

Thermal modulation and airflow distribution determine hair drying efficiency, moisture behavior in human hair in Republic of Korea: an ex vivo study

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Background: Hair drying is a routine cosmetic practice; however, excessive heat exposure and non-uniform airflow can compromise cuticle integrity, degrade hair sensory properties, and induce scalp discomfort. This study aimed to (i) identify a practical thermal window that minimizes perturbation of hair fiber surface and quantify late-stage thermal amplification during the drying process using percentage-based analysis.

Methods: Temperature-dependent hair fiber surface morphology was examined by scanning electron microscopy (SEM) after controlled exposure to 41°C, 60°C, 80°C, and 90°C using virgin and chemically damaged hair. The drying efficacy was assessed using the surface and internal moisture indices under airflow shaping (test) and uniform airflow (control) conditions. Hair fluttering (maximum angular displacement) was evaluated before and after drying under warm-cool alternating (60°C-80°C) versus constant hot airflow (80°C).

Results: SEM revealed temperature-dependent cuticle disruption, with markedly greater surface perturbation at 90°C than at 80°C. Infrared thermography demonstrated pronounced late-stage thermal amplification: at 150 seconds, the surface temperature increased by 295% (from 24.2°C to 72.0°C) at 90°C, compared with 207% (from 24.2°C to 50.7°C) at 80°C. Airflow shaping promoted preferential surface moisture removal (-13.6%) while limiting internal dehydration (-9.4%), whereas the control condition exhibited minimal surface drying (-4.6%) but substantial internal moisture loss (-22.2%). Warm-cool modulation increased hair fluttering by +11.0%, whereas constant hot airflow reduced it (-3.7%).

Conclusion: These findings indicate that spatial and temporal control of heat delivery represents a clinically relevant design strategy beyond the nominal temperature specification in hair-drying devices.

Key words: Hair; Temperature; Heat

INTRODUCTION

The frequent use of household hair dryers and heat-

styling devices is strongly associated with cuticle disruption, fiber embrittlement, loss of cosmetic quality (roughness, dullness, frizz), and scalp discomfort or erythema

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in susceptible users [1,2]. From a material perspective, hair performance deterioration is governed not only by the device set temperature, but also by the time-temperature history imposed on the fiber surface during drying. As the surface water is depleted, convective heating becomes more efficient, and local overheating can occur late in the drying process, producing a steep rise in the peak surface temperature even when the nominal device settings remain unchanged [1]. This phenomenon is clinically relevant because hair fibers show accelerated cuticle lifting, microcracking, and structural collapse when peak temperatures exceed practical safety thresholds. This risk is amplified in chemically treated hair with compromised cuticle/cortical integrity [1,3]. In addition, the drying outcomes were modulated by airflow architecture. Even with identical bulk temperature settings, the spatial distributions of momentum and heat can change the surface evaporation kinetics, internal dehydration rate, and peripheral heat exposure. Excessive diffusion may unnecessarily heat the scalp and surrounding skin without improving the drying efficiency, whereas focused airflow can deliver convective energy more selectively to the hair bundle [4].

Therefore, thermal modulation strategies have gained attention as a practical means of reducing the heat load. A warm-cool (or high-low) cycling algorithm can intermittently dissipate accumulated heat, potentially suppressing thermal spikes during the late drying stage while maintaining the drying efficiency [1,5]. However, most previous studies have emphasized either temperature alone or posttreatment hair outcomes, with limited integrated evidence linking airflow focusing and thermal cycling to simultaneous improvements in moisture removal dynamics, perceptible hair behavior (e.g., fluttering/softness proxies), and scalp tolerability endpoints.

In this *ex vivo* study, we compared a focused-airflow dryer operating in a warm-cool thermal cycling setting (Device A; 60°C–80°C alternating) with a conventional constant-temperature mode (Device B; 80°C constant). Additionally, we conducted a temperature-threshold verification (80°C vs. 90°C) using thermal imaging and scanning electron microscopy (SEM)-based surface assessment to contextualize safe operating ranges. The primary outcomes were hair moisture metrics (external vs. internal water content) and fluttering proxies (maximum angle).

METHODS

Hair substrates and preparation

Commercial human-hair tresses (Asian, virgin; 15 cm; $\sim 120 \pm 5$ fibers; Crown Wig Co., Ltd.) were shampooed with a neutral formulation (pH 6.5; 1 mL·g⁻¹; 30 seconds massage; 60 seconds rinse) and air-dried for 24 hours at room temperature (22°C–24°C and 40%–60% RH). For experiments requiring damaged substrates, tresses were chemically treated using a standardized bleaching protocol (L’Oreal Platine Precision Powder with Excel Cream Peroxide 6%/20 vol, pH 10 for 30 minutes each) and rinsed to neutrality.

Drying devices and operating modes

A custom-built hair drying device was developed for this study. Two devices were tested under controlled ambient conditions:

Conventional mode: a conventional dryer operating at a constant temperature of 80°C with a standard outlet/focused nozzle configuration.

Test mode: a temperature-regulated dryer equipped with an airflow-shaping nonfocused nozzle and an alternating warm-cool mode (60°C–80°C; duty cycle).

For all the tests, the nozzle-to-stress distance was fixed at 10 cm, the airflow setting was 95,000 rpm, and the static motion protocol at 30 rpm was standardized. The total exposure time was matched between conditions for 150 seconds, unless otherwise specified.

SEM assessment of cuticular surface morphology

The hair fibers were mounted on SEM stubs and sputter-coated with Au/Pd. Imaging was performed at 5 kV (SEM, S-4800; Hitachi). Temperature-dependent morphology was assessed across defined surface-temperature conditions (41°C, 60°C, 80°C, and 90°C) using representative fields (10 fields per 5 hair fiber of bundle of hair fibers).

Infrared thermography

The surface temperature was recorded during drying using an infrared camera (FLIR E85; FLIR Systems, Inc.). Regions of interest were defined on the full head of the mannequin model. The temperature statistics included the mean region of interest temperature and the peak values at each time point every minute. The primary endpoints were the late-stage peak temperature at 150 seconds and the peak-to-mean excursions.

Dryer apparatus and airflow characterization

A portable prototype equipped with a flow-focusing nozzle designed to confine the jet area was used for drying [6]. To quantitatively characterize airflow distribution, velocity field measurements were performed using particle image velocimetry. Aerosolized tracer particles were introduced into the airflow generated by the hair dryer, and sequential images were captured using a high-speed camera (Phantom VEO 640L; Vision Research) synchronized with a laser illumination system (LVI-W-532-20W; LVI Technologies). Velocity vectors were calculated using cross-correlation analysis, and mean velocity magnitude (U_{mean}) was mapped as a function of spatial position. The velocity distribution was analyzed along the transverse axis at multiple downstream distances (30, 40, 50, 60, 70, 80, 90, and 100 mm). Airflow spread was quantified using the full width at half maximum (FWHM) of the velocity profile. FWHM represents the spatial width where velocity magnitude exceeds 50% of the maximum velocity and provides a quantitative measure of airflow concentration versus dispersion.

Moisture evaluation: surface vs. internal moisture framework

The drying efficacy was quantified gravimetrically using a two-compartment infrared moisture analyzer (FD-660; Kett Electric Laboratory). Surface moisture was operationally defined as the fast-removable fraction after standardized blotting/brief equilibration, whereas internal moisture was defined as the remaining fraction removed only after extended drying/equilibration. The human hair tresses were cut at 2 cm intervals, and 0.5 g of each cut bundle was dried by heating at 105°C for 30 minutes using an infrared moisture meter. Outcomes are expressed as a percentage reduction from baseline and as a surface-to-internal moisture reduction ratio.

Hair fluttering/maximum angle metric

Forty human hair tresses were prepared: 20 each in the test control groups. Hair fluttering was assessed using a standardized imaging device (Bolero-Lite System; Bossa Nova Vision). The Bolero-Lite System is a representative device for measuring hair frizz [7], and was used to measure hair movement in this study. The Maximum angular displacement (Max angle, degrees) was computed using an image pipeline (ImageJ software; ImageJ 1.52a; National Institutes of Health). Measurements were conducted pre- and post-drying; the endpoints included the absolute Max angle and change from baseline.

Statistical analysis

Data are presented as mean $\pm$ standard deviation. Normality was assessed using the Shapiro–Wilk test, and paired two-tailed t-tests (or Wilcoxon signed-rank test) were applied as appropriate. Post-treatment differences were also evaluated using analysis of covariance (baseline covariate) and checked using a linear mixed-effects sensitivity model. Multiplicity was controlled using the Holm–Bonferroni test; a two-sided $p < 0.05$ was considered significant.

RESULTS

Airflow distribution characteristics differ between airflow shaping and conventional modes

Airflow velocity analysis revealed distinct differences in spatial airflow distribution between devices. Test mode exhibited a controlled and confined airflow distribution, with a measured FWHM of 38.1 mm at a downstream distance of 70 mm (Fig. 1A). This indicates moderate airflow dispersion, allowing controlled heat and momentum transfer. Velocity contour analysis confirmed that Device A produced a spatially uniform velocity gradient with gradual radial decay, enabling stable convective heat transfer without excessive localized airflow concentration (Fig. 1B). In contrast, conventional airflow distribution exhibited broader dispersion and less controlled spatial distribution, potentially contributing to less efficient moisture removal dynamics.

Temperature-dependent surface response and late-stage thermal amplification

Time-resolved infrared thermography demonstrated that thermal risk emerged predominantly during the late-stage drying rather than during the initial heating phase (Fig. 2A). At 150 seconds, surface temperature under the 90°C condition increased by +295% relative to baseline (24.4°C $\rightarrow$ 72.0°C), whereas the 80°C condition increased by +207% (24.2°C $\rightarrow$ 50.2°C) (Fig. 2B). This indicated a substantially amplified thermal excursion at higher set temperatures during the moisture-depleted drying stages. SEM analysis confirmed a temperature-dependent alteration in hair fiber surface morphology, with progressively increased cuticle lifting and surface roughening as exposure temperature increased from 41°C to 90°C. SEM observations across virgin hair and bleached hair (BH) further supported a temperature-dependent damage threshold; images at higher temperature exposure showed clearer cuticle disruption patterns, with BH demonstrating greater apparent vulnerability, consistent

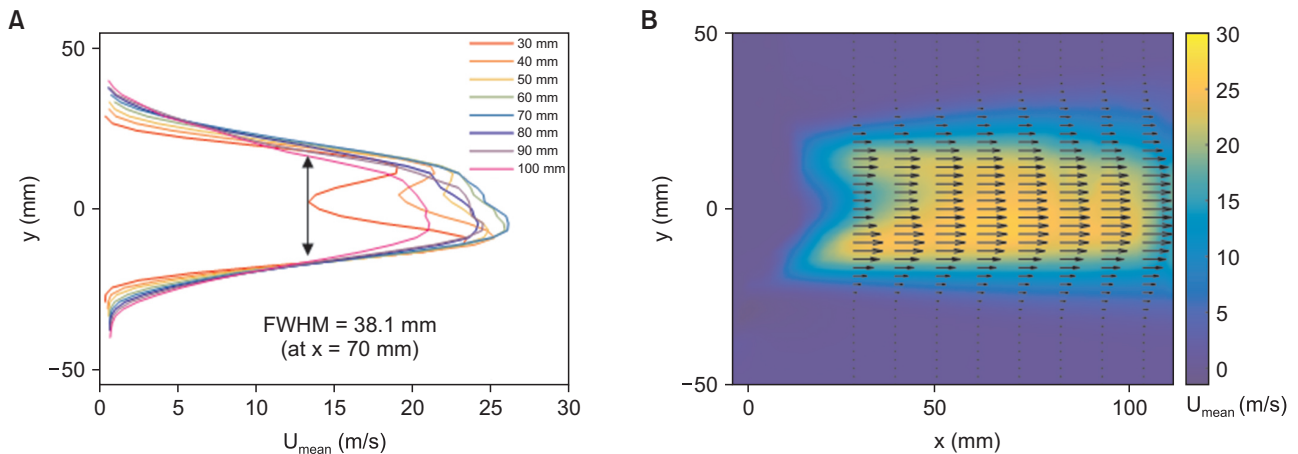


Fig. 1. Airflow distribution characteristics. (A) Transverse velocity profiles measured at multiple downstream distances (30–100 mm) from the dryer outlet using particle image velocimetry. The airflow spread was quantified using full width at half maximum (FWHM), with a measured value of 38.1 mm at $x = 70$ mm, indicating controlled airflow distribution in the test device. (B) Spatial velocity contour map and vector field visualization of airflow generated by test mode. Color scale represents mean velocity magnitude (U_{mean} , m/s), and arrows indicate airflow direction. Test mode produced a spatially uniform and controlled airflow distribution, minimizing excessive localized velocity concentration.

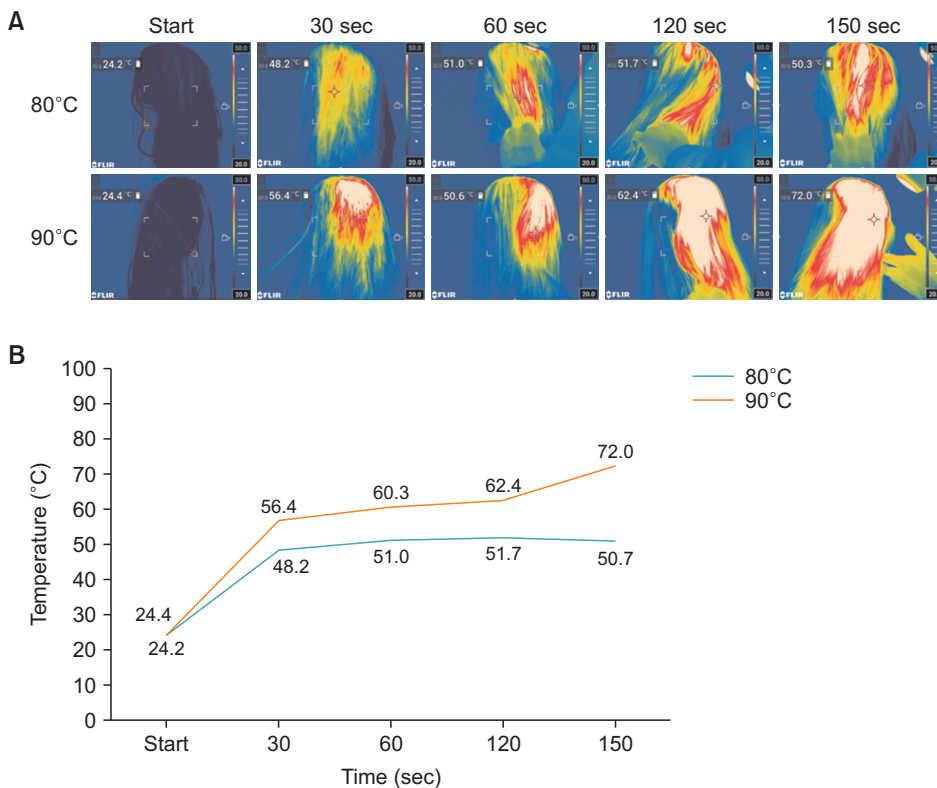


Fig. 2. Temperature-dependent hair fiber surface morphology and time-resolved thermal exposure during drying. (A) Representative infrared thermography images showing surface temperature distribution during drying at 80°C and 90°C setpoints over time. (B) Time-resolved surface temperature profiles derived from infrared thermography. While early-stage temperatures were comparable, late-stage drying (150 seconds) exhibited markedly higher peak temperatures at the 90°C setpoint (72.0°C) compared with the 80°C condition (50.2°C), indicating pronounced late-stage overheating at the higher temperature.

with reduced barrier integrity (cuticle melting and subsequent cortical exposure) (Fig. 3). Together, these data justify using $\leq 80^\circ\text{C}$ as a practical upper operating bound for safer drying and motivate a control strategy aimed at suppressing late-stage peaks.

Airflow shaping redistributes moisture removal toward the hair fiber surface

The airflow distribution produced distinct moisture removal patterns in the test and control modes. Under the airflow-shaping condition (test mode), surface moisture decreased from 6.792 ± 0.682 to 5.870 ± 0.731 ,

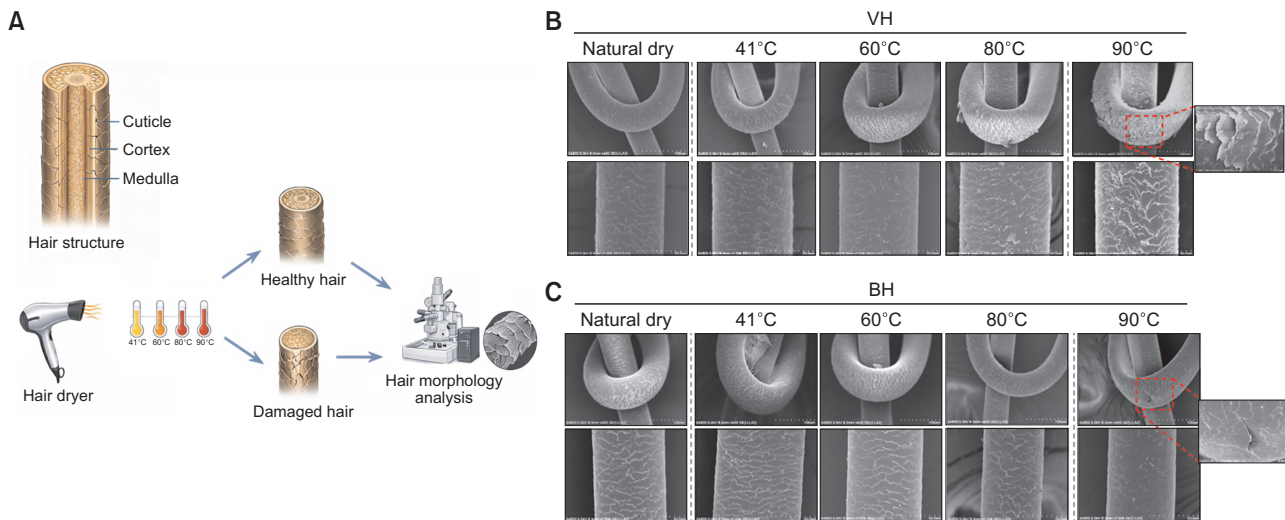


Fig. 3. Schematic overview of experiment and scanning electron microscopy (SEM) images. (A) Virgin hair exposed to different drying conditions: natural drying, 41°C, 60°C, 80°C, and 90°C (10 cm distance, 150 seconds exposure). The photos taken with a scanning electron microscope were taken at different dryer temperatures on (B) panel (virgin hair [VH]) and (C) panel (bleached hair [BH]). SEM images of chemically damaged hair (6% bleaching treatment) under identical conditions, showing enhanced thermal susceptibility relative to virgin hair, particularly at 90°C. Images were acquired at a magnification of $\times 1,000$, and the red-boxed region area corresponds to higher magnification of $\times 18,000$.

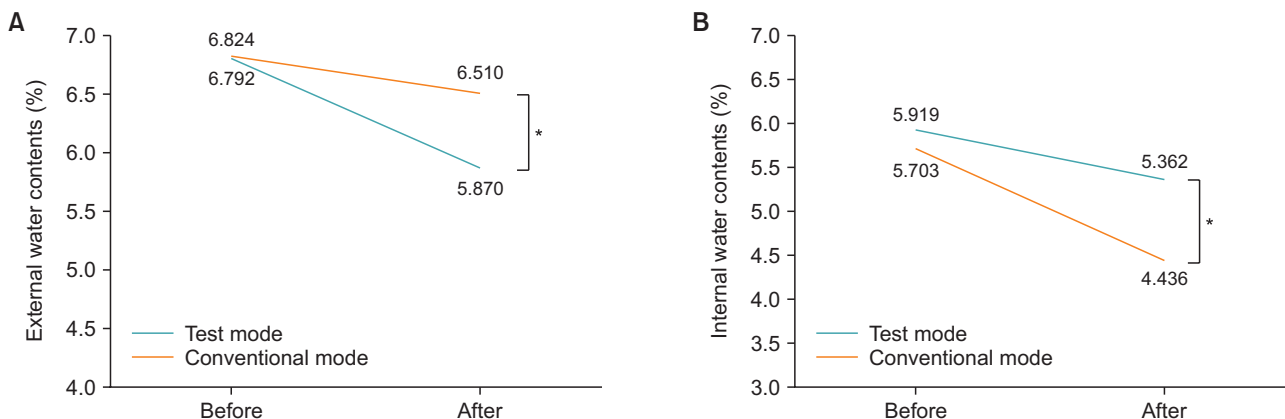


Fig. 4. Effect of airflow distribution on surface and internal hair moisture during rapid drying. (A) External water content (%) measured before and after drying treatment. Test mode reduced external water content from 6.792% to 5.870%, whereas Conventional mode reduced external water content from 6.824% to 6.510%, indicating greater surface moisture removal efficiency with airflow-controlled drying. (B) Internal water content (%) measured before and after drying treatment. Test mode reduced internal water content from 5.919% to 5.362%, whereas Conventional mode reduced internal water content from 5.703% to 4.436%. Test mode preserved significantly more internal moisture compared with Conventional mode, indicating reduced internal dehydration during drying. Data are presented as mean values. Asterisks indicate statistically significant differences between devices ($*p < 0.05$).

corresponding to a -13.6% change, whereas the control mode showed a smaller reduction of -4.6% ($6.824 \pm 0.770 \rightarrow 6.510 \pm 0.764$). In contrast, internal moisture loss was significantly attenuated in the test mode. Internal moisture decreased by -9.4% ($5.919 \pm 0.683 \rightarrow 5.362 \pm 0.754$) in the test condition, compared with a markedly larger reduction of -22.2% ($5.703 \pm 0.600 \rightarrow 4.436 \pm 0.711$) in the control condition (Fig. 4). These results demonstrate that

airflow shaping promotes preferential surface moisture removal, while limiting excessive internal dehydration.

Warm-cool alternating airflow enhances hair fluttering

Hair fluttering, expressed as the Max angle, showed opposing trends between the drying modes. Under the warm-cool alternating condition (test mode), Max

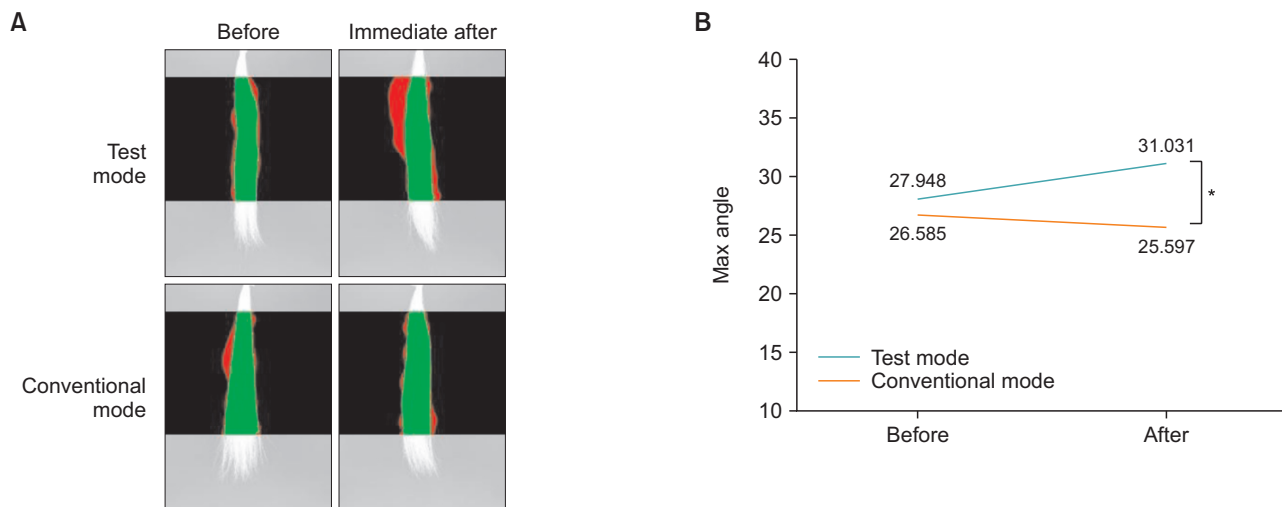


Fig. 5. Effect of warm-cool alternating airflow on hair fluttering. (A) Quantitative analysis of hair fluttering expressed as maximum angular displacement (Max angle) before and after drying. (B) Representative original and processed images used for max angle analysis, illustrating increased fiber mobility and reduced interfiber constraint following warm-cool alternating exposure. *Indicates a significant difference ($p < 0.05$) between the two groups.

angle increased from 27.948 ± 2.516 to 31.031 ± 4.940 , representing a +11.0% increase. In contrast, constant hot airflow (control mode) resulted in a -3.7% decrease in Max angle [$26.585 \pm 2.611 \rightarrow 25.597 \pm 2.776$] (Fig. 5). The directionally opposite changes suggest that cycling with focused airflow may improve the macroscopic hair behavior associated with softness/handle (potentially reflecting reduced interfiber friction or altered surface conditions) relative to constant-temperature drying.

DISCUSSION

The present study demonstrates that hair drying outcomes are governed by the combined effects of late-stage thermal amplification and airflow-mediated moisture redistribution, rather than by the nominal temperature alone. By applying a human hair fiber analytical framework across heterogeneous endpoints [8], we provide a coherent mechanistic explanation linking the surface morphology, thermal exposure dynamics, moisture fluttering, sensorial performance. SEM observations confirmed that hair fiber surface disruption increases sharply at higher temperatures, with markedly greater cuticle lifting observed at 90°C compared with 80°C. While this finding aligns with previous reports on temperature-dependent hair damage, infrared thermography revealed a more nuanced and practically important insight: the thermal risk was not uniformly distributed during the drying process.

Time-resolved surface temperature profiles dem-

onstrated that early stage drying produced similar surface temperatures across all conditions, even when the set temperatures differed. However, as the drying progressed and evaporative cooling diminished, a pronounced divergence emerged. At 150 seconds, surface temperature increased by +295% relative to baseline at 90°C, compared to +207% at 80°C. This transient but substantial amplification indicates that late-stage drying represents a critical window of vulnerability, during which relatively small differences in the set temperature can translate into disproportionately large thermal excursions at the hair fiber surface [9]. These findings challenge the adequacy of evaluating dryer safety based solely on nominal temperature limits. A dryer operating within an ostensibly “safe” temperature range may still expose hair to damaging thermal peaks if late-stage amplification is not controlled.

Airflow distribution has emerged as a key determinant in the partitioning of drying energy within hair fibers [10]. Under airflow-shaping conditions, surface moisture decreased by -13.6%, nearly threefold greater than the reduction observed under uniform airflow (-4.6%). At the same time, internal moisture loss was limited to -9.4% under airflow shaping, compared with -22.2% under the control condition.

This decoupling of surface drying from internal dehydration is cosmetically significant. Efficient surface moisture removal shortens the period during which hair is mechanically vulnerable and facilitates styling, whereas preservation of internal moisture helps maintain fiber

compliance and reduces brittleness [11]. In contrast, a uniform hot airflow appears to drive the drying energy deeper into the fiber, accelerating internal dehydration without proportionally improving the surface drying efficiency.

From a mechanistic standpoint, airflow shaping re-distributes convective heat and mass transfer toward the hair fiber surface, thereby limiting the penetration of thermal stress into the cortex [12]. This spatial control complements the temporal control provided by thermal modulation, forming a unified thermofluidic strategy.

Thermal modulation further constrains cumulative thermal exposure and translates it into measurable sensory and biological outcomes. Warm-cool alternation increased hair fluttering by +11.0%, whereas constant hot airflow reduced fluttering by -3.7%. Increased fluttering reflects enhanced fiber mobility and reduced interfiber friction, both of which contribute to perceived softness and manageability. Increased hair fluttering after drying is consistent with reduced inter-fiber resistance, as the tribological behavior of hair is strongly governed by cuticle condition and surface friction [13]. Also, moisture content directly modulates the mechanical behavior of human hair, with increased hydration reducing elasticity and altering its viscoelastic stress-strain response [14].

Although this study focused on the short-term outcomes under controlled conditions, the mechanistic coherence observed across multiple scales suggests broader implications for cumulative hair damage during routine drying. Future studies should extend this framework to repeated use scenarios, diverse hair phenotypes, and long-term scalp responses to validate its generalizability.

Collectively, the results support the stabilization of late-stage thermal exposure and shaping of airflow distribution, enabling efficient surface drying, preserving internal moisture, and enhancing fluttering.

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AUTHOR CONTRIBUTIONS

Conceptualization: TRK, KHY. Data curation: TRK, DH, BHY. Formal analysis: TRK, HJK. Investigation: TRK, DH. Methodology: TRK, SYP. Project administration: Jungkwan Lee, Jungwon Lee. Software: JK, JSL. Validation: NMB. Visualization: JK. Writing—original draft: TRK. Writing—review & editing: all authors.

CONFLICT OF INTEREST

Kwang Ho Yoo is the Editor-in-Chief of the journal, but was not involved in the peer-review of this manuscript. The authors declare no conflict of interest.

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DATA AVAILABILITY

Contact the corresponding author for data availability.

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SUPPLEMENTARY MATERIALS

None.

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