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Measuring and describing the discoloration of liquid foundation

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Abstract

Although it is widely known that the foundation color gradually changes over time after applying the makeup, no scientific clues are available, thereby remaining the "darkening" phenomenon equivocal. This study measured the discoloration of liquid foundations and suggested indices to describe the discoloration over time. Four liquid foundations were applied to opacity charts with a thickness of 100 μm, the surface color was obtained using a non-contact spectrophotometer, and reported in the CIE 1976 $L^*a^*b^*$ color space. A long-term measurement for 24 hours was conducted in that the initial 2 hours were measured with a 60-second interval. The discoloration was observed as the decrease of both lightness and hue angle (h^* of CIE $L^*C^*h^*$) of liquid foundation over time. Different degrees and speed of color change were observed across the four foundations. Also, the discoloration was tested on three healthy human skins in 2-hour intervals in repeated measurements. Positive correlations in changes of lightness and hue were found among the opacity charts and human skin. Furthermore, the study suggests indices, "Dt" and "$T\Delta E$" to describe the quantitative amount of discoloration over time and time duration of discoloration, respectively.

KEYWORDS

discoloration, lightness, liquid foundation, skin, time-resolved measurement

1 | INTRODUCTION

People use foundation to even their skin tone; cover the pores, blemishes, and wrinkles; and improve skin lightness and undertone.[1] Various textures have been introduced to the consumer market over the years differ in formulations, such as cream, liquid, cushion, and powder. Among them, the liquid foundation ensures better coverage and lasts for a whole day. Compared with powder or cream, the pigments in liquid foundation are mixed with more ingredients. Led by North American and North Asian regions, the foundation market has grown over 5% annually in the last 5 years.[2,3]

Foundation-coated skin has been a popular research topic in color science, image processing, and the development of cosmetics. Recently, foundations became diversified into a more densely distinguished brightness levels and various shade undertones, such as cool, neutral, and warm. For example, global brands have launched more than 50 foundation shades covering not only a wide

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range of brightness and also of undertones. Consequently, customers have more choices in shades and become accustomed to discerning these perceptual differences within a small amount of color difference.

The interests in personal color have also been boosted.[4] Studies have suggested how to estimate accurately the color of face after makeup using liquid foundation products. Doi et al applied the Kubelka-Munk (KM) model in their study because it simulates the situation of foundation-coated skin.[5,6] In their studirs, the KM-model was utilized to calculate the reflectance based on the thickness of the foundation layer. Another study used Singular Value Decomposition-based neural network, a machine learning method, to estimate the foundation-coated skin color.[7] Previous studies have tried to identify the nature of color of two semi-transparent layers and applied them on skin and foundation.

Regarding the appearance or visual perception of foundation-coated skin, spectral reflectance often has been considered. One study identified the relationship between the spectral reflectance by different viewing angles and perceived luminosity. In the study, the skins were coated with powder foundation.[1] Another study analyzed the oily-shine appearance of foundation-coated skin in CIEXYZ color space through images.[8]

Concerning the passage of time, there have been a few investigations into the changes in the spectral reflectance of foundations. One study suggested 800 nm spectral reflectance wavelength to observe the long-lasting effect of foundation on human skin.[9] The researchers proposed their measurement system using a hyperspectral imager and identified the foundation-coated skin color changes over time and differs based on the subject's oxygen saturation level. Another study analyzed the particle changes during the drying and computationally simulated the design of liquid foundation.[10] The studies have provided a better understanding of the appearance of foundation-coated skin, however, the color changes in color space over time remain unexplored.

Both color diversification and the advancement of color measurement have guided the consumers to be aware of a subtle amount of color difference. In this study, the high sensitivity to the color difference among foundation products leads the consumer to perceive the color changes over time. The color change, often called the "darkening effect" of a foundation product, is not a secret in the industry. The discoloration or "darkening effect" of foundation is a critical concern for both customers and sellers. In the case of an in-store shopping, some sellers have suggested customers to test the shade and go around the shopping mall for 20 to 30 minutes and recheck the color before purchasing. Other sellers have suggested customers purchase the shade that is one stage brighter than the jaw skin color to compensate for the darkening effect. By convention, the evaluation of cosmetics has been based on users' subjective utterances. Although admitted by consumers, quantitative observations regarding the color changes have not been reported yet.

In this circumstance, the scientific metrics are acquired for both consumers and companies to perceive the "darkening effect" as one of a product's properties. As mentioned, only a few studies have attempted to examine the color changes in color space of foundation-coated surfaces quantitatively with the change of time continuously. Therefore, this study aims to observe the color changes of liquid foundation over time using a non-contact spectrophotometer. To evaluate the long-lasting color values of foundation, we carried out a continuous measurement up to 24 hours and compared the color changes of the opacity charts with those of human skin.

2 | MATERIALS AND METHODS

2.1 | Materials

2.1.1 | Liquid foundation samples

Four kinds of silicone-based liquid foundations in equivalent brightness were collected from well-known global brands distributed worldwide. All four foundations include "long-lasting" or "long-wear" effect in their names or product descriptions as presented in Table 1.

2.1.2 | Application to opacity charts

To observe the discoloration of liquid foundations within a certain duration, the measurement was conducted on both opacity chart and human skin. The opacity chart

TABLE 1 The four liquid foundations with an emphasis on long-lasting effect

Brand	Product descriptions
A	24-h wear. Flawless, natural, matte foundation.
B	This water-based matte foundation fuses a soft, 14-h velvet texture and SPF 20 UV protection, for a long-lasting fresh appearance.
C	Sheer Fitting Film with excellent light reflectivity and blending is formed to give a clear glow that lasts for 24 h.
D	A uniquely lightweight foundation that provides 16 h of fade-resistant wear with buildable, medium to full coverage that looks and feels natural.

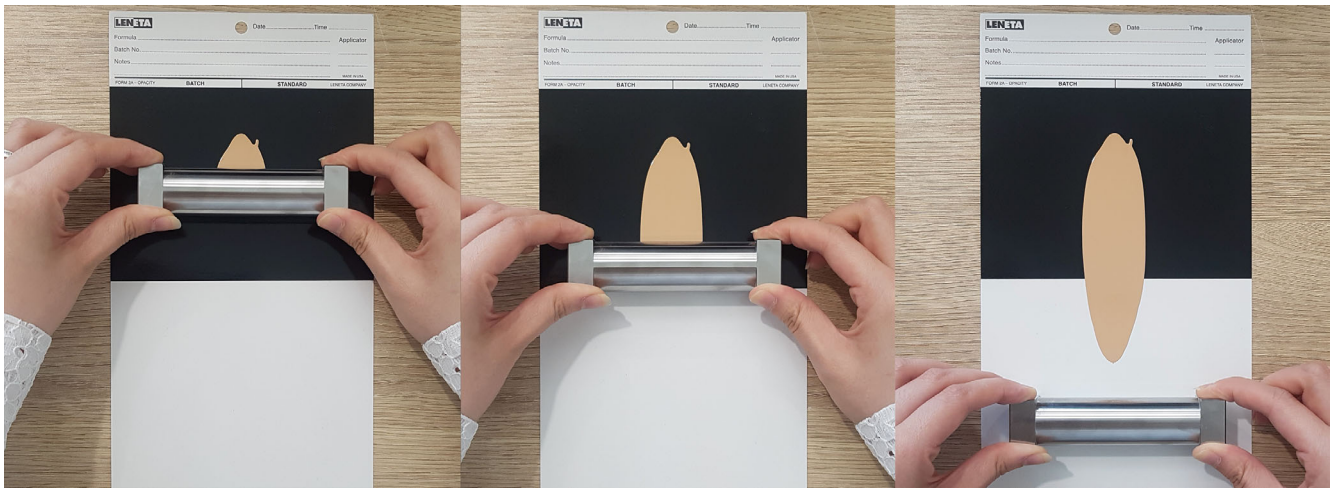

FIGURE 1 The process of applying liquid foundation on an opacity chart with an applicator with one side of thickness of 100 μm

was selected as a testing medium because the surface was smooth and flat for applying the foundation. It was coated and the liquid foundation would not be absorbed after application. A four-sided applicator with one side of thickness of 100 μm was used to apply the liquid foundation on the opacity chart. When the liquid foundation layer is not opaque, the color changes of the foundation coated layer will be influenced by the bottom layer, which refers to the bare skin or the opacity chart. Further calculation will be required to obtain the real color foundation layer. The thickness of 100 μm enabled the foundation to be completely opaque on the test chart, and enabled a direct observation for the color changes of the liquid foundation on different subjects. Four drops of the foundation were placed on the opacity chart. Two ends of the applicator were held, and the applicator was slid it from the top to bottom with a uniform strength. The measurement started immediately after the application. An example of the foundation-coated test paper is shown in Figure 1.

2.1.3 | Application to human skin

Three healthy people were recruited for the measurement. Their reported their facial skin types as dry, oily, and combined. They washed their face and applied the skincare products such as toner, lotion, and cream as usual. Five minutes later, two drops of liquid foundation were placed on the cheek region of each participant and then spread evenly around the cheek with a brush applicator. The measurement started rapidly after the application. An example of the foundation-coated skin is shown in Figure 2.

FIGURE 2 A participant with a foundation-coated cheek using a brush applicator

2.2 | Apparatus and measurement

A non-contact imaging spectrophotometer, X-rite MetaVue VS3200, was used for measurement on both opacity charts and human skin. The hardware and software are shown in Figure 3. The circular spot for the

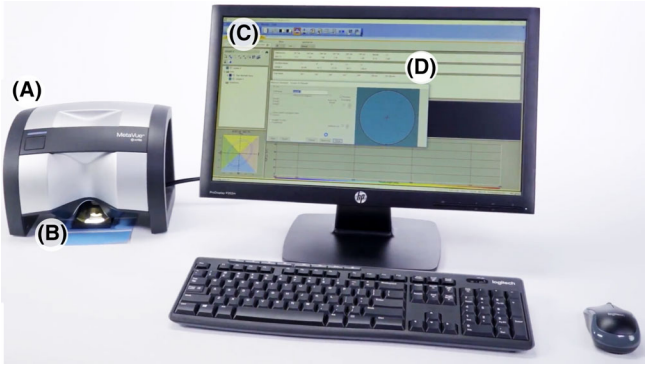

FIGURE 3 A scene of measurement using the MetaVueTM VS3200 and Color iQC software; A, non-contact imaging spectrophotometer; B, measurement window and material for measuring; C, interface of Color iQC software, which works with the spectrophotometer; D, live window to check the measurement target

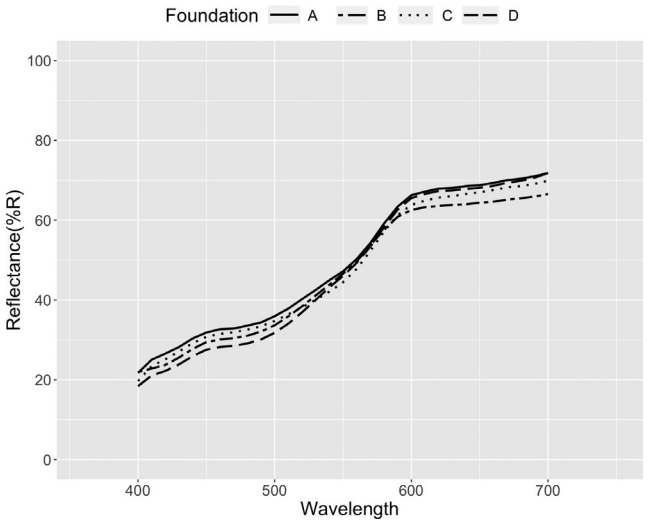

FIGURE 4 The spectral power distribution of the four foundations A, B, C, and D

measurement was set as 12 mm in diameter. When measuring the color, it blinked around 8 to 10 seconds and the sample under the measurement window would be measured without contact. This enabled the repeated measure for the same region.

The measurement resulted in both colorimetric data such as L, a, and b in CIE 1976 $L^*a^*b^*$ and the reflectance with a spectral range of 400 to 700 nm in 10 nm intervals that could be collected. L^* indicates the brightness, while a^* and b^* explains greenness-redness and blueness-yellowness, respectively. The a^* and b^* crossed at a right angle by creating an $a^* - b^*$ plane. In the analysis, the L^*, a^*, and b^* values were converted into CIE $L^*C^*h^*$ to refer the Chroma and hue straightforwardly. C^* stands for the Chroma, the vividness of the color, and was estimated through a Euclidean distance of a^* and b^* from achromatic orientation, $a^* = 0$ and $b^* = 0$. Lastly, the h^* refers to a hue angle of a color in the $a^* - b^*$ plane.

Before the measurement, we configured the light source as a standard illuminant (D65) and applied a 2° viewing angle. In Figure 4 the spectral reflectance distributions of the foundations from the four brands are illustrated. The corresponding colorimetry properties are shown in Table 2 as the initial (0 hour) values.

2.3 | Measure of time-resolved discoloration

In daily makeup, females usually use applicators to apply a light layer of liquid foundation on their skin. The applicators include cushion, pump, brush or even the hand. To simulate the situation, previous studies used pigskin,[11] artificial skin,[12] or alternative materials that were compared with the result on the human skin.[1]

In this study, we used a non-contact imaging spectrophotometer that enabled us to measure the surface color of a wet and light layer with a time interval. For example, to observe the color changes right after makeup was applied, we began the measurements of the foundation applied to the opacity chart every minute for the first 2 hour. We intended to figure out the patterns of the color change during 24 hour, and the measurements were conveyed with the time sequence of 0, 2, 4, 6, 8 and 24 hours. As it was inhumane to ask a person to stand perfectly for more than a couple of minutes, the continuous measurements were basically conducted using the opacity chart.

In addition, because we attempted to compare the discoloration on the opacity chart with that on human skin, a one-off measurement was conducted on both the opacity chart and human cheek in three repeated measurements. The measurement was performed only on the first moment when the foundation was applied and then when the entire measure period has passed. The measurement region was marked to ensure the two measurements were conducted on the same region. For each foundation, the measurement was performed on three participants with different skin types for three times. During the measurement, the participants stayed in the lab and the lab environment was controlled to have a fixed humidity and temperature range, 35% ± 5 and 25°C ± 1, respectively.

3 | RESULTS

To indicate the color change, we adopted the color difference, ΔE_{ab}, the Euclidean distance between two

TABLE 2 Time-resolved discoloration on opacity chart with four foundations over 24 hours measured with a non-contact imaging spectrophotometer (X-rite MetaVue VS3200)

Brand	Time	L^*	a^*	b^*	C^*	h^*	ΔL^*	Δa^*	Δb^*	ΔC^*	Δh^*	ΔE_{ab}	$L\%$	$E\%$
A	0 h	76.86	10.93	23.40	25.83	64.97								
	2 h	74.01	12.25	22.28	25.43	62.33	−2.85	1.32	−1.12	−0.40	−2.64	3.33	78%	73%
	4 h	73.37	12.79	21.78	25.26	59.57	−3.49	1.86	−1.62	−0.57	−5.40	4.27	96%	94%
	6 h	73.32	12.76	21.55	25.05	59.36	−3.54	1.83	−1.85	−0.78	−5.61	4.39	97%	96%
	8 h	73.23	12.74	21.49	24.98	59.33	−3.63	1.81	−1.91	−0.85	−5.64	4.48	100%	98%
	24 h	73.22	12.67	21.28	24.77	59.22	−3.64	1.74	−2.12	−1.06	−5.75	4.56	100%	100%
B	0 h	75.20	9.16	24.93	26.56	69.83								
	2 h	69.18	12.42	25.96	28.77	64.43	−6.02	3.26	1.03	2.21	−5.40	6.92	79%	79%
	4 h	68.20	13.06	26.27	29.34	63.57	−7.00	3.90	1.34	2.78	−6.26	8.12	92%	93%
	6 h	67.84	13.24	26.30	29.45	63.28	−7.36	4.08	1.37	2.89	−6.55	8.53	96%	98%
	8 h	67.79	13.25	26.31	29.46	63.26	−7.41	4.09	1.38	2.90	−6.57	8.58	97%	98%
	24 h	67.57	13.21	26.11	29.26	63.17	−7.63	4.05	1.18	2.70	−6.66	8.72	100%	100%
C	0 h	75.68	11.70	22.68	25.52	62.71								
	2 h	74.33	12.51	22.60	25.83	61.04	−1.35	0.81	−0.08	0.31	−1.67	1.58	58%	61%
	4 h	74.19	12.57	22.61	25.87	60.93	−1.49	0.87	−0.07	0.35	−1.78	1.73	64%	67%
	6 h	74.08	12.58	22.57	25.84	60.87	−1.6	0.88	−0.11	0.32	−1.84	1.83	69%	71%
	8 h	73.95	12.63	22.55	25.85	60.75	−1.73	0.93	−0.13	0.33	−1.96	1.97	74%	77%
	24 h	73.35	12.72	22.35	25.72	60.36	−2.33	1.02	−0.33	0.20	−2.35	2.56	100%	100%
D	0 h	75.61	11.98	28.61	31.02	67.28								
	2 h	74.65	12.29	27.40	30.03	65.85	−0.96	0.31	−1.21	−0.99	−1.43	1.58	65%	73%
	4 h	74.54	12.34	27.32	29.98	65.69	−1.07	0.36	−1.29	−1.04	−1.59	1.71	72%	79%
	6 h	74.49	12.34	27.29	29.95	65.67	−1.12	0.36	−1.32	−1.07	−1.61	1.77	76%	82%
	8 h	74.47	12.34	27.29	29.95	65.67	−1.14	0.36	−1.32	−1.07	−1.61	1.78	77%	82%
	24 h	74.13	12.35	27.08	29.76	65.48	−1.48	0.37	−1.53	−1.26	−1.80	2.16	100%	100%

Note: C^* and h^* from CIE-LCh. The humidity and temperature were a constant 35% and 25°C, respectively, during the measurement. Abbreviations: Δa^*, difference of a^*; Δb^*, difference of b^*; ΔC^*, difference of C^*; ΔE_{ab}, color difference; Δh^*, difference of h^*; ΔL^*, difference of L^*; $E\%$, ratio of color difference change to total; $L\%$, ratio of lightness change to total.

co-ordinates profiled by L^*, a^*, and b^*. Although we deliberately chose the foundations with similar colors, the initial color values of among the products differed slightly. Thus, we focused on the discoloration referring to the ΔE_{ab} from the initial measurement.

$$\Delta E_{ab} = \sqrt{\left(L_1^* - L_2^*\right)^2 + \left(a_1^* - a_2^*\right)^2 + \left(b_1^* - b_2^*\right)^2} \quad (1)$$

The measurement consisted of two phases. In the first phase, the measurement was taken every minute for the initial 2 hours. A total of 120 measurements were made in 1-minute time intervals. In the second phase, we continued the measurement with a time interval of 2 hours for the remaining 22 hours. Finally, we gathered the discoloration patterns of four foundations over 24 hours.

3.1 | Discoloration pattern observed with the opacity charts

3.1.1 | Discoloration for the initial 2 hours

We paid particular attention to the initial 2 hours, because this time period included a makeup itself and a check-up of overall outfits before the first makeup correction. For instance, the makeup reviews released on social media described the color quality of the facial makeup products just right after their application, assuming that the color was unchanged since the application. As presented in Figure 5, however, we discovered that the initial 2 hours are quite critical for some products. Their discoloration exceeded 2.3, which is the just noticeable difference (JND) in color.[13,14] Especially during the first 20 minutes,

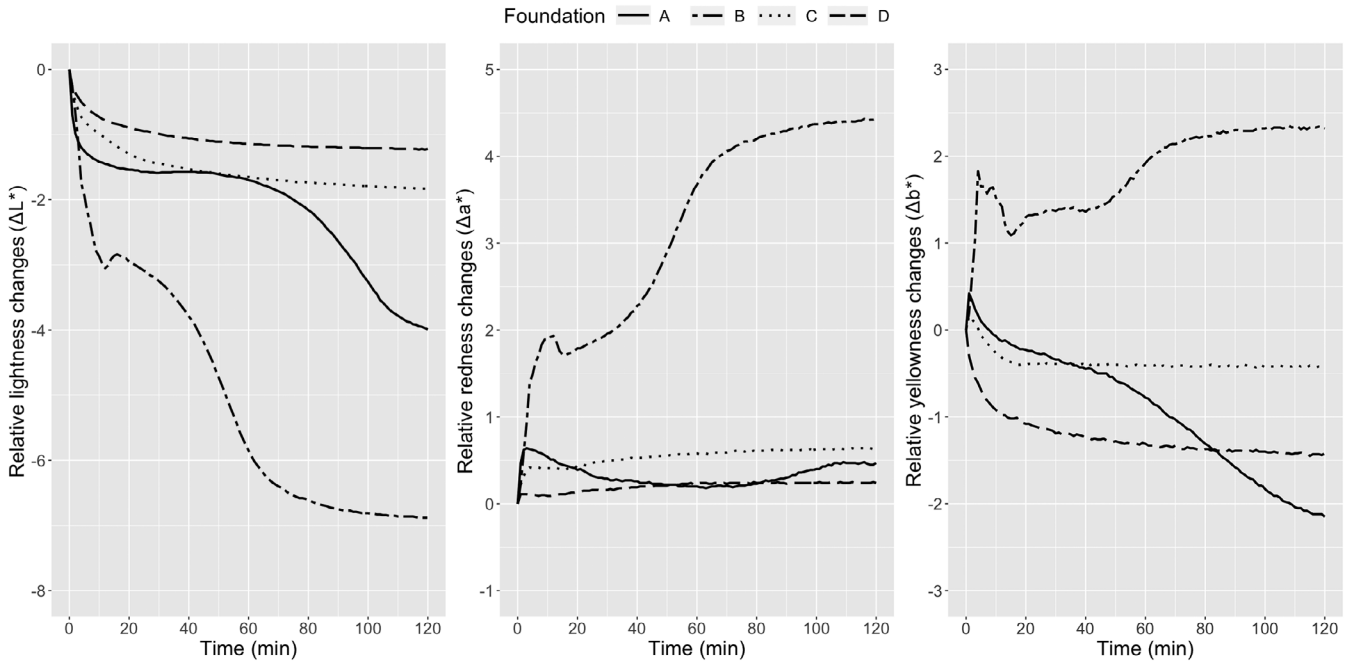

FIGURE 5 Relative changes of L^* (lightness), a^* (greenness-redness) and b^* (blueness-yellowness) for four foundations within the initial 2 hours

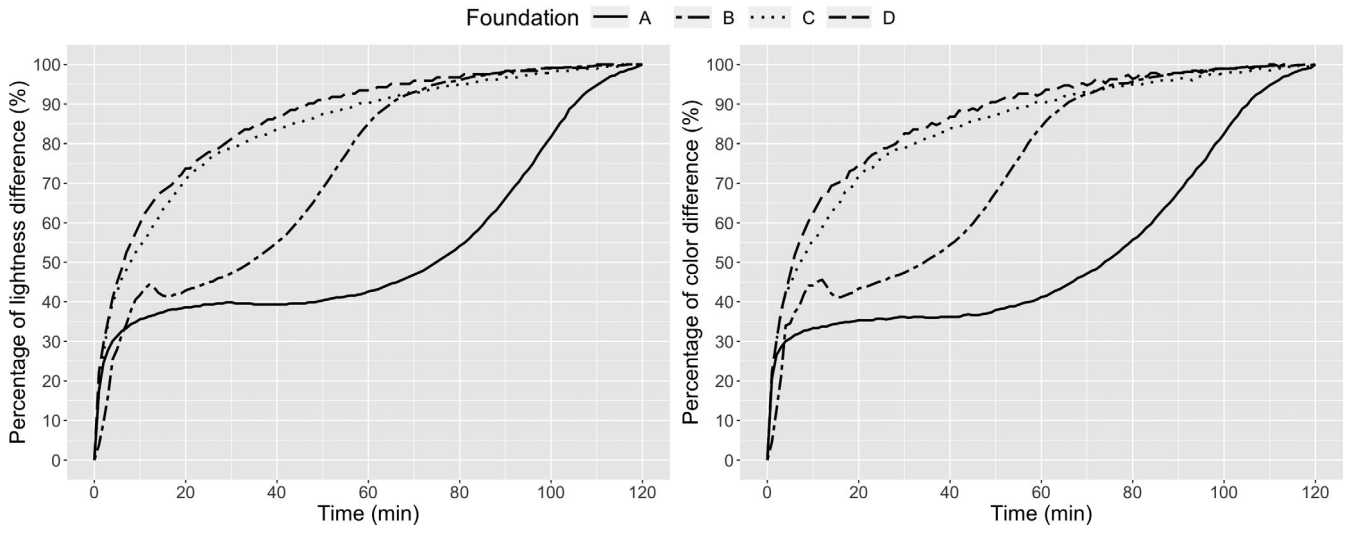

FIGURE 6 Lightness difference (left) and color difference (right) within 2 hours for four foundations

discoloration was noticeable across the color attributes, L^*, a^*, and b^*, as well as the products. In the case of foundation B, the discoloration occurred most drastically. It implies consumers visually experience the "darkening effect" after the application of makeup, which possibly elicits a negative emotion.

Furthermore, to figure out the patterns of time-resolved discoloration, the accumulation of lightness difference within the initial 2 hours is illustrated in Figure 6. An S-shaped increase is spotted for foundation A and B. For foundations C and D, a logarithmic increase is spotted displaying almost 50% of lightness change within the first 10 minutes. Also, the patterns in Figure 6 appear to be similar, which implies that the major color change of the liquid foundation relies on its lightness.

3.1.2 | Discoloration for 24 hours

We proceeded with further measurements along during the remaining 22 hours. The discoloration of the foundation-coated opacity chart is listed in Table 2. The

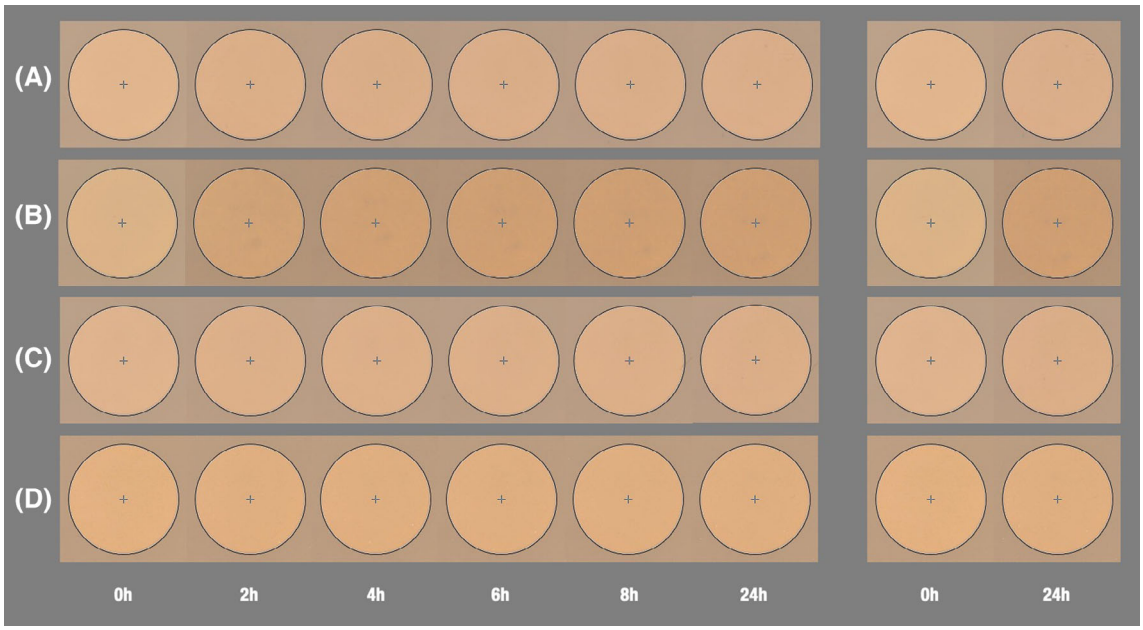

FIGURE 7 Sorted shades of four foundations over 24 hours. The individual images were captured right immediately after each measurement was obtained from the capture function of the Color iQC software

foundations C and D show less discoloration than foundations A and B, thus maintaining the trend of the initial 2 hours.

During the 24 hours, the lightness (L^*) of all four foundations decreased, indicating a "darkening effect" of foundation over time, as reported by consumers. In terms of chromaticity, the a^* of all four foundations were increased, thereby explaining that the color has become more reddish. Regarding b^*, all foundation except for foundation B were decreased, inferring that most of them became less yellowish than at the beginning. When we observed the h^*, a hue angle of color in the $a^* - b^*$ plane, all were decreased. The decrease of h^* corresponds to that all foundations becoming more reddish when time passes. The apparatus provides the photo records from each measurement, and Figure 7 presents the array the photos of each foundation along the time passage.

In addition, the speed of discoloration of the four foundations also differed. In general, over 60% of color changes were completed within the first 2 hours for all four foundations. Specifically, for foundation A and B, over 70% of color changes were completed within the first 2 hours and over 90% of color changes were completed within the first 4 hours. The discoloration for foundations A and B are strong during the first 4 hours, but the color remains relatively the same after then. For foundations C and D, over 70% of color changes were completed within the first 8 hours rather than 2 hours. The color changing process is relatively slow and durable.

3.2 | Discoloration on human skin

Similarly, the mean and SD of bare skin color, foundation-coated skin color and color changes of foundation-coated skin over 2 hours are listed in Table 3. In general, color changes appeared to be similar within the same foundation across different participants. L^* decreased and a^* increased for entire foundations on all participants, which was consistent with the measurement on opacity chart. While b^* was decreased for all foundations except foundation B on one participant. Specifically, foundation D had the smallest discoloration followed by the foundations C, A, and B. Furthermore, skin color varied below 55° of hue angle, while foundation-coated skin has the hue degree ranging from 60° to 70°. After 120 minutes, the hue degree decreased for all foundations and participants. This indicates that foundation is relatively more yellowish than skin but it becomes reddish over time.

3.3 | Comparison of discoloration on opacity chart and human skin

Thus, we compared the discoloration captured from the opacity chart with that from the human skin for the initial 2 hours right after the application. The comparison of color changes of the foundation-coated layer was listed in Table 4 with ΔL^*, Δa^*, Δb^*, ΔC^*, Δh^* and ΔE_{ab}. In general, the color changes on human skin are more drastic

TABLE 3 Time-resolved discoloration on human skin with four foundations

			Mean (SD)								
Brand	**Skin type**	**Time**	***L****	***a****	***b****	***C****	***h****	**Δ*L****	**Δ*a****	**Δ*b****	**ΔE_{ab}**
A	Dry	Bare skin	70.31 (0.30)	11.86 (0.11)	13.37 (0.11)	17.89 (0.06)	48.39 (1.20)				
		0 h	74.04 (1.17)	9.44 (0.45)	19.59 (1.79)	21.85 (1.69)	63.95 (1.70)				
		2 h	69.17 (0.66)	11.58 (0.45)	19.03 (0.90)	22.27 (1.01)	58.66 (0.24)	−4.86 (0.63)	2.14 (0.08)	−0.56 (0.95)	5.40 (0.70)
	Combined	Bare skin	64.20 (0.31)	12.65 (0.17)	17.12 (0.28)	21.35 (0.15)	53.40 (0.78)				
		0 h	74.83 (0.42)	9.13 (0.32)	20.22 (0.47)	22.19 (0.56)	65.67 (0.32)				
		2 h	68.85 (0.44)	11.06 (0.32)	18.47 (0.61)	21.53 (0.66)	59.09 (0.54)	−5.98 (0.74)	1.93 (0.23)	−1.75 (0.21)	6.53 (0.71)
	Oily	Bare skin	62.80 (0.20)	14.34 (0.25)	17.16 (0.13)	22.41 (0.14)	50.18 (0.64)				
		0 h	73.08 (0.57)	9.53 (0.48)	20.25 (1.19)	22.41 (1.22)	64.79 (0.27)				
		2 h	69.15 (1.09)	11.54 (0.62)	17.89 (1.22)	21.85 (1.08)	58.04 (1.05)	−3.93 (0.52)	2.01 (0.27)	−2.36 (1.08)	5.09 (0.40)
B	Dry	Bare skin	69.84 (0.28)	11.57 (0.17)	14.00 (0.01)	18.15 (0.09)	50.60 (0.42)				
		0 h	72.11 (1.08)	8.96 (0.32)	22.70 (1.55)	24.42 (1.34)	68.40 (1.97)				
		2 h	65.44 (0.24)	12.52 (0.30)	22.77 (0.66)	25.99 (0.65)	61.18 (0.71)	−6.17 (0.02)	3.56 (0.37)	0.29 (2.16)	7.67 (0.83)
	Combined	Bare skin	62.75 (0.20)	13.42 (0.28)	16.34 (0.34)	21.27 (0.18)	50.45 (1.08)				
		0 h	71.43 (0.29)	8.04 (0.22)	22.02 (0.65)	23.44 (0.63)	69.78 (0.46)				
		2 h	63.88 (0.62)	11.23 (0.63)	20.83 (0.17)	23.68 (0.17)	61.68 (1.52)	−7.55 (0.45)	3.20 (0.66)	−1.18 (0.52)	8.31 (0.47)
	Oily	Bare skin	61.66 (0.13)	16.80 (0.17)	16.04 (0.06)	23.25 (0.09)	43.72 (0.38)				
		0 h	71.45 (0.41)	9.12 (0.25)	24.44 (0.87)	26.09 (0.83)	69.54 (0.80)				
		2 h	63.26 (0.35)	11.20 (0.04)	20.27 (0.22)	23.16 (0.19)	61.09 (0.30)	−8.19 (0.46)	2.09 (0.27)	−4.16 (0.71)	9.45 (0.24)
C	Dry	Bare skin	70.00 (0.25)	11.63 (0.07)	13.67 (0.11)	17.95 (0.11)	49.52 (0.22)				
		0 h	74.23 (0.80)	10.04 (0.30)	19.78 (1.42)	22.19 (1.41)	63.05 (0.97)				
		2 h	71.21 (0.69)	11.02 (0.15)	18.94 (0.82)	21.91 (0.63)	59.78 (1.43)	−3.02 (0.16)	0.98 (0.42)	−0.85 (0.98)	3.39 (0.37)
	Combined	Bare skin	63.26 (0.59)	13.52 (0.30)	17.01 (0.10)	21.68 (0.13)	51.36 (0.74)				
		0 h	73.97 (0.46)	10.06 (0.41)	20.28 (0.25)	22.64 (0.40)	63.63 (0.67)				
		2 h	71.03	10.36	18.68	21.46	60.99	−2.94	0.30	−1.60	3.39

TABLE 3 (Continued)

Brand	Skin type	Time	Mean (SD)								
			L^*	a^*	b^*	C^*	h^*	ΔL^*	Δa^*	Δb^*	ΔE_{ab}
			(0.92)	(0.10)	(0.28)	(0.14)	0.51	(0.48)	(0.35)	(0.51)	(0.55)
	Oily	Bare skin	63.04 (0.41)	14.58 (0.33)	15.85 (0.15)	21.67 (0.10)	47.54 (0.93)				
		0 h	74.02 (0.46)	9.81 (0.41)	19.58 (0.13)	22.03 (0.27)	63.56 (0.97)				
		2 h	70.31 (0.26)	10.74 (0.37)	17.76 (0.49)	20.76 (0.61)	58.86 (0.19)	−3.71 (0.24)	0.94 (0.15)	−1.82 (0.62)	4.26 (0.48)
D	Dry	Bare skin	69.30 (0.20)	11.67 (0.06)	15.01 (0.17)	19.01 (0.16)	52.09 (0.27)				
		0 h	73.57 (0.42)	10.95 (0.18)	25.05 (0.49)	27.34 (0.52)	66.40 (0.11)				
		2 h	72.63 (0.36)	11.13 (0.48)	23.84 (0.88)	26.31 (0.99)	64.99 (0.39)	−0.93 (0.32)	0.18 (0.58)	−1.21 (1.09)	1.83 (0.38)
	Combined	Bare skin	64.16 (0.13)	13.12 (0.15)	16.30 (0.05)	20.93 (0.13)	51.21 (0.25)				
		0 h	73.36 (0.55)	10.37 (0.38)	24.74 (0.84)	26.83 (0.92)	67.26 (0.08)				
		2 h	71.63 (0.38)	10.74 (0.39)	23.86 (0.86)	26.17 (0.93)	65.78 (0.29)	−1.73 (0.32)	0.53 (0.00)	−0.88 (0.40)	2.03 (0.15)
	Oily	Bare skin	59.85 (0.08)	17.42 (0.10)	14.83 (0.05)	22.89 (0.06)	40.43 (0.23)				
		0 h	74.12 (0.42)	10.57 (0.25)	24.42 (0.69)	26.61 (0.73)	66.58 (0.17)				
		2 h	72.63 (0.29)	11.06 (0.07)	24.25 (0.19)	26.65 (0.15)	65.49 (0.29)	−1.49 (0.13)	0.49 (0.31)	−0.17 (0.54)	1.66 (0.08)

Note: The humidity and temperature remained a constant 35% and 25°C, respectively, during the measurement.

TABLE 4 Time-resolved discoloration on human skin and opacity chart for 2 hours for four foundations

Brand	Subject	Mean (SD)					
		ΔL^*	Δa^*	Δb^*	ΔC^*	Δh^*	ΔE_{ab}
A	Human skin	−4.93 (1.05)	2.03 (0.21)	−1.56 (1.08)	−0.27 (0.64)	−6.21 (1.16)	5.67 (0.85)
	Opacity chart	−3.11 (0.40)	1.52 (0.33)	−1.21 (0.14)	−0.37 (0.05)	−4.27 (0.80)	3.67 (0.52)
B	Human skin	−7.47 (0.85)	2.95 (0.78)	−1.76 (2.09)	−1.75 (1.97)	−8.97 (1.56)	8.48 (0.92)
	Opacity chart	−6.58 (0.49)	3.59 (0.29)	1.41 (0.44)	2.72 (0.53)	−5.65 (0.28)	7.64 (0.62)
C	Human skin	−3.22 (0.46)	0.74 (0.43)	−1.42 (0.77)	−9.01 (0.79)	−3.54 (1.09)	3.68 (0.60)
	Opacity chart	−1.48 (0.12)	0.74 (0.13)	−0.14 (0.11)	0.22 (0.16)	−1.61 (0.12)	1.67 (0.10)
D	Human skin	−1.38 (0.42)	0.40 (0.37)	−0.75 (0.79)	−0.63 (0.74)	−2.42 (1.77)	1.85 (0.28)
	Opacity chart	−0.94 (0.02)	0.30 (0.15)	−1.12 (0.09)	−0.91 (0.13)	−1.35 (0.23)	1.50 (0.06)

than those on the opacity charts across all four foundations over the same time duration. Consistent trends of color changes were observed through ΔL^*, Δa^*, Δh^* and ΔE_{ab}. Slightly different changes were observed on b^*, which also affected C^* as C^* was calculated based on a^* and b^*.

Specifically, in Figure 8, we plotted the total color changes, lightness changes, and hue changes for the human skin and opacity chart. For a clear visualization, $-\Delta L^*$ ($L_1^* - L_2^*$) and $-\Delta h^*$ ($h_1^* - h_2^*$) were plotted here to make the bar chart in the same direction. From this figure, we conclude that the total color difference was best

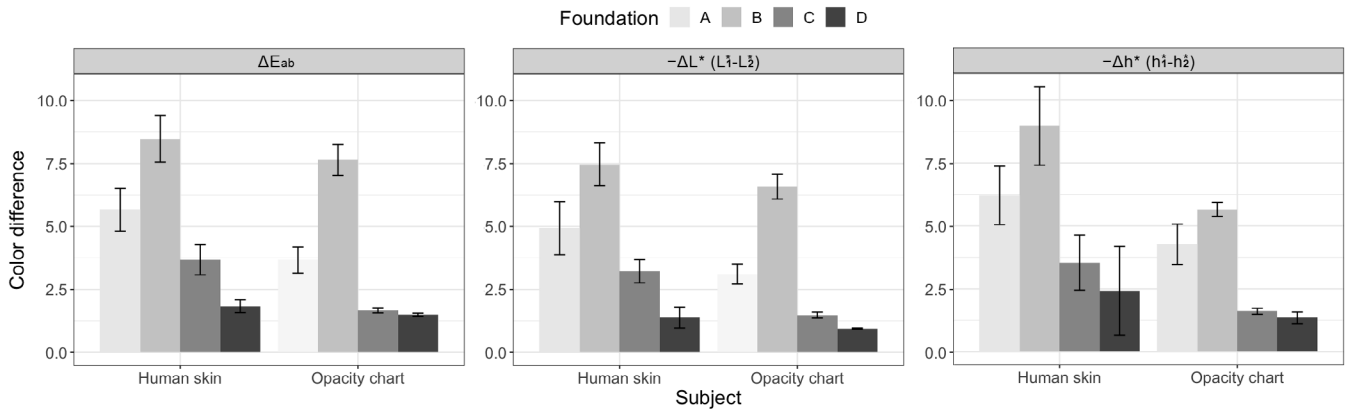

FIGURE 8 Time−resolved discoloration on human skin and opacity chart for 2 hours for four foundations on ΔE*, −ΔL* (-) and −Δh* (-). For a clear visualization, negative difference of L*, and negative difference of h* are plotted

presented through lightness change and hue change. Both human skin and opacity chart share the same tendency for these three color features. In addition, the standard deviation for the human skin is slightly larger than the opacity chart. This also indicates that testing the discoloration on opacity chart ensures more stable results although the color changes are less drastic.

4 | COMMUNICATION OF DISCOLORATION

As we observed the patterns of discoloration, we profiled the quantity of color changes in terms of time after the application, lightness (L^*) difference, hue difference considering a^* and b^*, and the perceptual impact of the changes. An index should pursue self-explanatory and robustly applicable for any diverse case (ie, various foundation brands). In this study, we aimed at an index that communicates the ability of long-lasting color of foundation and tried two approaches: the first index indicates the color difference after certain time, while the other index shows the time until certain discoloration level has been reached.

4.1 | Proposal of *Dt*, the discoloration with the passage of time

The "*Dt*" expresses the discoloration amount after a passage of time. The "*D*" stands for discoloration, and the "*t*" is the time in hours. Thus, the *Dt* of a foundation communicates the discoloration quantity after "*t*" hours, and the unit is ΔE_{ab}. For the application of *Dt* in practice, we forecast $D_{0.5}$, D_2, D_8, D_{16} or D_{24} can be meaningful. Each is mapped to sequential scenarios, such as after the makeup (in 0.5 hour), makeup check during the first coffee break (in 2 hours), makeup check leaving one's work place(in 8 hours), makeup removal for the sleep(in 16 hours), and a complete 1 day as in advertisement (in 24 hours), respectively.

TABLE 5 An example of look-up table to confine the discolouration quantity

Discolouration level	D_2	D_{24}
Close to zero	<1	<1.5
Merely	1-2	1.5-3
Noticeable	2-3.5	3-5
Very noticeable	>3.5	>5

Based on the concept of *Dt*, we suggest a look-up table wherein the long-lasting quality is evaluated, as presented in Table 5. For example, the D_2 and D_{24} refer to the two major time milestones. In previous studies, noticeable color difference has been suggested based on a standard observer. Five levels of color difference were proposed, from no difference, noticed by experienced observer, noticed by unexperienced observer, clear difference, to two different colors.[14] In terms of the color of beige, not only for skin but also foundations, the sensitivity to the color difference differs from experience to experience. Therefore, we imported the first four levels and renamed into "close to zero," "merely," "noticeable," and "very noticeable," and maintain the numeric values for D_2. According to Table 2, around 60% to 80% of discoloration happened in the first 2 hours concerning the total color change within 24 hours. Based on this ratio of color changes for 2 and 24 hours, critical values for D_{24} were interpreted. Through these indices, both the quantity and the evaluation of long-lasting ability can be communicated explicitly. For the four foundations measured in

this study, foundation C and D are "merely," foundation A is "noticeable," and foundation B is "very noticeable" for both D_2 and D_{24}. In a future research, the threshold range must be more refined to respond to various environmental conditions reliably.

4.2 | Proposal of $T\Delta E$, the time until a critical discoloration

Alternatively, we can report the time until the discoloration is reached to a certain amount. For example, "T2.3" can refer to the time until the discoloration is controlled within the JND in color perception. In Table 2, the discoloration of foundation D was 2.16 only, which implies that its T2.3 will be longer than 24 hours. Hence, among the four foundations, foundation D is the only one that deserves a name of 24-hour long-lasting. Currently, the foundation D declares a 16-hour for the lasting period, but it can be prolonged to 24 hours, if the long-lasting is dedicated to lasting of color. Also, different ΔE_{ab} amounts can be applied depending on the criteria; thus, foundations are qualified or unqualified. However, the current regulation does not request any clinical evidence when a brand tries to appeal the concept of "long-lasting."

Resuming to the above mentioned two indices, there should be alternatives to notate the phenomenon discoloration, particularly as to the specification of foundation cosmetics. If a brand has achieved low discoloration over time, the discoloration level will be highlighted for the promotion. In contrast, if a brand struggles with consumers' complains about the discoloration, it could diagnose the color change following the method introduced in this study. In this regard, this study provides methods to measure the discoloration and to make an interpretation thereof.

5 | DISCUSSION

This study attempted to discover the phenomenon of the, "darkening effect" of liquid foundation through the repeated measurements with time intervals. The darkening effect is notorious among consumers, and ironically brands promote their foundation products with a particular emphasis on "long-lasting" effect to appeal consumers. However, no trials have been made to measure the color changes of liquid foundation over time quantitatively.

The difficulty of observation results from three aspects. First, both skin and foundation layers are thin and translucent. For normal daily makeup, foundation layer has a thickness around 15 μm.[15] Even with a foundation of strong coverage, foundation-coated skin has two translucent layers. Further calculations are required to simulate the foundation layer's color change.

Second, the condition of skin is hard to control. When foundation is applied on the skin, the water and oil can evaporate and be absorbed by skin. As time goes by, skin secretes as well. This process can be greatly affected by the environment temperature and humidity. Furthermore, skin type for every person is different and changes daily. Therefore, it is hard to obtain accurate and detailed condition of the skin.

Third, long time or continuous observation is hard to proceed. Foundation-coated layer is not completely dry from the very beginning. One-off measurement can be conducted with a contact spectrophotometer while continuous measurement is challenging to realize. Furthermore, observation around 2 to 8 hours might be possible on human skin, but a duration longer than 8 hours is difficult.

Under these circumstances, we addressed to this long-lasting issue of liquid foundation, observed the phenomena of the color of liquid foundation changing over time, and titled it as discoloration of liquid foundation. In particular, measurements were conducted on opacity charts and then human skin facilitated with a non-contact imaging spectrophotometer on four foundations in thickness of 100 μm. Although it is much thicker than daily makeup, it helped us to record and observe directly the color changes of liquid foundation over time.

In terms of the opacity chart, with the help of the non-contact instrument, the measurement can be repeated for the same region over time. First, a continuous measurement with a 60-second interval was conducted with an opacity chart for the initial 2 hours. Then the discoloration within the remaining 22 hours was measured using 2-hour intervals as a long-term observation. Additionally, the discoloration on the opacity chart was compared with three healthy human skins for different facial skin types for 2 hours. The measurement region on skin was marked first. Participants did not need to have their face in the measurement window. Through the live monitoring interface of the software, the same region was measured over time. From a series of measurements, the color changing over time—specially, the decrease of lightness and hue angle of liquid foundation—does occur.

Through a series of measurement, we conclude that color of liquid foundation noticeably changes over time, as consumers have reported. The discoloration is mainly the decrease of lightness and hue angle toward being reddish. However, the variability of darkening degree is remarkably high depending on the products. In spite of similar initial colors right after the application, the darkening amount and speed varied across the foundations. For the four foundations selected in the study, different degree and speed of color changing was observed. For

example, in cases of foundation A and B the discoloration was mostly visible within the initial 20. Therefore, the patterns and amount of discoloration should interest consumers especially those who concern the "darkening effect."

Furthermore, this kind of "darkening effect" can be of vital importance for foundation shade selection when considering the original skin color. For example, for the participant with dry skin, although a lighter foundation shade was selected (for foundation A and B), the foundation-coated skin color can become darker than the original bare skin. This would affect the satisfaction of the user experience for makeup. Therefore, observation and quantitative analysis for the discoloration of liquid foundation can provide more scientific clues and evidence for a satisfying foundation shade selection.

However, the reason behind this phenomenon needs exploration in future studies. The evaporation process of the liquid foundation might be important for discoloration. Depending on which phase the foundation color was fully developed, color shift might not happen for some foundations.[16] Not only water, but also silicone evaporates. After evaporation, some ingredients remain with the pigment through different forms. What kind of molecule they are and how they remain can affect the color. Use of silicone acrylate copolymers was supposed to be helpful for long-lasting foundation formular[17] due to the ability to form a durable film resistant to abrasion and wash-off.[18]

Still in our study, the time-resolved discoloration was observed for four silicone-based liquid foundations. In the future study, with controlled ingredients and manufacturing process, the reasons for the discoloration should be investigated.

Nevertheless, this study, for the first time, proved that the phenomenon of discoloration for liquid foundation, known as "darkening effect," results from decreased lightness and hue degree, which was consistent with the empirical experience. We concluded the evaporation process of the liquid foundation plays an important role in discoloration. In this circumstance, the opacity chart is considered to be an appropriate alternative material to help observe the phenomenon instead of conducting a long experiment on human skin. Furthermore, the proposed indices can be helpful to communicate the discoloration level of products and give them a chance to make it a property. Different from other liquid foundation properties, such as lightness, tone, texture, and coverage, it is hard to describe discoloration with customers or among brands because every personal experience differs. With the proposed index, it is possible to identify the level of discoloration with standard materials. In addition, the measurement method proposed in the study can be utilized by companies and manufactures to explore the color quality of the foundation and develop better long-lasting liquid foundations. In a future study, it is expected that a further investigation will identify the discoloration patterns in more liquid foundation products.

6 | CONCLUSION

In this study, the color change of the liquid foundation was investigated over time, that which is commonly denoted as the long-lasting quality of foundation products. Based on the colorimetric measurements, alternatives of notation are proposed to illustrate the discoloration phenomena.

A non-contact spectrophotometer enables the repeated measurements on the wet surface, and this study was motivated to investigate quantify the discoloration of foundation products and to provide the information in a meaningful way. A continuous measurement within 2 hours and long-term measurement up to 24 hours were conducted using on opacity charts. Furthermore, the results on the opacity charts were also compared with the results on three healthy humans with different skin types in repeated measurements.

From the series of measurements, we concluded that discoloration of foundation is kind of phenomenon of lightness decrease and hue angle decrease. As time goes by, the foundation-coated layer becomes darker and reddish. In addition, we found a similar tendency of discoloration between foundation-coated opacity chart and foundation-coated human skin among all four foundation products. From the repeated measurements the proposed method with opacity chart was more reliable than the measurement on the human skin. In addition, we proposed "*Dt*" and "*T*Δ*E*." The "*Dt*" was to identify the discoloration quantity within a certain time duration, and the "*T*Δ*E*" (eg, "T2.3") was to express the time until the target discoloration, such as JND, in color perception occurs. The application of both indices was discussed in context of communication between brands and consumers. Although the phenomenon of discoloration of liquid foundation has been quantitatively observed and recorded in this study, together with the general color tendency, the reason behind remains uncovered. We suggested two possible factors that influenced the color changes. More studies are expected to be conducted to better explain the reason behind discoloration in details.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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