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ORIGINAL ARTICLE

A comprehensive comparison of facial skin hydration based on capacitance and conductance measurements in Chinese women

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Abstract

Objectives: The aim of this study was to compare the data of conductance and capacitance measurements of facial skin hydration and to evaluate and discuss the advantages and disadvantages of the different approaches.

Methods: We measured skin capacitance (Corneometer® CM 825) and skin conductance (Skicon-200EX®) on 30 pre-defined facial sites of 125 Chinese women, resulting in 3750 readings per device. The data were analysed and compared, and continuous colour maps were generated on a 3D avatar for capacitance, conductance, relative difference (Δ%) and correlation (R-value) by interpolating between the individual readings and converting the values to colours. This visualization allows a better interpretation of the results.

Results: The complexity of facial skin hydration is revealed by this approach. The similarities and discrepancies in the facial hydration maps are clearly apparent. Due to the superiority of the Skicon in measuring high hydration levels, differences in skin hydration were evident on the forehead compared with the Corneometer maps, which may be related to the more superficial measurement of the Skicon within the stratum corneum. Conversely, a greater understanding of the complexity of facial skin hydration in the nasolabial fold was obvious when using the Corneometer. The best congruence between the instruments was found at two specific but separated facial areas, one around the inner eye region and the other one on a line between the nasolabial sulcus and the oblique, lateral jaw. Interestingly, the data were not normally distributed for both instruments and they had opposite skews. All facial clusters were statistically different from each other ($p < 0.001$), except the cheek and jaw for the Skicon. Larger than expected percentage coefficients of variance were found for the Corneometer on some facial sites that might be explainable by differences in stratum corneum physiology and biochemistry. Corneometer values of 48 AU and Skicon values of 132 μS were taken as the cutoff for normally hydrated facial skin.

Conclusions: Both devices have their advantages and disadvantages suggesting that bio-instrumental measurement of skin hydration is actually more complicated than commonly thought and that the different facial zones and the use of multiple instrumentation have not been adequately considered.

KEYWORDS
colour mapping, facial skin hydration, moisturization, skin capacitance, skin conductance, stratum corneum

Résumé
OBJECTIFS: L'objectif de cette étude était de comparer des données issues de mesures d'hydratation de la peau du visage par conductance et capacité électrique, et d'évaluer et discuter les avantages et désavantages de ces différentes approches.
METHODES: La capacité électrique de la peau (Corneometer® CM 825) et saconductance (Skicon-200EX®) ont été mesurées en 30 points pré-définis du visage de 125 femmes chinoises, menant ainsi à 3750 mesures par appareil. Les données ont été analysées et comparées, puis transposées visuellement sur avatar 3D via la création de cartographies continues de couleur par conversion de chaque valeur en une coordonnée de couleur et interpolation colorielle entre les différents points. Des cartographies de capacité électrique, de conductance ainsi que celle de la différence relative (Δ%) et de corrélation (R-value) ont été générées, ces visualisations permettant de mieux interpréter les résultats.
RESULTS: Cette étude a mis en lumière la complexité de l'hydratation de la peau du visage. Les similarités et différences entre les cartographies d'hydratation faciale apparaissent clairement. Du fait de la supériorité du Skicon pour la mesure de hauts taux d'hydratation, des différences sont clairement visualisées entre les cartographies d'hydratation des deux appareils au niveau du front, et pourraient être dues à une mesure plus superficielle au sein du stratum corneum avec le Skicon. A l'inverse, l'utilisation du Corneometer permet une bien meilleure compréhension de la complexité de l'hydratation de la peau au niveau du sillon nasogénien. Les appareils montrent les résultats les plus similaires au niveau de deux zones spécifiques et séparées du visage, une au niveau du coin interne de l'œil et l'autre sur une ligne séparant le sillon nasolabial et l'oblique latéral de la machoire. Il est intéressant de noter que les distributions des données ne suivent pas une loi normale, pour aucun des deux appareils, et présentent des biais de distribution opposés. Tous les résultats obtenus au niveau des clusters faciaux étudiés montrent des différences statistiquement significatives entre eux ($p\langle 0.001$), à l'exception de la joue et de la mâchoire, avec le Skicon. Des pourcentages de coefficients de variation plus élevés qu'attendus ont été obtenus avec le Corneometer en certaines zones du visage, qui pourraient être expliqués par des différences physiologiques et biochimiques du stratum corneum. Des valeurs de 48 UA avec le Corneometer et de 132 µS avec le Skicon ont été retenues comme valeurs seuil d'une peau du visage normalement hydratée.
CONCLUSIONS: Les deux appareils montrent des avantages et désavantages, suggérant que la mesure bio-instrumentale de l'hydratation cutanée du visage est en réalité plus compliquée que communément admise et qu'une approche

multiinstrumentale n'a pas été suffisamment considérée à ce jour pour appréhender les différentes zones du visages.

INTRODUCTION

Skin, or more precisely stratum corneum (SC) hydration, is of extreme interest for understanding the basal physiology of healthy skin and also dynamically following treatment with moisturizers [1]. The main workhorse instruments are based on the electrical properties of the skin, such as conductance and capacitance measurements, and several authors have compared the relative merits of the different instruments [2–4]. However, skin hydration assessment is complex and is complicated by the physiological differences in SC biochemistry and cellular biology amongst different body sites, such as the thickness of the SC, differences in skin lipids and natural moisturizing factor levels and corneocyte maturation status [5, 6]. This is relevant not only for comparison between different body sites but even on different zonal regions of the face [7–10].

The complexity of regional facial skin hydration has been highlighted in recent years and building on from the literature [11, 12] this has culminated in the generation of continuous hydration colour maps, essentially heat maps, which give a better description and visualization of multiple single point skin 'hydration' measures. The maps are based on interpolation between each measured value, conversion of the values into colours and superimposing these heat maps onto facial images [8, 10]. Indeed, using this approach ethnic differences in facial skin hydration gradients (capacitance) were clearly apparent generally in the order Black Africans > Indians > Caucasians > Chinese [8]. Generally, gradients of decreasing capacitance were observed from the middle cheek to the eye region to the central chin, from the top of the nasolabial fold to the oblique/lateral jaw and from the lower forehead and outer eye canthus to the upper forehead.

Using this approach, treatment of the face over a four-week period with a saccharide isomerate and niacinamide-containing moisturizer highlighted, how relative to other facial sites, that the moisturization of the nasiolabial fold and parts of the cheek is refractory to moisturizer-induced hydration changes to some extent when measuring skin conductance and capacitance, respectively [8, 10]. This was exemplified further most recently by Pierre et al. in shorter term clinical trials using a glycerin-containing moisturizer and measuring skin capacitance [13]. Similar approaches have also been taken by Barrionuevo-Gonzalez et al. with only moderate differences in skin capacitance amongst three different ethnic groups using dexpanthenol-containing moisturizers [14]. These studies expose the weakness and lack of comparative information that can be obtained from single point measurements on the forearm and highlight the need for facial moisturizers to be tested on the face [15].

The measurement of skin hydration for both the Skicon and the Corneometer has recently been compared with in vivo confocal Raman microspectroscopy as a more precise tool to measure skin water levels spectroscopically [16, 17]. However, the effects of moisturizers on skin hydration measured by skin capacitance and in vivo confocal Raman microspectroscopy gave some rather surprising results [18]. The Corneometer values in the study of Crowther et al. after using a niacinamide and glycerin-containing moisturizer for 2 weeks did not reflect the increased water content as measured with the Raman equipment [18]. This finding may be related to the additional mechanism of action of niacinamide thickening the SC by increasing corneocyte layers and/or axial swelling by increased hydration. Nevertheless, SC integrity measurements suggest changes in SC biology [19] and reduced desquamation by decreased activity of desquamatory enzymes and other serine proteases [20]. In addition, our own work showed that topically applied niacinamide improves corneocyte rigidity that could also have an impact [21]. Bielfeldt et al. also compared skin hydration measurements with the Corneometer and SC water content with in vivo confocal Raman microspectroscopy [16]. Unexpectedly, a negative correlation was observed for SC water content and positive correlation for epidermal water content, whereas a positive correlation was observed for the in vivo confocal Raman microspectroscopy water gradient while SC thickness showed a negative correlation with the Corneometer measurements. Comparing the Skicon and Raman instruments, linear and non-linear correlations depending on level of hydration were shown following tape stripping. Boncheva et al. proposed that conductance measurements can be used to distinguish between normal and dry skin, provided transepidermal water loss (TEWL) was ≤12 $g/m^2/h$ [17]. Moreover, Skicon measurements have been shown to correlate with those obtained with attenuated total reflectance-Fourier transform infrared spectroscopy (ATR-FTIR) measurements [22]. Thus, skin hydration measurement correlations are complex when comparing with chemical-specific spectroscopy methods but it should be pointed out that these studies were not conducted on facial skin, which, as we have described, is more complex than other body sites.

In this study, we compared and analysed comprehensive data sets of facial capacitance and conductance measurements from Chinese women with expert graded moderately dry and rough skin and generated continuous facial colour maps for skin hydration, comparative relative delta percent (Δ%) and correlation. Our aim was to shed light on the complexity of facial skin hydration using a combined approach of different bio-instruments and expert grading.

MATERIALS AND METHODS

Study population and general approach

The cross-sectional study was approved by the Guangdong Light Industry Association Institutional Review Board and was conducted in accordance with the Declaration of Helsinki Principles. Written, informed consent was obtained from all participants before enrolment. One hundred and twenty-five (125) healthy Chinese women, 35.2 ±8.7 years old (mean ± SD), age range 21–49 years, living in Beijing for more than 3 years, participated in this observational study which took place from April 11 to May 15, 2017. The study participants had self-perceived dry facial skin and a Corneometer reading of ≤45 AU at 3 cm vertically beneath the outer edge of the eye (mean 38.2 ± 5.6 AU).

The panellists did not apply any dermatological or cosmetic products on their faces for 3 days prior to the visit. For this conditioning phase, the participants cleansed the face with tepid water in the morning. In the evening, the face was cleaned with a gentle facial cleanser (Cetaphil, Galderma, Zug, Switzerland) and rinsed with lots of lukewarm water. Before the expert grading and the instrumental evaluation, the skin was cleaned by gently swabbing with a cotton pad soaked in distilled water at ambient temperature and allowed to dry for 20 min and then acclimatized for 30 min at 22 ± 1°C and 50 ± 3% relative humidity.

Expert grading of facial dryness and roughness (whole face)

A dermatologist visually and tactually evaluated the skin condition according to skin dryness and roughness grading scales as listed in Table 1. The study participants had moderate dry skin (grade 4.9 on a 1–9 scale).

Bio-instrumental evaluation

The SC capacitance was measured using a Corneometer® CM 825 (Derma Unit SSC 3, Courage + Khazaka Electronic, Cologne, Germany) and conductance using a Skicon-200EX® (I.B.S. Co., Hamamatsu, Japan) on 30 predefined sites on the left-hand side of the face (Figure 1 and Table 2). Skin capacitance and conductance were expressed as the mean of triplicate readings. In total, 3750 values were collected for each device [2, 3, 8].

Creation of facial colour maps for skin hydration, Δ% and correlation

In order to visualize the hydration levels based on the two instruments and to highlight the differences, facial colour mappings were generated for the following values: median Corneometer and Skicon readings, Spearman's correlation coefficient and relative Δ% between the two instruments. For the latter, a linear scale of 0%–100% was set for both devices between 0 and the highest median of each test site and the difference (Δ%) was calculated (% Corneometer−% Skicon) (Table 3). This value provides information about the comparability of the devices on the different facial regions.

TABLE 1 Scales for expert gradings of facial dryness and facial roughness

Score	Facial dryness	Facial roughness
1	No evidence of dryness	No roughness: perfectly smooth and soft skin surface
2–3	Slightly dry skin	Slight roughness: slight unevenness and slight roughness when tangentially touching
4–6	Moderately dry skin	Moderate roughness: clearly uneven and rough appearance and possibly feeling of a slight roughness when vertically touching
7–8	Severely dry skin	Severe roughness: very marked roughness and uneven feeling
9	Extremely dry skin	Extreme roughness: rough feeling

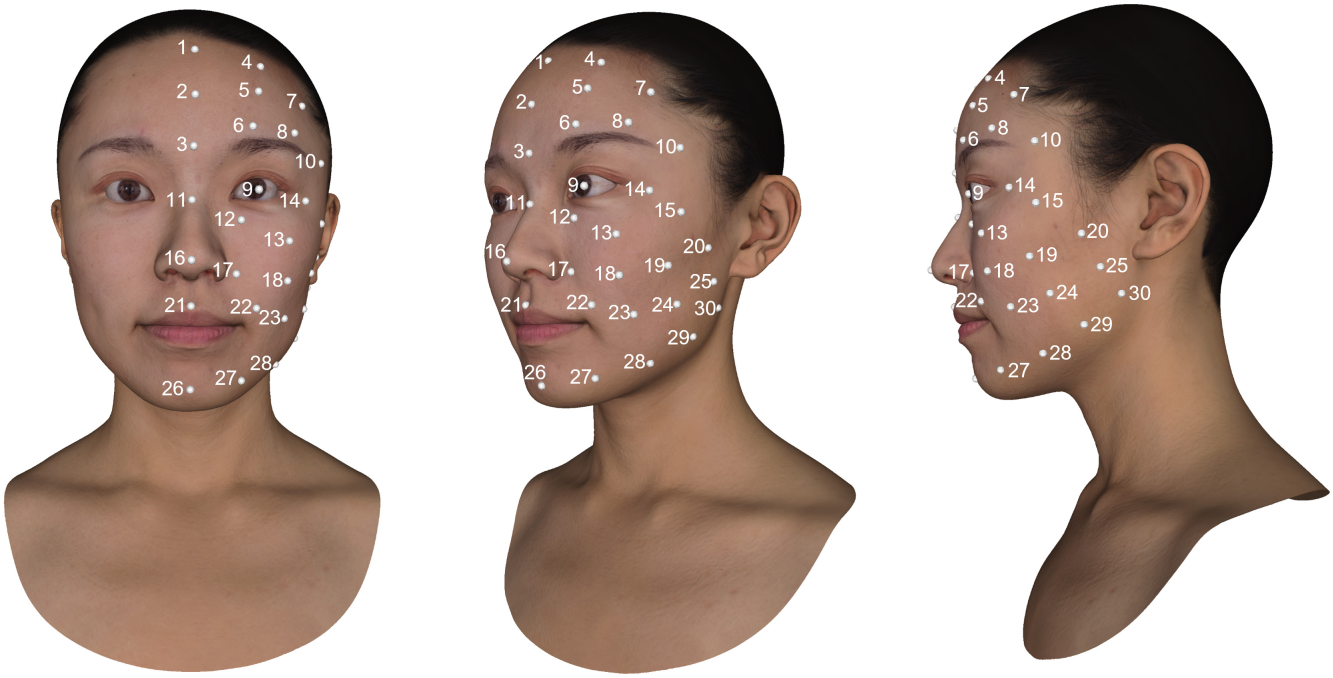

FIGURE 1 Mapping layout, anterior, oblique and lateral view of 30 pre-defined facial measurement points. Test site 9 was the closed eyelid. [Colour figure can be viewed at wileyonlinelibrary.com]

For this purpose, a high-resolution realistic 3D Chinese female avatar with a uniform texture was used. Each of the 30 predefined test sites was precisely positioned on the left profile of the 2D texture image of the avatar and symmetrized on the right profile (Figure 2). The values were then linked to the corresponding test sites. Between each test site, the values were linearly interpolated using a thin plate spline transform, allowing to obtain a value for all pixels of the 2D texture image. Thereafter, the data were converted into colours (CIELAB colour space) and colour maps were applied representing a continuous distribution of the values on the face. The corresponding colour was superimposed to the original skin tone with a transparency level. Finally, the colour mappings were transferred to the 3D image.

For the Corneometer and Skicon mappings, it was decided to show well hydrated skin in blue and low hydrated skin in red. The colour scale for Corneometer values ranged from 10 AU (arbitrary units) (red, lowest median) to 70 AU (blue, highest median) and for the Skicon from 80 µS (microsiemens) (red, lowest median) to 250 µS (blue, highest median). For the limit condition, shown in white (normal hydrated skin), the medians of the 3750 readings were chosen (48 AU for capacitance and 132 µS for conductance). Similarly, good correlation (Spearman) is represented in blue and poor correlation in red. The scale ranged from red ($R = 0.2$) to blue ($R = 0.8$) and the transition value was set to white ($R = 0.5$). Finally, high positive Δ% are represented in blue and low negative Δ% in red. The colour scale ranged from blue (30%) to red (−30%), the transition value was 0%, shown in white.

Statistical analysis

All data were collected in Microsoft Excel 365 and analysed with Minitab 19.2020.1. The data were checked for normality using the Ryan–Joiner normality test and Spearman's correlation coefficient tests were performed. For comparisons of the different facial clusters, medians were calculated and non-parametric Friedman and Wilkoxon signed-rank tests were performed. To adjust for multiple comparisons, a Bonferroni correction was applied.

RESULTS

Table 3 summarizes all measured and evaluated values, which are discussed hereafter. The total of 3750 individual readings for both devices was not normally distributed (Ryan–Joiner). For the Corneometer, the readings from 17 test sites were normally distributed and for the Skicon, only from one test site. The distributions had opposite skews, more counts for low values for the Skicon and more counts for high values for the Corneometer (Figure S1). The coefficient of variation in % (%CV) for the Corneometer ranged from 14.7% to 83.2% and for the Skicon from 37.3% to 65.6% depending on the test site.

TABLE 2 Mapping layout, description of the 30 predefined facial measurement points

Site #	Description of test site	Localization
01	Forehead, central, upper	Central brow top, close to hairline
02	Forehead, central, middle	Central brow mid, exactly between 01 and 03
03	Forehead, central, lower	Central brow lower, between eyebrows
04	Forehead, middle left, upper	Midbrow top, close to hairline, exactly between 01 and 07
05	Forehead, middle left, middle	Midbrow mid, exactly between 04 and 06
06	Forehead, middle left, lower	Midbrow lower, exactly between 03 and 08
07	Forehead, left, middle	Outer brow mid; close to hairline
08	Forehead, left, lower	Temple brow
09	Eyelid	Eyelid
10	Forehead, outer, level with eyebrow	Temple, outer edge of brow
11	Nose, bridge	Nose, bridge
12	Under eye, inner corner	1.5 cm below medial canthus, slightly outward bended, parallel to nose
13	Under eye, middle	2 cm below pupil, slightly below the central infraorbital margin
14	Outer eye canthus	1.5 cm horizontally from outer lateral eye canthus
15	Cheek, lateral	Outer cheekbone ±4 cm below site 10
16	Nose, apex	End/top of nose
17	Nasolabial sulcus, top	0.5 cm left of nostril
18	Cheek, middle, oblique	In slightly curved line with 17, 19 and 20
19	Cheek, middle, oblique/lateral	In slightly curved line with 17, 18 and 20
20	Cheek, middle, lateral	In slightly curved line with 17, 18 and 19
21	Philtrum	Middle of upper lip in cleft
22	Nasolabial sulcus, midpoint	Midpoint of nasolabial fold
23	Cheek, lower, oblique	In slightly curved line with 22, 24 and 25
24	Cheek, lower, oblique/lateral	In slightly curved line with 22, 23 and 25
25	Cheek, lower, lateral	In slightly curved line with 22, 23 and 24
26	Chin, central	Middle of chin
27	Jaw, anterior/oblique	Exactly between 26 and 28
28	Jaw, oblique	Exactly between 26 and 30
29	Jaw, oblique/lateral	Exactly between 28 and 30
30	Jaw, lateral	Slightly above mandibular angle

Note: Site 15 was considered as part of the eye area.

In Figure 3, the box-and-whisker plots of the Skicon and Corneometer readings for the individual test sites are illustrated. The interquartile range (25th–75th percentile) appeared to be more broadly and more homogeneously distributed for the Skicon than for the Corneometer. With both devices, the whiskers show a similar relative extension, except for test site 9 (eyelid) for the Skicon. The median values for the Skicon are generally located above the means in contrast to the Corneometer.

The % scale values (0%–100%) of the individual test sites are shown in a spider diagram (Figure 4). These were calculated as a linear scale of 0%–100% for both devices from 0 to the highest median of each test site. Under basal conditions, the Skicon values are at a much lower part of the instrument's measuring range compared with the Corneometer values for all test sites, except for well hydrated areas (e.g., the eyelid, #9) and dry regions (e.g., nasolabial fold, #17, middle cheek, #23 and #24) where both instruments recorded similarly high and low readings in their measuring ranges.

The correlation of the medians of the individual test sites for the two devices best followed a second-order polynomial ($R = 0.80$) (Figure 5). The different facial regions can be grouped into clusters, which are shown in coloured ovals. The medians of the different facial clusters (forehead, eye region, nasolabial fold, cheek, jaw) are shown in Table 4. For both devices, these clusters were statistically significantly different from each other ($p < 0.001$ each), except for the cheek versus jaw comparison for the Skicon.

TABLE 3 Summary of data and evaluations.

Site	Description of the sites	Facial area	Corneometer			Skicon			Δ%	Correlation		Regression
			Median	Mean	% CV	Median	Mean	% CV	Median	*R*	*p*-value	linear
1	Forehead, central, upper	Forehead	50.8	50.0	27.2	141	152	48.4	15.1	0.78	<0.001	0.141x + 28.53
2	Forehead, central, middle	Forehead	58.5	57.8	19.7	146	151	40.9	23.7	0.76	<0.001	0.133x + 37.82
3	Forehead, central, lower	Forehead	44.6	44.3	27.9	113	124	47.1	17.7	0.44	<0.001	0.085x + 33.75
4	Forehead, middle left, upper	Forehead	53.5	54.5	22.0	152	161	41.4	14.7	0.76	<0.001	0.132x + 33.28
5	Forehead, middle left, middle	Forehead	63.9	62.2	16.7	169	173	37.3	22.4	0.75	<0.001	0.119x + 41.64
6	Forehead, middle left, lower	Forehead	53.7	53.3	20.9	120	134	41.9	27.5	0.71	<0.001	0.143x + 34.20
7	Forehead, left, middle	Forehead	57.8	56.6	20.1	159	162	41.3	17.9	0.59	<0.001	0.104x + 39.82
8	Forehead, left, lower	Forehead	57.8	55.3	22.2	137	153	41.9	26.6	0.71	<0.001	0.131x + 35.19
9	Eyelid	Eye region	71.4	71.1	13.0	251	268	41.5	0.0	0.73	<0.001	0.059x + 55.39
10	Forehead, outer, level with eyebrow	Forehead	58.6	57.6	20.1	149	152	42.6	22.7	0.77	<0.001	0.133x + 37.29
11	Nose, bridge	Nose	41.5	41.1	25.9	145	146	32.3	0.6	0.36	<0.001	0.077x + 29.84
12	Under eye, inner corner	Eye region	46.3	45.7	29.2	154	167	48.3	3.4	0.51	<0.001	0.089x + 30.82
13	Under eye, middle	Eye region	53.8	53.8	21.7	167	179	46.2	9.0	0.58	<0.001	0.087x + 38.33
14	Outer eye canthus	Eye region	62.6	61.5	20.5	183	194	45.3	14.8	0.60	<0.001	0.089x + 44.33
15	Cheek, lateral	Eye region	65.9	63.4	17.8	166	173	44.2	26.5	0.77	<0.001	0.107x + 45.00
16	Nose, apex	Nose	46.0	45.3	22.2	140	142	45.4	8.8	0.72	<0.001	0.109x + 29.85
17	Nasolabial sulcus, top	Nasolabial	12.8	15.4	78.6	83	104	65.5	−15.1	0.31	<0.001	0.063x + 8.87
18	Cheek, middle, oblique	Cheek	40.2	37.6	19.1	119	117	41.0	9.1	0.62	<0.001	0.091x + 27.00
19	Cheek, middle, oblique/lateral	Cheek	49.4	48.4	19.3	149	153	42.5	9.8	0.38	<0.001	0.056x + 39.93
20	Cheek, middle, lateral	Cheek	47.8	47.7	23.3	147	146	43.4	8.3	0.54	<0.001	0.085x + 35.27
21	Philtrum	Philtrum	49.9	49.9	25.1	134	144	57.0	16.4	0.73	<0.001	0.112x + 33.82
22	Nasolabial sulcus, midpoint	Nasolabial	24.4	26.3	49.7	85	99	61.0	0.5	0.42	<0.001	0.069x + 19.54
23	Cheek, lower, oblique	Cheek	11.3	14.7	83.2	108	106	50.5	−27.3	0.20	<0.05	0.031x + 11.43
24	Cheek, lower, oblique/lateral	Cheek	31.5	30.9	44.5	120	126	45.5	−3.8	0.24	<0.01	0.041x + 25.76
25	Cheek, lower, lateral	Cheek	39.1	40.1	31.7	104	110	48.4	13.2	0.73	<0.001	0.178x + 20.60
26	Chin, central	Jaw	49.7	49.5	20.5	108	120	53.9	26.8	0.70	<0.001	0.097x + 37.93
27	Jaw, anterior/oblique	Jaw	47.9	45.9	28.4	108	125	54.7	24.1	0.67	<0.001	0.122x + 30.64
28	Jaw, oblique	Jaw	41.4	39.5	37.2	94	111	57.0	20.6	0.59	<0.001	0.139x + 24.12

(Continues)

TABLE 3 (Continued)

Site	Description of the sites	Facial area	Corneometer			Skicon			Δ%	Correlation		Regression
			Median	Mean	% CV	Median	Mean	% CV	Median	*R*	*p*-value	linear
29	Jaw, oblique/lateral	Jaw	36.3	36.1	34.2	119	127	50.7	3.6	0.40	<0.001	0.056x + 29.33
30	Jaw, lateral	Jaw	46.4	45.5	26.0	119	131	45.8	17.6	0.69	<0.001	0.135x + 27.85

Abbreviations: %CV, coefficient of variation in %; Δ%, relative difference of Corneometer and Skicon readings based on a linear 0%–100% scale each; R, Spearman correlation coefficient and equation for linear regression.

Once more, the eyelid (#9) occupied an exceptional position and showed for both instruments the highest value, very pronounced for the Skicon. This is reflected by the low slope of the linear regression of this test site ($y = 0.059x + 55.4$, $R = 0.73$) (Table 3). The three test sites (#17, #22, #23) at the other end of the curve also have a low slope but a low correlation coefficient.

The continuous facial colour mappins for capacitance and conductance are shown in Figure 6. The heat maps for both devices are very similar despite differing values, with the lower parts of the face showing lower values and the upper facial zones higher values. With both instruments, the eye region had the darkest blue colour (highest values) and the nasolabial sites (#17 and #22) and the lower, oblique cheek (#23) the darkest red colour (lowest values).

The correlation of the individual test sites showed the best fit with linear trendlines (Table 3). All test sites correlated significantly. For 12 sites, the Spearman correlation coefficient was greater than 0.7, and for 22 greater than 0.5. In general, the highest *R* values were found on the forehead and the eyelid, while the lowest ones on the middle cheek and the nasolabial sulcus. There is a trend of a greater correlation in better hydrated areas.

The Δ% map revealed that the test sites around the inner eye region and the nose bridge (#9, #11, #12) and a narrow linear zone below the lower cheek (#22, #24, #29) were the most congruent (close to white). The least matched areas with comparatively high Corneometer values (blue) were the forehead and the area around the chin, and those with comparatively high Skicon values (red) were the nasolabial zone and the midcheek.

DISCUSSION

In this observational study, we compared the continuous skin hydration maps generated with a Corneometer and a Skicon independently in Chinese women graded with moderately dry and rough facial skin. We chose a cutoff for normal skin at 48 AU for the Corneometer which is slightly higher for forearm data and slightly lower for other facial data reported by others [23, 24] but it was virtually identical to that of Seo et al. [25]; for a review on recent data, see [26]. This equates to 132 µS for the Skicon. Interestingly, we observed non-normal and opposite distributions between the two sets of instrumental data. The %CV ranged from 13.0% to 83.2% depending on the test site for the Corneometer and 32.3% to 65.5% for the Skicon. Although the values are generally accepted to be higher for the Skicon, the Corneometer is not usually reported to have such high %CVs [27, 28]. These differences are also highlighted in the box-and-whisker plots (Figure 3). This combined approach further highlights the

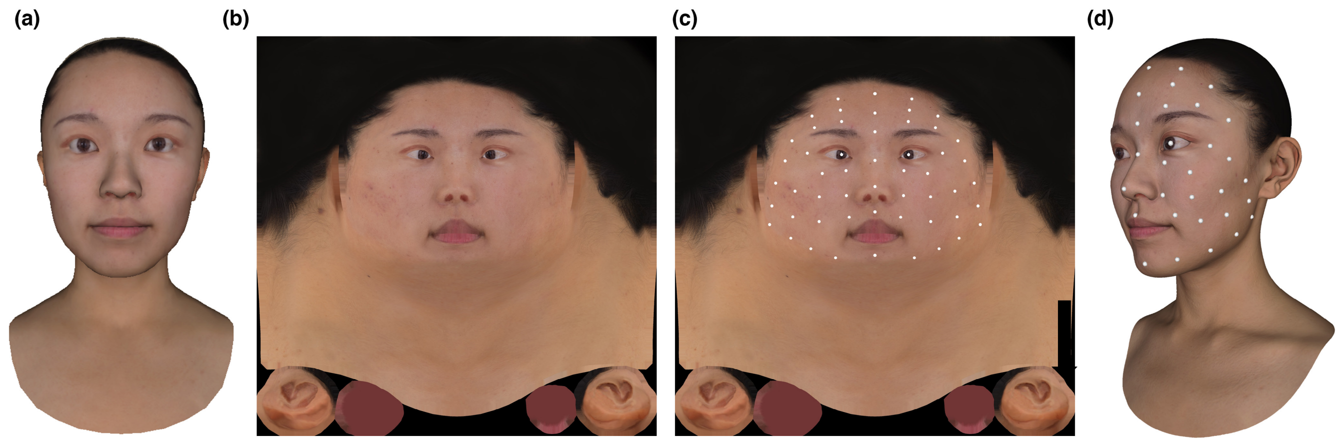

FIGURE 2 A 3D Chinese female avatar (a) with a uniform texture was used for the colour mapping approach. In order to position the test sites accurately, a 2D texture image was created (b). Each of the 30 pre-defined test sites was precisely positioned on the left profile of the 2D texture image and symmetrized onto the right profile (c). Finally, the mappings were transferred back to the 3D image (d). [Colour figure can be viewed at wileyonlinelibrary.com]

complexity of facial skin hydration, especially when using different instruments to derive a better picture of facial skin hydration.

Although the colour maps of the facial hydration measurements (Figure 6) are quite similar, relative differences between the readings of the two instruments can be seen in the Δ% maps and the correlation maps. The correlation tends to be better in hydrated facial areas while the comparison of the two devices based on the Δ% approach is more complex. The best congruence (white to light blue and light red, Δ% from −4 to 4) was found in two particular areas with adjacent test sites. One area was found around the inner eye zone including the eyelid (#9), the inner eye corner (#12) and the nose bridge (#11), the other one on a line between the nasolabial sulcus and the oblique lateral jaw (#22, #23 and #29). Most other test sites showed greater differences in comparability (>10 Δ%). Why test sites #17 and #23, of all sites, showed a distinct lower % value for the Skicon (Figure 4) is not clear to us and requires further clarification.

The capacitance maps of the current study and a previous study [8] look quite similar, except for the forehead, which was drier in the previous study. Reasons for this may be different subjects and differences in exposome and seasons.

Surprisingly, compared with our data, some studies also observed differences between the forehead and cheek capacitance values, while others did not [11, 26, 29–31].

The reasons for the differences in the relative skin hydration status between the two instruments can be a result of multiple causes. Besides the differences in the electrical measurement principles (conductance vs. capacitance), these mainly include the biochemistry of the type and quantity of molecules on and in the skin, the thickness of the SC, and the different cellular anatomy of the test sites [5, 6].

Moreover, although the contact pressure of both probes is controlled (Corneometer® CM 825, 1.1–1.5 N; Skicon-200EX®, 0.8 N) [32], the individual application of the probe and the various anatomical conditions of the face may have an impact on the measurements and as pointed out by Crowther the roughness and dryness of the skin influences contact between the instruments and the skin [4].

The SC thickness may have the greatest impact on apparent skin hydration readings. For the Skicon-200EX®, the penetration depth is reported to be very superficial (15 µm), while that for the Corneometer® CM 825 is approximately 45 µm [7]. In a simplified model based on Warner's pivotal and groundbreaking findings using cryoelectron microscopy [33], the water gradient in the SC has a linear progression, reaching a constant level in the epidermis. Warner's finding was later confirmed by numerous studies using confocal Raman spectroscopy in vivo [16, 18]. We assume that the electrical devices evaluate the area under the gradient curve (Figure 7). In case the measuring depth reaches the living epidermis, either by a thin SC or by a greater measuring depth, the reading is 'elevated' due to the increased water levels of the living epidermis compared with the SC:

$$\text{Water content}\,(\%) = \frac{x_{SC}\frac{\left(y_{outer\ SC}+y_{inner\ SC}\right)}{2} + \left(x_{epi}\, y_{epi}\right)}{\left(x_{SC} + x_{epi}\right)}$$

where x = depth, y = water concentration, SC = stratum corneum, and epi = living epidermis (measuring depth).

Moreover, changes in the water gradient can also occur with a thinner SC having a steeper water gradient and thereby much greater apparent water on the skin surface [18].

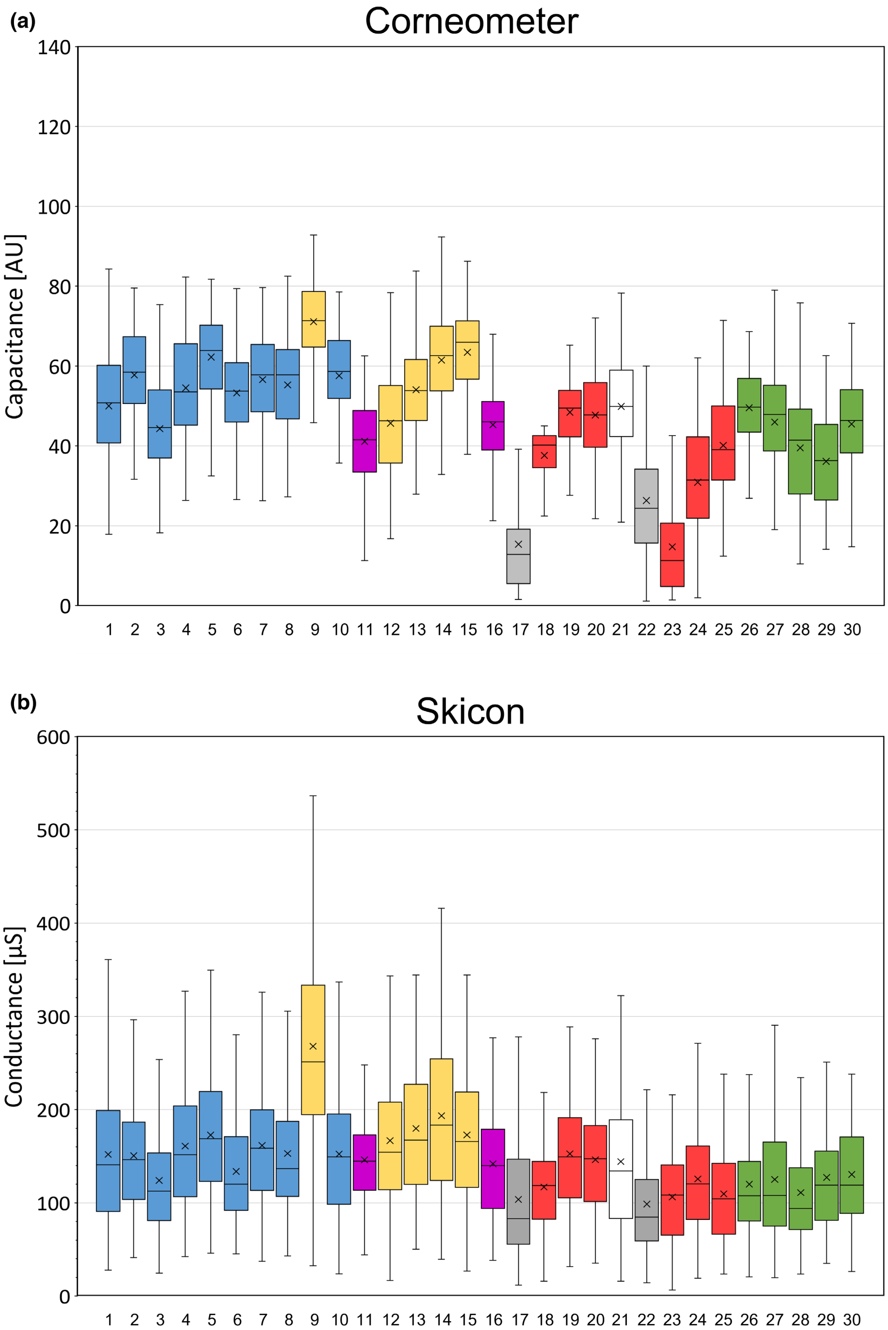

FIGURE 3 Box-and-whisker plots for the individual test sites of the Skicon and the Corneometer readings. Blue, forehead; yellow, eye region; pink, nose; grey, nasolabial; red, cheek; white, philtrum; green, jaw line. [Colour figure can be viewed at wileyonlinelibrary.com]

These arguments may be important for the findings of Bielfeldt et al. and Boncheva et al. [16, 17]. Unfortunately, there is no published information on the thickness of the facial SC on the different test sites we have measured but there are small changes in the number of cell layers, with the eyelid skin having 20% less cell layers than cheek skin [34]. This thickness change may account for our high values measured on the eyelid and compare well with others reported in the literature [34, 35]. Variations in SC thickness may also be contributing to the differences in skin hydration measurements reported by Koabayashi et al. [36] and reviewed by Tagami [37].

Comparing our conductance and capacitance values to literature data showed clear differences (Figure 8) [7]. The main reason is most probably not the difference in ethnicity (Chinese vs. Caucasians), the gender (male and female vs. only females), the age of participants (21–71 years vs. 21–49 years) or the season but rather the test sites measured. Clarys et al. [7] evaluated different body sites (very dry: foot sole, hand palm; dry: knee front, forearm dorsal, upper arm volar; hydrated: forearm volar, leg calf, cheek, abdomen, very hydrated: forehead, forearm volar), whereas we focused on the face only. It should be noted that Clarys et al. did not define the facial locations as

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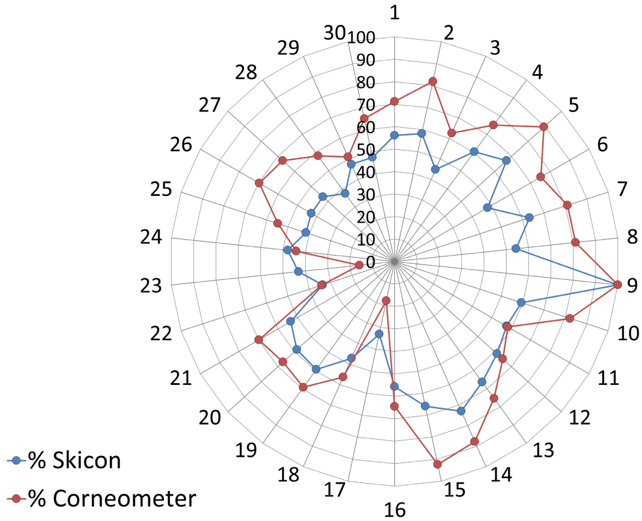

FIGURE 4 Diagram representing the relative values (0%–100%) of the Skicon (blue line) and the Corneometer (red line) for the individual 30 facial test sites [1–30]. [Colour figure can be viewed at wileyonlinelibrary.com]

accurately as we did in our study. These comparisons are important, as normal hydrated skin was reported to have a greater value than 40 AU using Corneometer® CM 825 measurements [23]. However, this statement was made based on forearm data. Clearly, this would give values of 100 µS with the Skicon with literature measurements [7] on different body sites but our data correlating between the two instruments on purely facial data show this value to be greater at 125 µS. However, from the comparison of the correlation of all 3750 readings of the Skicon and the Corneometer the medians 48 AU and 132 µS were chosen as the limit condition to generate the continuous facial hydration maps. Clear differences in the relative hydration on different sites could be observed.

The correlation of the two instruments clearly showed the performance differences at low and high hydration levels that may be related to the opposite skewness in the two data sets (Figure S1). Correlation coefficients were not too dissimilar to the literature but were obviously less

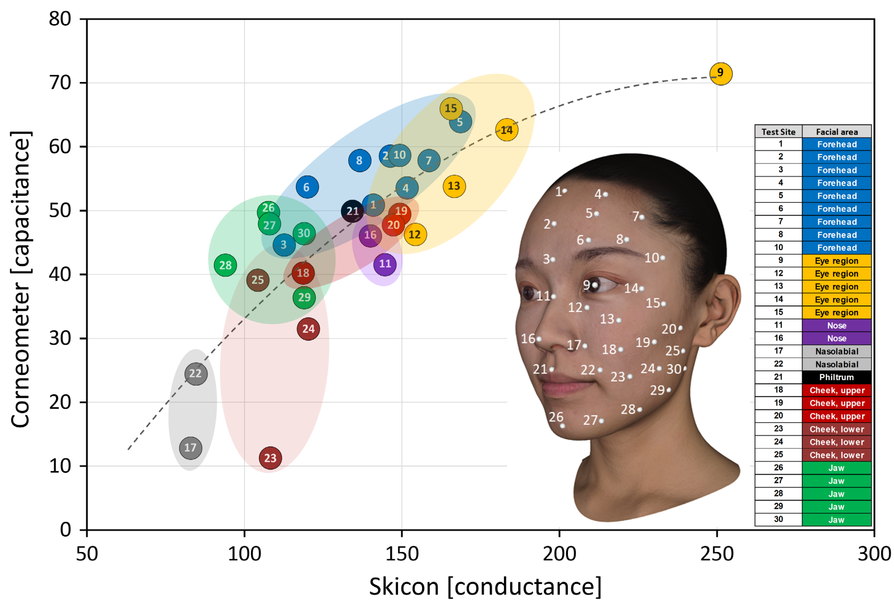

FIGURE 5 Correlation of the medians of the 30 facial test sites of the Corneometer and the Skicon. The different facial regions form obvious clusters. Regression (second-order polynomal), $y = -0.0016x^2 + 0.819x - 32.592$; $R = 0.8$.

TABLE 4 Medians of facial clusters, and minimum and maximum Corneometer and Skicon values.

		Corneometer [AU]			Skicon [µS]		
Facial cluster	**Test sites**	**Median**	**Min**	**Max**	**Median**	**Min**	**Max**
Forehead	1–8, 10	57	18	84	141	24	365
Eye region	9, 12–15	61	4	93	186	17	657
Nasolabial fold	17, 22	19	1	60	95	12	356
Cheek	18–20, 23–25	40	1	72	122	7	467
Jaw	26–30	44	10	79	108	20	435

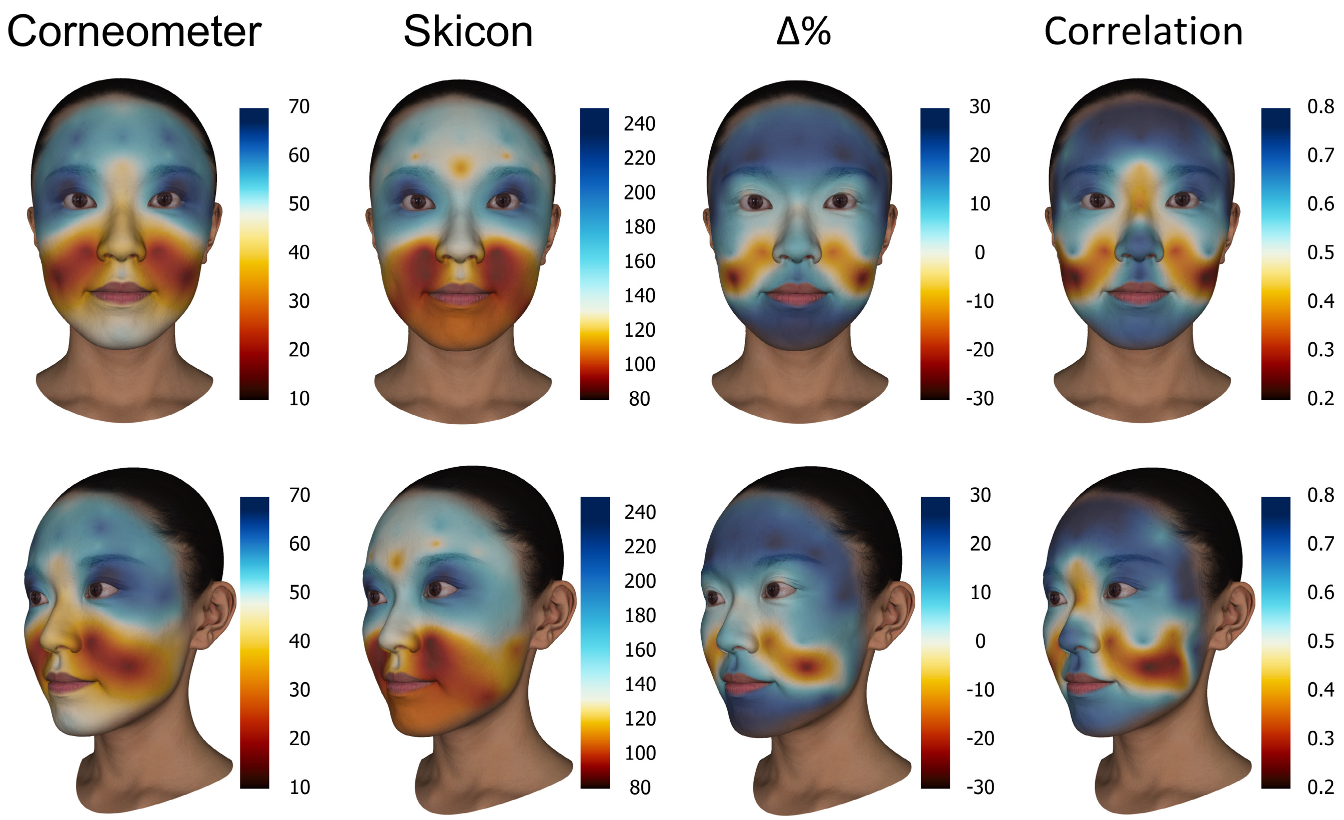

FIGURE 6 Continuous colour maps for skin hydration readings by the Corneometer and the Skicon as well as Δ% and correlation (from left). The red–blue colour codes for Corneometer values (10–70 AU (arbitrary units); limit condition 48 AU) and the Skicon (80–250 μS (microsiemens); limit condition 132 μS) are indicated on the scales to the right of each image. For the limit for normal skin hydration, the median was chosen. For the Δ% map, the colour scale ranged from −20% to 25%, with the limit condition at 0% and for the correlation map from R = 0.2 to R = 0.8, with a limit condition at R = 0.5. [Colour figure can be viewed at wileyonlinelibrary.com]

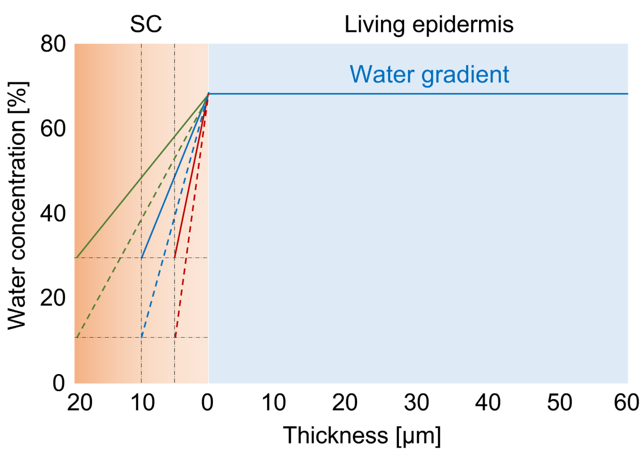

FIGURE 7 A simplified linear model of the (facial) epidermal water gradient (drawn lines, normal hydrated stratum corneum (SC); dotted lines, dry SC; green lines, thick SC; blue lines, normal SC; red lines, thin SC). [Colour figure can be viewed at wileyonlinelibrary.com]

than those reported probably due to the wider range of measurements taken. Indeed, when performing the correlation of the instruments at the different sites measured, the poorest correlation was observed at the lowest hydration levels, e.g., test sites 23 and 24 (Figure 3). Skicon measurements have previously been reported to be more sensitive at high hydration values and the Corneometer more sensitive at low hydration values [27, 38, 39]. This is reflected in the shape of the correlation curve (Figure 5), which is steeper for the lower values and flatter for the higher values.

Due to the superiority of the Skicon at measuring high hydration levels, differences in forehead skin hydration were clearly apparent compared with the Corneometer maps that may relate to the more superficial measurement of hydration within the SC. Conversely, a greater understanding of the complexity of facial skin hydration in the nasolabial fold was evident when using the Corneometer. However, in order to understand the complexity of facial skin hydration, it is obvious that using both instruments together provides a more powerful description of facial skin hydration.

In our study, expert grading scales are based on the assessment of the entire face only and derive a single global value for dryness and roughness. This standard approach is not really reliable as it does not differentiate the individual facial regions, which puts the importance of this assessment into perspective. The development and establishment of an appropriate zonal expert grading scale that applies to all differently pigmented skin types is therefore strongly recommended similar to the zonal electrical measurements we have taken. This is supported by the greater flaking scores usually observed on the forehead compared to the cheek [40].

We should bear in mind that electrical methods are not measuring water specifically. Any polar substance (endogenous or applied) may contribute to the electrical signal being recorded with the instruments [4]. We have described an observational study and the condition, situation and interpretation will be even more complex in an application study as the devices can be influenced by the components of the test products, e.g., the Corneometer particularly by glycerin and the Skicon by electrolytes [4, 27, 41–44].

Although we do not yet understand the biochemical reasons for these apparent skin hydration differences on the face, an analysis of the literature gives us some clues. Compared with cheek areas, the forehead possesses more and longer chain length ceramides, especially acylceramides [45]. Preliminary research also indicates that the SC is more depleted of natural moisturizing factors in the cheek areas [46]. Compared with other non-photodamaged sites, corneocyte envelopes are also more immature on the cheeks which relates to reduced 12R-lipoxygenase (12R-LOX), epidermis-type lipoxygenase 3 (eLOX3) and transglutaminase-1 levels and activities together with reduced ceramide EOS levels [47–51]. Nevertheless, more studies are needed to decipher the biological and anatomical differences on the different facial locations in order to explain the relative differences in the hydration maps between the two instruments.

Obviously, use of these instruments is key to understanding dry skin which is still a largely unmet consumer need worldwide, especially among the elderly [52–55]. Indeed, as Albert Kligman pointed out *Nobody dies of old skin ... but skin problems abound in the aged* [56]. Perhaps, one of the reasons for consumer disappointment with moisturizing products is our lack of understanding of regional differences in facial skin moisturization, which is hampered by single site measurements and use of surrogate testing sites, e.g., the forearm versus the face for testing facial products [15]. Moreover, it is over 40 years ago since such electrical measurements on skin started to be recorded [57] and 35 years since the first reports on dry facial skin [58]. Moreover, 20 years ago, Peter Dykes [59] pointed out in his paper entitled *What are meters measuring?* that the measurements of 'water' using electrical instruments are imperceivable to consumers and expert graders alike and as such should be used together with visual grading to assess the impact of moisturizers on skin. Indeed, more recently it has been recommended that multiple measuring techniques are best to decipher moisturizer mechanisms of action [60]. However, to quote Wa and Maibach, *understanding the regional differences inherent to the face will help us improve therapeutics* [61].

CONCLUSION

From this study, it is recommended that a combined approach of multiple measuring techniques such as skin conductance and capacitance measurements to generate

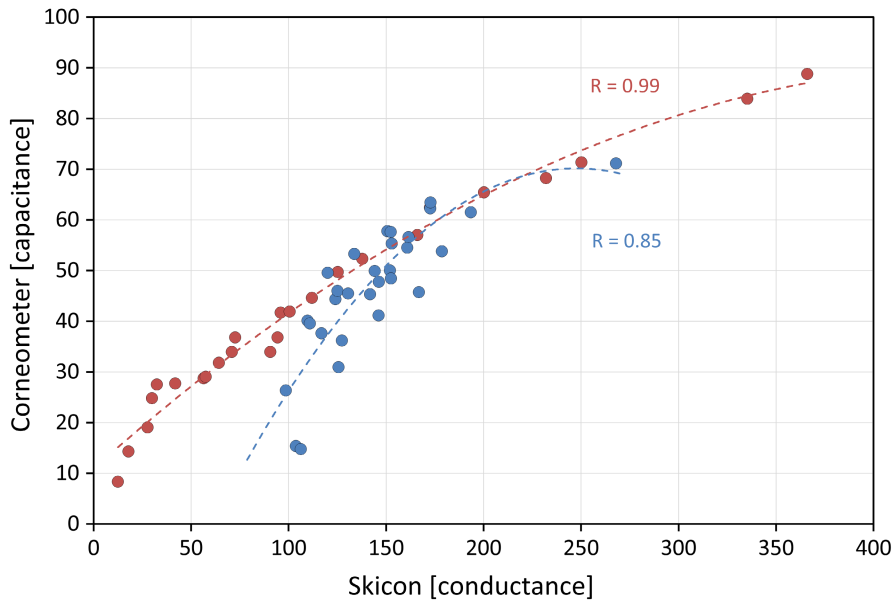

FIGURE 8 Comparison of the correlation of Skicon and Corneometer with published data. Clarys et al. [7] (red) evaluated 25 unspecified test sites on 11 different body sites, while the current study focused on 30 facial test sites only (blue). The best fit for the trendlines was in both cases a second-order polynomal. [Colour figure can be viewed at wileyonlinelibrary.com]

facial skin hydration mappings together with a differentiated zonal expert dry skin grading is best to derive a better picture of facial skin hydration, dryness and roughness even for basal skin conditions. Moreover, their relationship with SC thickness should be determined, e.g., with confocal methods. We suggest that bio-instrumental measurement of skin hydration is actually more complicated than commonly thought and that the different facial zones and the use of multiple instrumentation have not been adequately considered.

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CONFLICTS OF INTEREST

RV and RS are employees of DSM, AVR is a consultant to DSM and MC is an employee of Newtone.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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