

A novel automated approach to rapid and precise *in vivo* measurement of hair morphometrics using a smartphone

Ali Majd, MD¹, Mohammed AlJasser, MD, FRCPC^{1,2}, Hengameh Mirzaalian, PhD³, Jerry Shapiro, MD, FRCPC^{1,4,5}, Ghassan Hamarneh, PhD³, Harvey Lui, MD, FRCPC^{1,4,6}, Leopoldo Duailibe Nogueira Santos, MD¹, Thomas Chu, MD⁷, Tim K. Lee, PhD^{1,4,6}

¹Department of Dermatology and Skin Science, University of British Columbia, Vancouver, BC Canada

²Division of Dermatology, King Saud bin Abdulaziz University for Health Sciences, Riyadh, Saudi Arabia

³Medical Image Analysis Lab, School of Computing Science, Simon Fraser University, Burnaby, BC Canada

⁴Vancouver Coastal Health Research Institute, Vancouver, BC Canada

⁵The Ronald O. Perelman Department of Dermatology, NYU Grossman School of Medicine

⁶Cancer Control Research Program and Integrative Oncology – Imaging Unit, BC Cancer, Vancouver, BC Canada

⁷Department of Dermatology, Wayne State University School of Medicine, Detroit, Michigan

Corresponding Author:

Tim K. Lee, PhD

Email: tlee@bccrc.ca

Telephone: 604-675-8053

Fax: 604-675-8180

Address: 675 W 10th Ave., Vancouver, BC, Canada, V5Z 1L3

Funding Sources: None

Conflict of interest: None

Data Availability: The data are not publicly available due to privacy or ethical restrictions.

Acknowledgements: N/A

Ethical approval: Clinical Research Ethics Board of the University of British Columbia (H14-01874)

Abstract word count: 250

Manuscript word count: 3180

Number of tables: 3

Number of figures: 4

Number of references: 17

Running title: Automated hair morphometrics measurement

Key words: trichometry; trichoscopy; scalp; image processing; alopecia.

This is the peer reviewed version of the following article: ***Majd A, AlJasser M, Mirzaalian H, et al. A novel automated approach to rapid and precise in vivo measurement of hair morphometrics using a smartphone. Skin Res Technol. Published online July 12, 2021:srt.13076.***

which has been published in final form at

<https://doi.org/10.1111/srt.13076>. This article may be used for non-commercial purposes in accordance with Wiley Terms and Conditions for Use of Self-Archived Versions. This

article may not be enhanced, enriched or otherwise transformed into a derivative work, without express permission from Wiley or by statutory rights under applicable legislation. Copyright notices must not be removed, obscured or modified. The article must be linked to Wiley's version of record on Wiley Online Library and any embedding, framing or otherwise making available the article or pages thereof by third parties from platforms, services and websites other than Wiley Online Library must be prohibited.

Abstract

Background

Although many hair disorders can be readily diagnosed based on their clinical appearance, their progression and response to treatment are often difficult to monitor, particularly in quantitative terms. We introduce an innovative technique utilizing a smartphone and computerized image analysis to expeditiously and automatically measure and compute hair density and diameter in patients in real-time.

Methods

A smartphone equipped with a dermatoscope lens wirelessly transmits trichoscopy images to a computer for image processing. A black-and-white binary mask image representing hair and skin is produced and the hairs are thinned into single-pixel-thick fiber skeletons. Further analysis based on these fibers allows morphometric characteristics such as hair shaft number and diameters to be computed rapidly. The hair-bearing scalps of fifty participants were imaged to assess the precision of our automated smartphone-based device in comparison to a specialized trichometry device for hair shaft density and diameter measurement. The precision and operation time of our technique relative to manual trichometry, which is commonly used by hair disorder specialists, is determined.

Results

An equivalence test, based on two one-sided t-tests, demonstrates statistical equivalence in hair density and diameter values between this automated technique and manual trichometry within a 20% margin. On average, this technique actively required 24 seconds of the clinician's time whereas manual trichometry necessitated 9.2 minutes.

Conclusion

Automated smartphone-based trichometry is a rapid, precise, and clinically feasible technique which can significantly facilitate the assessment and monitoring of hair loss. Its use could be easily integrated into clinical practice to improve standard trichoscopy.

Introduction

Hair loss and thinning are commonly encountered problems in dermatology, and diseases causing such hair abnormalities are usually diagnosed clinically. However, in some situations, additional bedside tools might aid further in reaching the correct diagnosis and monitoring therapeutic response.

Quantitative trichoscopy (henceforth referred to as trichometry) is one such tool that has emerged as an accurate and non-invasive means of measuring various hair growth parameters *in vivo* including density, diameter, length, and shaft elongation rate [1]. Trichometry can be performed using a dedicated camera for scalp imaging that can achieve 50-100X magnification. It is used to acquire photographs which are then transmitted through a USB cable to a computer program. In trichometry, the software can be used to derive various hair morphometric parameters, but it usually requires the user to manually delineate features of interest using on-screen tools such as digital calipers [2]. The quantitative assessment of these morphometric parameters is of great clinical value, not only in monitoring the progression and response to treatment for hair loss and thinning, but also in predicting post-transplantation outcomes [3]. Furthermore, androgenetic alopecia (AGA), which is the most common type of hair loss, is characterized by progressive hair follicle miniaturization and it has been demonstrated that measurement of hair shaft diameter can help clinicians diagnose this disorder in its earlier stages [4-7]. Some of the drawbacks to current trichometry systems are that they are time consuming to operate, usually rely on manual user input, and require specialized task-specific equipment. As such, they are most suited for research

purposes and specific use in hair disorders clinics [1]. Although some modern trichometry devices are capable of performing automated measurements of hair morphometric parameters, most require the hairs to be clipped, which is also time consuming and undesirable to most patients [2].

Trichoscopy has been employed as a non-invasive and qualitative approach to examining and imaging the scalp and hair to enable visualization of diagnostic features that are not apparent to the unaided eye. Trichoscopy can now be performed by combining or enabling smartphones with dermatoscopes and/or specialized optical attachments to capture high-magnification photographs of the scalp without requiring any specialized hair-specific equipment [8-9]. However, this method is generally not intended for quantitative analysis of hair morphometric parameters, and therefore does not directly link to software to facilitate this task. On the other hand, trichoscopy can be performed more easily, rapidly and in a more clinically reasonable timeframe than trichometry [1,8-9].

Herein we present a novel technique that employs a smartphone to achieve high-magnification trichoscopy of the scalp and utilizes automated computer-assisted image analysis to rapidly measure hair density and diameter equivalent to a specialized, commercial device for trichometry. Our objective is to compare the statistical equivalence of values for hair density and diameter that are measured using an automated smartphone-based trichometry technique to those yielded from a manual

trichometry device based on user-provided inputs. We further assess the relative utility of these two approaches by comparing the times needed to assess hair morphometrics with each respective system.

Materials and Methods

Automated vs. manual trichometry

To achieve high-magnification visualization of hairs on a smartphone, we utilize an iPhone® 4 (Apple Inc., Cupertino, CA) alongside a Canfield DermScope® lens adaptor (Canfield Scientific Inc., Fairfield, NJ) for trichoscopy. Using the smartphone's built-in 'zoom' capability alongside the DermScope's optical magnification (20X), a cumulative magnification of up to 90X is achieved. Trichoscopy images acquired by this device are automatically transferred through a Wi-Fi connection to a laptop computer which is equipped with software to perform rapid image processing, compute hair diameter and density, transmit these results back to the smartphone for presentation to the user, and thereby perform automated trichometry. The image processing software was developed using MATLAB (MATLAB® R2011a with the Statistics and Machine Learning Toolbox, The MathWorks Inc., Natick, MA).

A commercial USB-equipped magnifier developed for trichometry with magnifications of up to 100X was used (Folliscope® [LeadM Corp., Seoul, South Korea]). It employs standard epiluminescence microscopy to facilitate the measurement of hair morphometrics and requires manual user input when the patient's hair is not clipped

[2,10-12]. This setup is demonstrated in Fig. 1. The sequence of events of automated and manual trichometry are outlined in Fig. 2.

Image processing algorithm in automated trichometry

Once the trichoscopy image is acquired (Fig. 3A), an algorithm is used to isolate the hairs from the skin and produce a black-and-white binary hair mask image where hair is represented by 1 (white) and skin is represented by 0 (black) (Fig. 3B). The technical details of the algorithm, which uses a series of state-of-the-art computational color image filters to detect tubularity of structures and thus detect hairs, have previously been published [13-14]. Only a short outline is presented here for completeness. The tubularness $v(\mathbf{x}, s)$ of every pixel $\mathbf{x} = (x, y)$ in a hair image is computed with respect to a scale s , where $s \in \{s^1, s^2, \dots, s^K\}$ using Frangi filters as:

$$v(\mathbf{x}, s) = \begin{cases} 0 & \lambda_2(\mathbf{x}, s) > 0 \\ \exp\left(-\frac{R^2(\mathbf{x}, s)}{2\beta^2}\right) \left(1 - \exp\left(-\frac{S^2(\mathbf{x}, s)}{2c^2}\right)\right) & \text{otherwise} \end{cases} ,$$

$$R(\mathbf{x}, s) = \frac{\lambda_1(\mathbf{x}, s)}{\lambda_2(\mathbf{x}, s)}, \text{ and}$$

$$S(\mathbf{x}, s) = \sqrt{\sum_{i \leq 2} \lambda_i^2(\mathbf{x}, s)}.$$

where λ_1 and λ_2 , ($|\lambda_1| \leq |\lambda_2|$), are the eigenvalues of the Hessian matrix of the hair image computed at scale s . R and S are the measures of blobness and second order structureness, respectively. β and c are system parameters. Then the optimal scale selection among $\{s^1, s^2, \dots, s^K\}$ is performed by a Markov Random Field (MRF)

optimization, which attempts to maintain the same scale selection for neighboring pixels. The MRF method defines a graph $G(V, E)$ where the vertices V are the pixels of the hair image and the edges E connect the neighboring pixels. The vertex V is assigned to a label, i.e. the scale of Frangi filtering. The optimal scale is determined by minimizing the energy function $E(l)$ as

$$E(l) = \eta \sum_{x_p \in V} \varphi_p(l_p) + (1 - \eta) \sum_{(x_p, x_q) \in E} \varphi_{pq}(l_p, l_q),$$

where l_p and l_q are the labels of the p^{th} pixel and its neighboring q^{th} pixel, respectively. φ_p is the likelihood of the label assigned to pixel x_p disregarding the labels of its neighbours. φ_{pq} is the penalty of the p^{th} pixel and its neighbouring q^{th} pixel having a different label. η is the weight of the spatial regularization term. In other words, the optimal scale is defined as the label among $\{s^1, s^2, \dots, s^K\}$ that has the least penalty with the mismatched labels from its neighbours. Finally, the binary mask is obtained by applying Otsu's thresholding to the tubularness values with the optimal scale.

A morphological image processing operation called “thinning” is then iteratively applied to the binary mask image and results in the “skeleton” of the hairs, which are single-pixel-thick lines traversing along the centre of each hair shaft [15]. Fig. 3B demonstrates the binary image with superimposed skeletons in red. Specifically, the thinning process generates an eight-neighbour matrix by examining a sliding window of 3x3 pixels and removing the central pixel x if it is located at the border of a blob, while preserving diagonal lines. The iterative procedure operates until no further changes occur in the

mask. In the algorithm's first subiteration, pixel p is deleted if and only if the conditions C_1 , C_2 , and C_3 are all satisfied. In the second subiteration, pixel p is deleted if and only if the conditions C_1 , C_2 , and C_3' are all satisfied. One iteration of the thinning algorithm consists of the two subiterations.

Condition C_1 : $X_H(p) = 1$,

where $X_H(p) = \sum_{i=1}^4 b_i$ and $b_i = \begin{cases} 1, & \text{if } x_{2i-1} = 0 \text{ and } (x_{2i} = 1 \text{ or } x_{2i+1} = 1) \\ 0, & \text{otherwise} \end{cases}$,

and x_1, x_2, \dots, x_8 are the values of the eight adjacent neighbors of p , starting with the east neighbor and numbered in a counter-clockwise order.

Condition C_2 : $2 \leq \min\{n_1(p), n_2(p)\} \leq 3$,

where $n_1(p) = \sum_{k=1}^4 x_{2k-1} \vee x_{2k}$ and $n_2(p) = \sum_{k=1}^4 x_{2k} \vee x_{2k+1}$

Condition C_3 : $(x_2 \vee x_3 \vee \overline{x_8}) \wedge x_1 = 0$

Condition C_3' : $(x_6 \vee x_7 \vee \overline{x_4}) \wedge x_5 = 0$

Once the skeleton is generated, the diameter of the hair shaft at any point along the skeleton is defined as twice the shortest Euclidean distance between that specific point and the border of the hair shaft. Using all points along all skeletons, the average hair diameter in the trichoscopy image is derived. This comprehensive algorithm is far

superior to diameter measurement by manual trichometry, which in turn relies on the measurement of the diameter of a few sampled points along a few arbitrarily selected hairs. In order to determine the hair density, the algorithm computes the total number of endpoints of all hair skeletons in the image. Dividing this number by two represents the estimated total number of hair shafts in the field of view and is used to compute hair density.

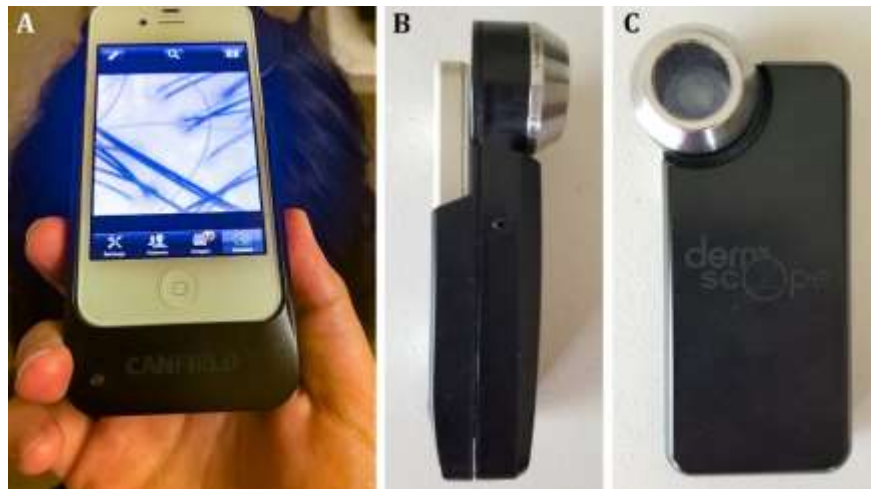


Figure 1 – (A) The setup of automated trichometry on the vertex scalp using the smartphone combined with the dermatoscopy lens adaptor. The coupled devices are also shown from the side (B) and back (C).

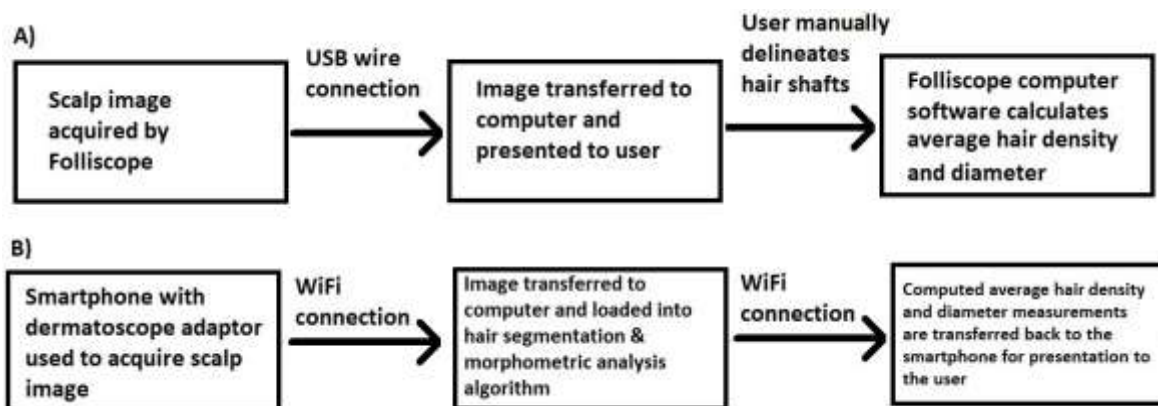


Figure 2 – The scheme for manual (A) and automated trichometry (B) are outlined.

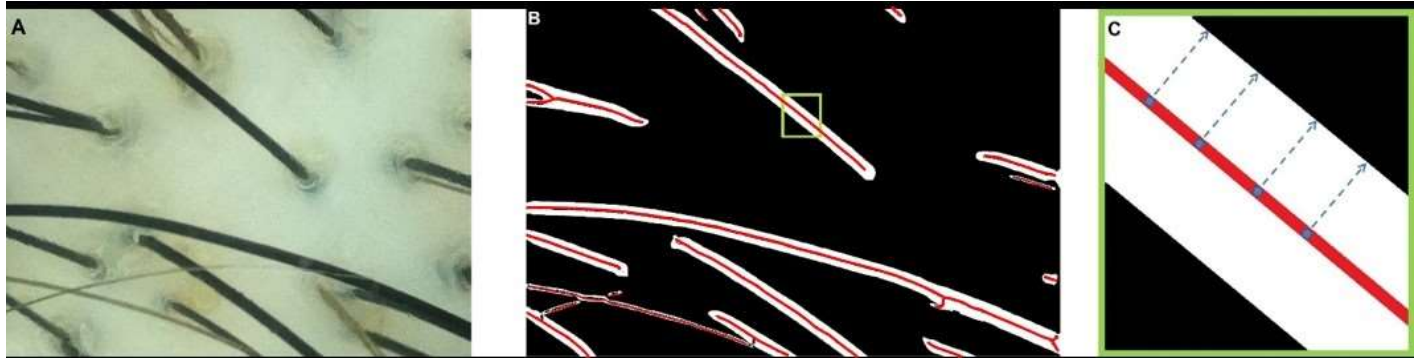


Figure 3 – An image of the scalp acquired using smartphone-based trichoscopy (A) is converted to a binary image with superimposed hair skeletons (red lines – which have been exaggerated in thickness for the purpose of demonstration) coursing centrally along the hair shafts (B). (C) The red-coloured skeleton of a magnified hair shaft with blue arrows indicating half of the thickness of the hair at each respective point. Field of view = 4.3 mm x 2.5 mm in (A) and (B).

Hair diameter and density

To evaluate the precision of this novel method relative to manual trichometry, a prospective study was conducted in which the two modalities were used to measure average hair density and diameter in fifty patients (all consenting patients were included) presenting with a variety of hair disorders. These disorders and the baseline demographics of study participants have been outlined in Table 1. Participants were recruited in consecutive series from the Hair Clinic at the Vancouver General Hospital Skin Care Centre, which is affiliated with the University of British Columbia; The investigation received full approval by the Clinical Research Ethics Board of the University of British Columbia (H14-01874) and written informed consent was acquired from all patients. Recruitment and measurements were performed by the author AM. To maximize the quality of the images and accuracy of measurements on the manual trichometry device, this user was trained in the operation of the device in a specialized hair disorders clinic under the supervision of three dermatologists with extensive

knowledge in this domain. Measurements were taken from the scalp vertex at 15 cm above the glabella (or the site of hair disease closest to this point) and the site of imaging on the scalp was marked using an erasable marker to preserve topographic consistency between the two devices. For increased accuracy, the maximum available magnification for automated trichometry (90X) and manual trichometry (100X) are used. This yields images with dimensions of 2592 x 1536 pixels on the smartphone. Ultimately, equivalence testing was performed between the two devices for average hair density and diameter to determine whether they can be deemed equivalent in their measurement of these parameters.

The 'hands-on' time is defined as the total time that the user is actively engaged in the operation of the device, whereas the time required for the device to compute and present the morphometric data without any user engagement is referred to as the 'hands-off' time. The hands-on time includes the time that is required to utilize automated trichometry or the manual trichometry device that has already been powered on and initialized to start recording images of the scalp. It also includes the process of image acquisition, which requires the hair shafts surrounding the region of interest to be moved outside of the field of view. In the case of smartphone-based automated trichometry, it further includes the process of initiating transfer of the image to a computer for image analysis. For manual trichometry, the hands-on time includes manual identification and marking of all hair shafts in the field of view, as well as the process of delineation of the diameters of five randomly selected hair shafts in the image. The time that is required to set up and initialize the manual trichometry device

and smartphone trichoscopy equipment, while comparatively significant, have not been included in the hands-on time as they were only required to be performed once per clinic day and not per patient. The hands-off time for manual trichometry is virtually non-existent as the user is continually engaged in operating the device throughout the entire procedure. The hands-off time for automated trichometry includes the time that is required for the acquired image to be transferred over Wi-Fi from the smartphone to the computer, for rapid automated image processing to be performed, and for average hair density and hair diameter to be computed and transmitted back to the smartphone for presentation to the user. We record the 'hands-on' time for manual trichometry, as well as the 'hands-on' and 'hands-off' times for automated trichometry.

Statistical analysis

Two one-sided t-tests (TOST, using SAS 9.4 [SAS Institute Inc., Cary, NC]) were performed for hair density and diameter to assess for equivalence between the automated trichometry technique and manual trichometry. This is a variation of a hypothesis test wherein an upper and lower equivalence bound is specified. Two null hypotheses are tested, with one greater than or equal to the upper bound, and the other less than or equal to the lower bound. Rejection of both null hypotheses through one-sided tests suggests that the observed effect falls within the equivalence bounds and is therefore statistically equivalent. The average discrepancies of the smartphone-acquired parameters relative to those established through manual trichometry were calculated. In addition, t-tests were used to evaluate the times required to operate each imaging system. The normality of the acquired data was confirmed by Shapiro-Wilk tests.

Results

The recruited cohort included patients with Fitzpatrick skin types I-VI, hair colours of gray, black, brown, white, and red, and an average age of 42.3 years (range 19-57). Automated diameter measurement was performed successfully for all fifty patients with no adverse event. Smartphone density and diameter measurements were, on average, 7.5% greater and 3.6% lower than those of manual trichometry, respectively. TOST demonstrates equivalence in hair density and diameter values between the two devices within a 20% margin and these results are outline in Table 2.

	Count
Total patients	50
- Female	42
- Male	8
Mean age	42.3 years
Hair disorders	
- Androgenetic alopecia	26
o Sinclair scale (females)	–
▪ Stage I	19
▪ Stage II	2
▪ Stage III	2
o Hamilton-Norwood scale (males)	–
▪ Stage III	3
- Alopecia areata	10
- Frontal fibrosing alopecia	6
- Discoid lupus erythematosus	4
- Lichen planopilaris	3
- Chronic telogen effluvium	1

Table 1 – Baseline demographics of study participants (N = 50).

Manual trichometry’s average total procedure duration was approximately 9.2 minutes, whereas the automated trichometry required an average ‘hands-on’ time of 24 seconds

and 'hands-off' time of 1.4 minutes. Therefore, the smartphone was more than five times more rapid than the manual trichometry on average ($P = 0.001$) and resulted in a twenty-three-fold reduction in the 'hands-on' time required for density and diameter measurement, as summarized in Table 3.

	Average Difference Relative to Manual Trichometry	Range of Equivalence	P value of Equivalence Test
Hair Density	+7.5%	20%	≤ 0.0001
Hair Diameter	-3.6%	20%	0.003

Table 2 – Summary of the precision and equivalence testing of automated smartphone trichometry relative to manual trichometry on 50 patients.

	Mean Hands-On Time \pm SD (minutes)	Mean Hands-Off Time \pm SD (minutes)	Mean Total Time \pm SD (minutes)
Manual Trichometry	9.2 \pm 0.6	—	9.2 \pm 0.6
Automated Trichometry	0.4 \pm 0.2	1.40 \pm 0.02	1.8 \pm 0.2
P value	< 0.0001	—	≤ 0.0001

Table 3 – Comparison of the operation time of the automated smartphone trichometry system relative to manual trichometry in 50 patients. The total time does not include initial device setup time. The differences in means for hands-on time and total time between the two devices are statistically significant as $p < 0.05$.

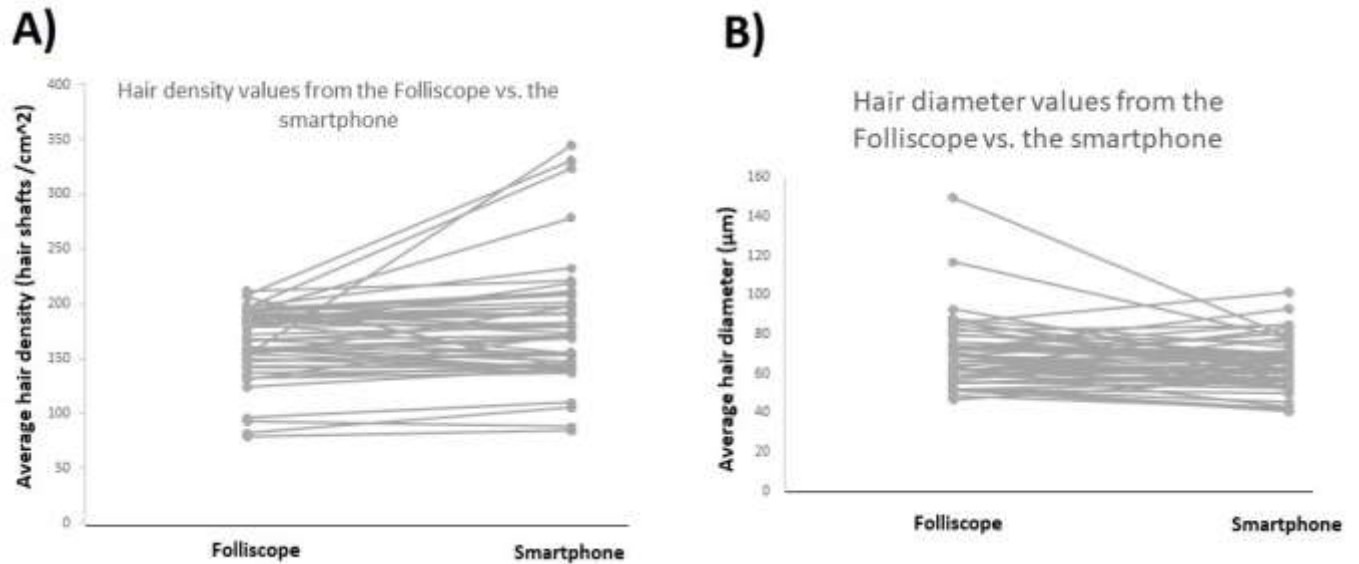


Figure 4 – Comparison of average hair density (A) and diameter (B) measured by manual trichometry vs. the automated smartphone-based technique.

Discussion

Although potentially time consuming, the quantitative assessment of hair density and diameter can be beneficial in the diagnosis and monitoring of hair disorders. We have previously demonstrated in another study through discriminant analysis that the diameters of hair shafts can be used to diagnose AGA with a sensitivity of 88.5% and specificity of 75% [7]. Automated hair parameter measurement through smartphone-based trichometry has demonstrated promising performance and its measurements of hair density and diameter are deemed to be statistically equivalent to those yielded by the accepted manual trichometry method within 20%. This novel technique also reduces the amount of time that a user needs to be engaged with the device by twenty-three-fold to an average of 24 seconds, thereby rendering it a clinically feasible adjunctive procedure for physicians to implement in their routine assessment of patients with hair disorders.

This study demonstrates that equipment that is readily available to dermatologists, including a dermatoscope, smartphone, and Wi-Fi-enabled computer can be combined with analytical software to efficiently assess hair morphometrics in real-time in a busy clinical setting. Furthermore, a direct comparison is made between this technique and manual trichometry which is widely used among hair disorder specialists, and their equivalence is assessed. Much of the total time required by the automated system is for the transfer of the acquired high-resolution images from the smartphone to the computer through Wi-Fi. As such, this process could be further expedited by only capturing trichoscopy images and then later running the algorithm on all acquired images in a batch for measurement of hair morphometric parameters to obviate the need for file transfer. Even with the current procedure, the clinician was only required to actively spend an average of 24 seconds with the smartphone-based trichometry device to capture images for computerized analysis. The clinician was able to carry out other elements of the patient encounter while the 'hands-off' phase was taking place, such as providing patient education and counseling regarding hair loss.

One of the greatest strengths of the algorithm that we have developed is its ability to measure the diameters of hair shafts at every single pixel-point along their lengths, thereby producing an average hair diameter that is very precise and reflective of subtle alterations in hair shaft diameter. In fact, hair diameter diminution is one of the earliest changes seen in AGA and it has a greater impact on the appearance of global hair loss

than decreased hair density [16]. Nevertheless, both parameters are affected and important to assess in AGA, as well as in many other hair and scalp disorders [4-5,17].

Equivalence testing demonstrated a range of 20% for the results from the two quantitative modalities and numerous factors may have contributed to this difference. Although manual trichometry using the Folliscope is a common and clinically accepted means of quantifying hair morphometrics, it is by no means a gold standard. There is some degree of dependence on the operator's technique and experience, and hair shafts can be missed during the counting procedure without close attention.

Furthermore, a few hair shafts are manually and arbitrarily selected for digital diameter measurement, which contrasts with our algorithm's systematic method of determining average hair diameter along the entire lengths of all imaged hair shafts. Since hair shafts are inherently greater in diameter at the level of the follicular ostia than they are at their distal end, it is plausible that these two conceptually different approaches of measuring average hair diameter yield varying results. One of the main limitations of this automated system is its occasional failure to detect certain vellus hairs. In addition, some white hairs in patients with fair skin were also undetected by the algorithm. The most extreme outliers (as seen in the dot-line graph in Fig. 4) were found to be attributed to poor image quality during the image acquisition phase. A common cause for poor image quality during the study was perspiration on the scalp of participants. This was overcome in most cases by drying the scalp as much as possible before imaging. It is important to note that artificial intelligence could be implemented in the future to help overcome some of the limitations in the hair detection algorithm used in

this study, including better identification of hairs in images with suboptimal quality, and detection of hairs with a wider range of colors. Dyeing the hair shafts in the area of imaging could also improve detection in patients with vellus or white-colored hairs. Finally, although a wide variety of hair disorders with varying severities were captured in this study, our cohort did not include participants without hair disorders. Our algorithm may have decreased detection of individual hair shafts in this population with increased average hair density and diameter.

Conclusion

In conclusion, while the measurement of hair morphometric parameters during initial and follow-up visits would be greatly beneficial in patients being assessed for hair loss, such accommodation might be unfeasible for busy dermatology clinics with scarce resources. Computer-assisted smartphone-based automated trichometry is an excellent solution which expedites this process and yields precise results. Furthermore, its use could be easily integrated into dermatologists' standard examination of the scalp as many use a dermatoscope in this process for trichoscopy, and the remaining automated image analysis phase is an entirely 'hands-off' process. In the future, this technology can be made available on a cloud so that any individual with access to a smartphone and a dermatoscope or other similar optical attachment can perform trichometry rapidly.

Throughout the COVID-19 pandemic, telemedicine has become widely adopted in medical non-procedural dermatology and is expected by some patients. Trichoscopy

and trichometry are key elements of patient examination in hair and scalp disorders, and this new technology fits well into the modern hair telemedicine visit.

References

1. Dhurat R, Saraogi P. Hair evaluation methods: merits and demerits. *Int J Trichology*. 2009;1(2):108-19.
2. Folliscope © 2.8 –Photo Trichogram ver 1.1.1. – USER MANUAL
3. Vogel JE, Jimenez F, Cole J, et al. Hair restoration surgery: the state of the art. *Aesthet Surg J*. 2013;33(1):128-51.
4. Fabbrocini G, Cantelli M, Masarà A, Annunziata MC, Marasca C, Cacciapuoti S. Female pattern hair loss: A clinical, pathophysiologic, and therapeutic review. *Int J Womens Dermatol*. 2018;4(4):203-211.
5. Lulic Z, Inui S, Sim WY, et al. Understanding patient and physician perceptions of male androgenetic alopecia treatments in Asia-Pacific and Latin America. *J Dermatol*. 2017;44(8):892-902.
6. Bhamla SA, Dhurat RS, Saraogi PP. Is trichoscopy a reliable tool to diagnose early female pattern hair loss?. *Int J Trichology*. 2013;5(3):121-5.
7. Majd A, Santos LDN, Chu TW, Shapiro J, Lui H, Lee TK. Hair distribution width - a novel trichoscopy parameter for hair miniaturization in androgenetic alopecia. *J Eur Acad Dermatol Venereol*. 2019.
8. Börve A, Terstappen K, Sandberg C, Paoli J. Mobile teledermoscopy-there's an app for that!. *Dermatol Pract Concept*. 2013;3(2):41-8.
9. Börve A, Dahlén gyllencreutz J, Terstappen K, et al. Smartphone teledermoscopy referrals: a novel process for improved triage of skin cancer patients. *Acta Derm Venereol*. 2015;95(2):186-90.
10. Lee BS, Chan JY, Monselise A, Mcelwee K, Shapiro J. Assessment of hair density and caliber in Caucasian and Asian female subjects with female pattern hair loss by using the Folliscope. *J Am Acad Dermatol*. 2012;66(1):166-7.
11. Oh GN, Son SW. Efficacy of korean red ginseng in the treatment of alopecia areata. *J Ginseng Res*. 2012;36(4):391-5.
12. Kim JH, Lee SY, Lee HJ, Yoon NY, Lee WS. The Efficacy and Safety of 17 α -Estradiol (Eli-Cranell® alpha 0.025%) Solution on Female Pattern Hair Loss: Single

Center, Open-Label, Non-Comparative, Phase IV Study. *Ann Dermatol.* 2012;24(3):295-305.

13. Mirzaalian H, Lee TK, Hamarneh G. Hair enhancement in dermoscopic images using dual-channel quaternion tubularness filters and MRF-based multilabel optimization. *IEEE Trans Image Process.* 2014;23(12):5486-96.

14. H. Mirzaalian and G. Hamarneh, Vessel scale-selection using MRF optimization, *CVPR* 2010.

15. Lam, L., Seong-Whan Lee, and Ching Y. Suen, "Thinning Methodologies-A Comprehensive Survey," *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol 14, No. 9, September 1992, page 879, bottom of first column through top of second column.

16. Ishino A, Takahashi T, Suzuki J et al., "Contribution of hair density and hair diameter to the appearance and progression of androgenetic alopecia in Japanese men," *Br J Dermatol.* 2014;171(5):1052-9.

17. Yin NC, Tosti A. A systematic approach to Afro-textured hair disorders: dermoscopy and when to biopsy. *Dermatol Clin.* 2014;32(2):145-51.