \left(U_f - e(t)\right) \mathrm{d}t \tag{1}$$

$$R0 = U_f b \tag{2}$$

$$E_R = R_E / R0 \tag{3}$$

For the human skin, we could calculate the E_R using the above equations from the corresponding response curves. Since the t_{IP} separates the elastic and viscoelastic responses, the E_R of skin is graphically represented by the trapezoid bordered by $e(t_a)$ and $e(t_{IP})$ in Figure 1. Then, the viscoelastic recovery (V_R) can be quantified by the area within the boundaries of $e(t_{IP})$ and $e(t)$. Their corresponding mathematical representations are shown as:

E_R area:

$$R_E = \left(U_f - e(t_{IP})\right)(b - t_{IP}) + \int_0^{t_{IP}} \left(U_f - e(t)\right) \mathrm{d}t \tag{4}$$

V_R area:

$$R_V = \int_{t_{IP}}^{b} \left[e(t_{IP}) - e(t)\right] \mathrm{d}t \tag{5}$$

The skin's E_R and V_R can then be defined as:

$$E_R = \frac{R_E}{R0},\ V_R = \frac{R_V}{R0} \qquad (6)$$

And the total elasticity:

$$T_R = E_R + V_R \qquad (7)$$

Since these values are area ratios, E_R, V_R, and T_R are dimensionless quantities which result in values between 0 and 1, with the higher values of E_R and T_R indicating more elastic skin. Particularly, the parameter E_R is an area-ratio representation of the R7 (*Ur*/*Uf*) which describes the elastic recovery of the skin after distortion. Setting the suction and relaxation time of *a* and *b* equaling to 2 s, the resulting elastic parameters can be compared among different people and skin sites. The relationship of those parameters to the corresponding *Q*-parameters in the current Cutometer analysis software are the following:

$$R0 = Q_0, \qquad R_E = Q_E, \qquad R_V = Q_R,$$

$$T_R = Q_1, \qquad E_R = Q_2, \qquad V_R = Q_3.$$

From our database of 746 volunteers of different age, gender, and ethnicity, we calculated the values of *Q*2 and plotted them in Figure 4 to show the distribution of this elastic property in general population. The mean *Q*2 value in this population was 0.511 with a standard deviation of 0.146 and the maximum and minimum values of 0.858 and 0.186, respectively.

AGE EFFECT ON SKIN VISCOELASTIC PROPERTIES

Using the *Q*-parameters, we calculated skin E_R and V_R from a population of 463 female Caucasian volunteers, and the results were correlated with their chronological age (Figure 5). These results show that the E_R or Q_2 decreased with age in a logarithmic fashion with $r^2 = 0.664$. The V_R, Q_3, increased slightly with age but the correlation was less strong than the E_R ($r^2 = 0.5352$). These results agree directionally with the age-elasticity correlation reported in the literature (18). The observed increase in age correlation was a direct result of the increased measurement accuracy of the *Q*-parameter method.

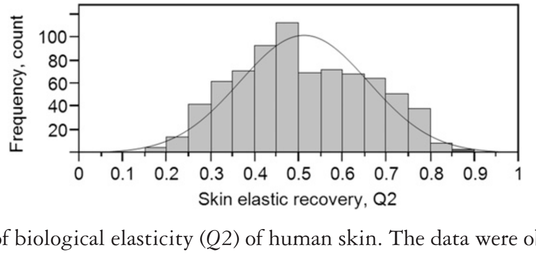

Figure 4. Distribution of biological elasticity (*Q*2) of human skin. The data were obtained from a combination of three volunteer populations of 746 people of different age, gender, and ethnicity.

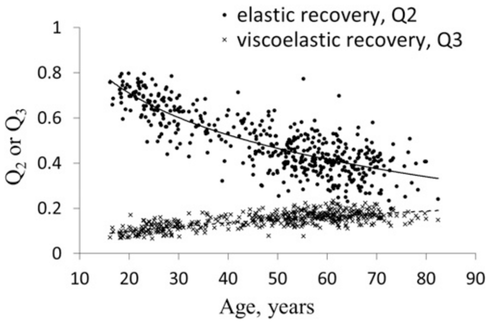

Figure 5. Age correlation of skin viscoelastic parameters from a panel of 463 female Caucasian volunteers. The solid dots are the values of elastic recovery (E_R) of skin and the crosses are the viscoelastic recovery.

CONCLUSION

In this study, we show that the relaxation phase of a mode 1 response curve is a more accurate region for calculating skin viscoelastic properties. Determination of the t_{IP} from each individual response curve is demonstrated to be a method more accurately reflects the skin's elastic properties of each person than the current method that assumes a single empirical value. Using the thus calculated individual t_{IP}, a set of simplified skin viscoelastic parameters can be defined based on the area ratios calculated from each response curve. Statistically significant correlation was obtained (by Pearson's R test) when compared the $Q2$ results with the study volunteers' chronological age. We have demonstrated that the area-based skin elasticity parameters, the Q-parameters in Cutometer, provide a simple and more accurate method for measuring skin elasticity.

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