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BRIEF REPORT

Predicting Age-Related Facial Hyperpigmentation via Dermatologist Knowledge Elicitation and Generative Modeling

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ABSTRACT

Introduction: Facial hyperpigmentation is a primary marker of skin aging in Asian populations. While many artificial intelligence (AI)-based aging simulators exist on social media, they often lack scientific transparency and dermatological validation. This study introduces and validates a novel facial aging simulator specifically engineered to provide personalized, evidence-based predictions of pigmentary spot progression according to varying levels of ultraviolet (UV) exposure and photoprotection.

Methods: The simulator utilizes a dual-tool framework: Elicitation Based Aging Simulator (EBAS) and AgingMapGAN (AMGAN). EBAS leverages the collective expertise of 28 dermatologists via a structured Delphi process and causal Bayesian belief networks (BBNs) to model skin aging trajectories. AMGAN, a conditional generative adversarial network, provides high-resolution visual representations of these trajectories. The model was trained on a standardized dataset of 600 individuals and focused on the density of pigmentary spots (DPS) on the cheek. Model performance was benchmarked against expert clinical grading using correlation metrics.

Results: The simulator demonstrated high accuracy in replicating expert logic (Pearson's correlation 0.96). In a case study of a 38-year-old female of Chinese descent, the model predicted the 15-year probability of a clinically significant progression (a two-grade increase in DPS). In the absence of photoprotection, the probability of reaching this elevated grade by age 53 was 71.35%, whereas regular daily application of SPF 50+ sunscreen reduced this probability to 39.24%.

Conclusions: This framework represents the application of a scientifically validated image-generation tool for predicting age-related hyperpigmentation based on individual exposome factors. By integrating dermatological knowledge, this simulator provides a robust educational and research resource for personalized skincare

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strategies. The findings confirm that consistent photoprotection significantly mitigates the 15-year trajectory of premature facial aging, offering a scientifically validated foundation for public health communication on prevention.

PLAIN LANGUAGE SUMMARY

Facial hyperpigmentation is a well-established marker of skin aging and photoaging; it represents both a significant indicator of premature aging and a major esthetic concern, particularly in Asian populations. Many smartphone and social media applications claim to predict facial aging, but most lack scientific validation. This work presents a scientifically rigorous facial aging simulator that generates personalized probabilities and visual predictions of age-related pigmentation changes. The tool integrates two previously published and validated works: first, the elicitation of 28 dermatologists' intrinsic knowledge across the world, and second, an AI-powered image generation system. The simulator enables users to visualize realistic 15-year projections of their facial hyperpigmentation, such as solar lentigo, incorporating both visual representations and probabilistic data, under varying degrees of sun exposure and photoprotection scenarios. Beyond the Asian skin model illustrated in this study, which evaluated scenarios ranging from no protection to daily high-SPF (50+) use, occasional application, and combined chemical/physical barriers, the simulator can be adapted to explore various levels of sun exposure, photoprotective behaviors, genetic factors, and environmental influences across diverse skin tones. This simulator, developed with dermatological expertise, is useful for scientifically and rigorously addressing the expectations of consumers concerned with specific markers of premature facial aging, such as facial hyperpigmentation. Furthermore, this tool enables public health initiatives focused on photoprotection and skin longevity, given their intrinsic link to premature aging.

Keywords: Facial hyperpigmentation; Solar lentigo; Skin aging; Photoprotection; AI; Artificial intelligence; Elicitation; Skin; Predictive model

Key Summary Points

The age-related progression of facial hyperpigmentation is a marker of aging and a major concern, affecting a substantial proportion of the population.

Consequently, numerous AI simulators have emerged and are widely used on social media platforms, despite a lack of rigorous scientific validation and methodological transparency.

The present study introduces a novel simulator developed from two validated and published studies, based on dermatologist knowledge via expert elicitation and a machine learning model that generates personalized facial aging images.

This allows for the individualized prediction and visualization of facial hyperpigmentation 15 years from the baseline image, according to varying degrees of sun exposure and photoprotection.

Through this scientifically robust, dermatologist-designed tool, dermatologists, researchers, and consumers can access reliable information regarding the prevention of premature facial aging.

INTRODUCTION

This paper presents a scientifically validated facial aging simulator developed through a dermatologist-expertise-driven approach. This tool is specifically engineered to provide personalized aging predictions, with a particular emphasis on the role of aging, and UV exposure in the emergence of premature facial hyperpigmentation.

The density of facial pigmentary spots, such as solar lentigo, increases with age and is considered a key marker of facial aging [1–4]. For Asian

women, particularly within Chinese and Japanese cohorts, the early onset and progression of these hyperpigmented lesions represent a major dermatological concern, underscoring the need for proactive prevention. Given that these age-associated macules are primarily solar lentigo, daily photoprotection constitutes a fundamental preventive strategy [1, 5–14].

Predictive simulations of facial hyperpigmentation, frequently marketed under the label of artificial intelligence within social media and gaming platforms, often lack robust scientific validation and methodological transparency. Leveraging the implicit knowledge of experienced dermatologists, who have individually assessed 75,000–150,000 patients over their careers, can substantially improve the precision of these tools. This study introduces a simulator designed to provide personalized predictions and visualizations of age-related facial hyperpigmentation, specifically according to varying degrees of sun exposure and photoprotection.

METHODS

Personalized predictive images were generated using a novel dual-tool approach, the Elicitation Based Aging Simulator (EBAS) and AgingMapGAN (AMGAN), developed in collaboration with dermatologists and data science experts [15–18].

First, using the Elicitation Based Aging Simulator (EBAS), predictive models for skin aging were constructed by leveraging the collective expertise of 28 international dermatologists (representing cohorts from France, the USA, China, Brazil, South Africa, and Senegal) [15]. The quantification of this expert knowledge was achieved through a structured Delphi method, facilitating a consensus-based data elicitation process. The underlying architecture employs causal Bayesian belief networks (BBNs) to model the probabilistic and causal dependencies between exogenous lifestyle factors, including tobacco consumption, ultraviolet (UV) exposure, photoprotection, and chronological age. These models quantify the 15-year cumulative progression of clinical aging signs (e.g., wrinkles, pigmentary disorders, and ptosis) for women of Asian, European, and African descent, beginning at age 18.

The EBAS output provides a probability distribution of potential clinical aging grades for each sign, alongside a calculated mean predicted score. This knowledge-driven approach ensures that predictions remain grounded in established dermatological principles, specifically regarding the interplay between photoprotection and actinic damage. Model validation was conducted by the dermatologists who participated in the construction of the models, and by an independent cohort of dermatologists who were not involved in the initial design phase. Simulations were benchmarked against established clinical skin aging references. In previous publications [15–17], we studied the effect of certain exposome factors, such as UV exposure and tobacco, on the increase of wrinkles with age without considering facial hyperpigmentation, The current iteration focuses specifically on the impact of chronological aging, sun exposure, and photoprotection on the premature emergence of facial pigmentary spots.

Second, visualization of personalized facial aging was performed using AMGAN, a conditional generative adversarial network (GAN) [18, 19]. See Supplementary Table S1 for details. This generative model utilizes the quantitative outputs from the EBAS framework to modify source images, thereby providing a visual representation of clinical aging progression. Regarding data acquisition, baseline images were acquired using a Canfield imaging system, ensuring standardized and controlled illumination. This high degree of environmental control minimized lighting-related variance, allowing for robust model performance without the requirement for an extensively large training dataset. The model was initially trained on a dataset of 600 individuals, with ground-truth clinical scores derived from the average of 15 expert graders. Given the strictly non-interventional nature of this study, in which no products were applied to the volunteers, formal ethics committee approval was not required. Written informed consent authorizing the use of their images for research and scientific publication was obtained before the study from all participating volunteers. Furthermore, to ensure strict anonymity and protect privacy,

the photographs presented in this manuscript have been heavily cropped.

To enhance model generalization, standard data augmentation techniques were employed, including horizontal mirroring, random cropping, and controlled perturbations of color and illumination. The AMGAN architecture processes localized image crops corresponding to specific anatomical regions, including the peri-ocular, glabellar, nasolabial, inter-ocular, infra-orbital, peribuccal, and forehead areas. Both the source crops and target aging scores were standardized according to validated photographic skin atlases [16], which utilize linear grading scales ranging from 0 to 8.

In this article, we focus exclusively on the density of spots on the cheek as a clinical sign of skin aging. This parameter, referred to as density of pigmentary spots (DPS) in the Atlas of Skin Aging—Vol. 2: Asian Type, is graded on a scale ranging from 0 to 7 [20]. Regarding the model's performance on this clinical parameter, the strong alignment between the ground-truth scores provided by clinical experts and the model's predictions was confirmed by high correlation metrics (Pearson's correlation 0.96; Spearman's correlation 0.95). These results demonstrate the model's ability to accurately replicate expert logic.

The use of this image generation software thereby enables the visualization of aging trajectories for pigmentary spot density, a parameter known to be associated with lifestyle factors such as sun exposure and photoprotection.

RESULTS

This study introduces a simulator designed to provide personalized predictions and visualizations of age-related facial hyperpigmentation, specifically according to varying degrees of sun exposure and photoprotection. A high-resolution facial image of a 38-year-old subject of Chinese descent (Fig. 1a), captured using the Nexa® system (Canfield Beauty, Parsippany, NJ, USA), was processed via AMGAN technology to simulate a two-grade progression in the laterofacial pigmentation density parameter. The primary objective of presenting this case is not the technical validation of the underlying generative models, as this has been established in previous extensive studies [15–19]. Instead, it serves to illustrate a practical framework for integrating dermatologist expertise with AI to create robust educational, preventive, and diagnostic-support tools. For confidentiality purposes and to focus the visualization solely on this clinical sign within this article, the presented image was cropped and centered on the relevant area; although the simulator is capable of modeling the transformation of all facial clinical signs associated with aging and photoaging, only this specific clinical sign is illustrated in this image (Fig. 1b).

Figure 2 illustrates the probabilities, calculated by the EBAS simulator, which was developed in collaboration with dermatological experts, of advancing by two grades in the laterofacial pigmentary density score over a 15-year period. These probabilities reflect varying levels of photoprotection: no photoprotection, irregular versus regular daily application of SPF 50+ sunscreen, and the use of physical photoprotection in addition to topical measures. The selection of a two-grade increment was determined through consultation with dermatologists and clinical experts, reflecting a clinically relevant progression observable over a 15-year longitudinal period, thereby enabling the calculation of significant probabilities. Furthermore, this increment provides a significant and clearly discernible delta in spot density severity, facilitating the visualization of pigmentary changes for readers unfamiliar with clinical grading atlases. Confounding variables were minimized by maintaining constant levels of sun exposure (mild working day sun exposure, moderate recreational sun exposure), a normal body mass index (BMI), no smoking (or less than 10 pack-years), and no excessive pollution exposure. Only the use of sunscreen (SPF 50) varied across different frequencies (never, intermittently, always).

Starting from the baseline laterofacial pigmentary spot score shown in Fig. 1a (at age 38), Fig. 2 presents the probabilities of reaching the elevated grades depicted in Fig. 1b by age 53. For instance, the probability of advancing by at least two pigmentary spot grades by age 53 is 71.35%

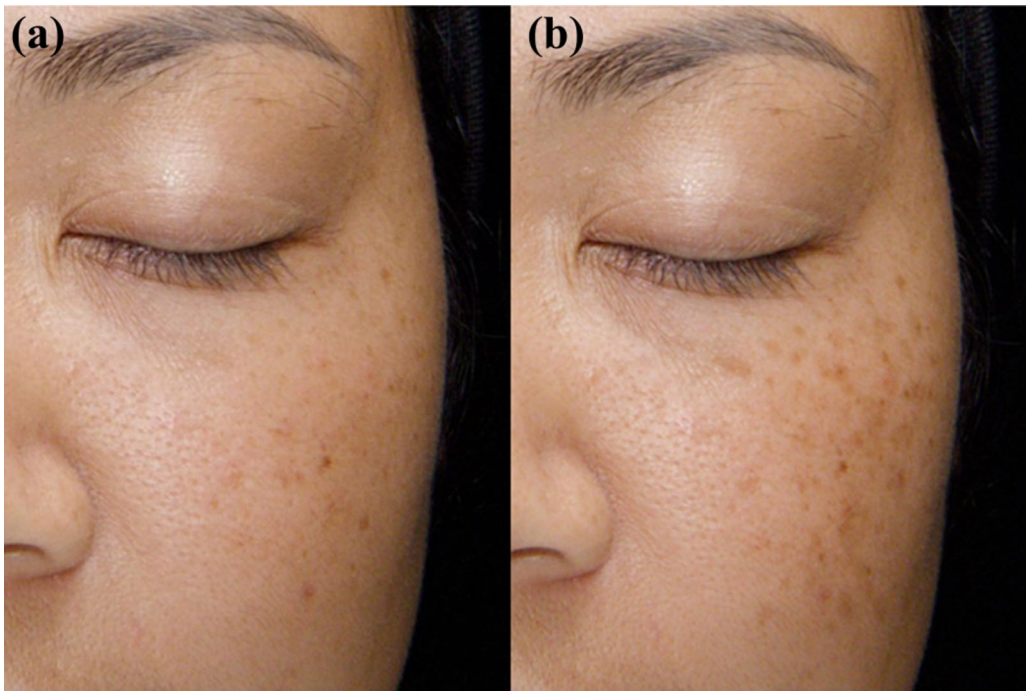

Fig. 1 Illustration of a two-grade spot density increase simulated by AMGAN. (a) Baseline facial spot density of a 38-year-old volunteer. (b) AMGAN-simulated image based on a, depicting a two-grade increase in spot density. These figures visually exemplify the specific two-grade increase in spot density, the probabilities of which are calculated by the EBAS model and detailed in Fig. 2

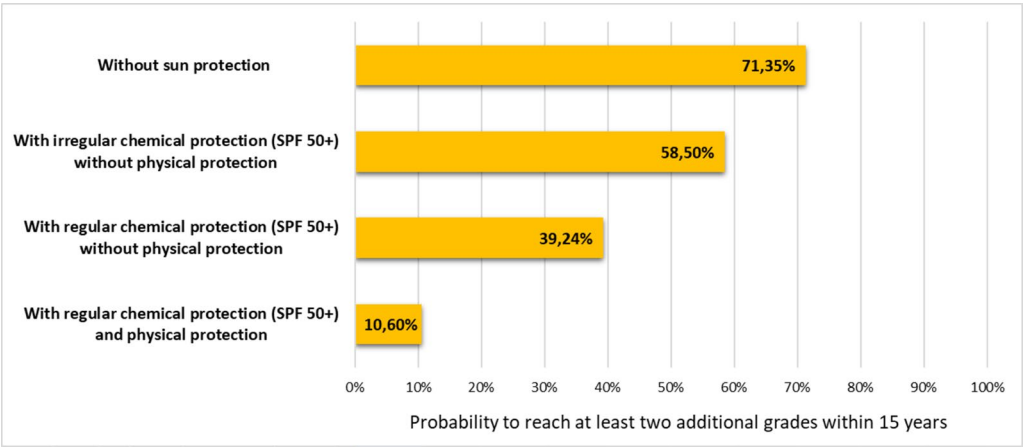

Fig. 2 Comparative probabilistic analysis of the 15-year evolution of age-related pigmentary spot density in the cheek region. This figure presents the cumulative probability of reaching at least two additional severity grades for a 38-year-old volunteer by age 53, based on sun protection habits. While regular use of chemical and physical protection maintains the probability at 10.60%, the absence of protection leads to a 71.35% probability. The data stem from the EBAS simulator, where expert dermatologists utilized clinical grade atlases to model aging trajectories. The model incorporates expert-weighted intrinsic and extrinsic variables to quantify the transition probabilities between severity grades from a defined baseline

in the absence of photoprotection, whereas it decreases to 39.24% for those with regular use of a topical SPF 50+ product. Furthermore, regular use of combined chemical and physical protection maintains the probability at 10.60%. Ultimately, this tool provides a quantitative and visual assessment of the 15-year impact and prognostic probabilities associated with different levels of photoprotection.

DISCUSSION

This study presents the first application of this innovative method for predicting facial pigmentation spots associated with aging, and more specifically with photoaging. This method combines two scientifically robust and published models that integrate a probabilistic model based on the elicitation of dermatologists' intrinsic knowledge with an image generation model. This new simulator enables personalized prediction of spot density 15 years later according to each individual's exposome, particularly their degree of sun exposure and photoprotection, as illustrated in Figs. 1 and 2.

Although the effect of UV radiation on the age-related occurrence of pigmentary spots, specifically solar lentigo, is well established, this simulator provides, for the first time, a personalized quantification and visual illustration of this effect specific to individual exposure patterns.

The impact of photoprotection and the risks associated with both chronic daily and intermittent recreational UV exposure, specifically regarding facial hyperpigmentation, premature facial aging, and skin carcinogenesis, are extensively characterized and published [1–6, 21]; yet, public understanding and practical knowledge about photoprotection, especially in Asia, despite the significant concern regarding facial hyperpigmentation, alongside the scientific rigor and formal dermatological validation of existing simulators, remain notably limited [22, 23]. In this context, the development of a scientifically validated tool appears necessary given the proliferation of non-validated applications, particularly recreational ones, that many users employ. Although our teams routinely conduct internal benchmarking against commercially available social media aging applications, these evaluations were excluded from the present study. These recreational simulators rely on proprietary methodologies, often lack training panel diversity, and yield lower-resolution outputs. Furthermore, their frequent, commercially driven updates introduce methodological instability that precludes rigorous scientific publication. Whereas unrealistic models may have a counterproductive effect on photoprotection adherence, applications perceived as scientifically robust foster greater engagement with sun protection strategies in response to UV-related risks. Such simulations, incorporating high SPF as well as the combination with physical photoprotection, are particularly relevant when investigating Asian cohorts where these habits are commonly practiced.

To avoid altering the visualization of the pigmentation parameter, other signs of aging already published were not illustrated in this work, nor were other factors that may induce pigmentary spots such as pollution, aggressive pigmentogenic routines, or other benign cutaneous tumors such as seborrheic keratoses or dermatosis papulosa nigra. Some of these parameters are particularly relevant in other simulator models that we have not presented here, such as the model for fair skin tones of European descent or for deep skin tones of African American descent. Although not presented in this study, the simulator can evaluate the impact of varying degrees of sun exposure and photoprotection adapting to phototype and individual typology angle (ITA) across diverse skin tones, as previously published.

If we want these tools to be used by the general public, as well as in research to disseminate scientifically rigorous information based on dermatologists' expertise, the simulator's future development must enable the processing of smartphone-captured images, including selfies, while maintaining the model's scientific robustness. Our current model was developed for the Nexa Canfield acquisition system, which captures high-quality facial images under controlled and standardized lighting conditions. While this standardized approach, combined with data augmentation, significantly reduces the required

dataset size and has allowed for extensive validation both in the initial publication [18] and in subsequent unpublished projects, expanding the dataset in future projects will be essential to prevent any potential biases that could theoretically emerge from an initial cohort of 600 volunteers. To address this limitation, we are already collecting and processing data that will enable us to extend the model to uncontrolled lighting environments [24]. Regarding image transformation, our improvement efforts focus on new generative approaches that do not rely on GAN frameworks, such as denoising diffusion models, which have demonstrated equivalent or superior performance for image generation tasks.

Beyond the esthetic implications of preventing pigmented spots, these predictive models could be utilized to evaluate behaviors related to photoprotection and sun exposure, as well as other contributing factors to pigmentation, such as pollution and genetic factors. Indeed, by utilizing historical photographs, we are currently working to enable the simulator to predict the expected aging trajectory based on images from 15 years prior, in order to assess whether a subject exhibits signs of premature aging.

Although this study presents an example using the Asian model, our development efforts aim for universal applicability to all skin phototypes, given the importance of photoprotection across diverse skin tone [25, 26]. Throughout this development process, we aim to preserve the scientific rigor of these tools as well as the invaluable expertise of the dermatologists involved in their creation. These anticipated improvements, while maintaining the accuracy and reliability of the data collected from dermatologists, are intended to facilitate dissemination to a wide audience regarding public health prevention of UV exposure risks and cosmetic concerns for premature skin aging.

CONCLUSIONS

By combining knowledge elicitation data from dermatologist expertise with AI-generated images, this simulator integrates two previously validated methodologies and completes our previous works on clinical signs of facial aging by enabling personalized, quantitative predictions of age-related facial pigmentary spot density based on individual photoprotection behaviors. Our findings confirm that regular photoprotection use reduces the 15-year probability of clinically significant pigmentary progression, thereby substantially mitigating premature skin aging. This simulator uniquely provides personalized quantification and visualization of these age-related probabilities. This evidence-based tool addresses the critical need for validated aging prediction in an era dominated by non-validated social media applications, offering both a scientifically robust educational resource for UV risk communication and a foundation for personalized prevention strategies aimed at skin longevity. Future development focused on smartphone compatibility and integration of additional environmental factors will enable broader dissemination of this technology for both public health prevention of premature photoaging and dermatological research applications.

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appropriately recognized as co-authors in the original publication (Jouni H et al., *Skin Research and Technology* 2024). They were not involved in the current work because modulators had already been validated and published in submission collaboration with them. Their input was not required for the operation of either the EBAS simulator (which generates probabilities for each facial sign) or the AMGAN simulator (which generates a full face with predicted grades) in this specific study.

Author Contributions. Conceptualization was led by Edouard Raynaud, Laudine Bertrand, and Hussein Jouni, with all authors contributing to the overall study design. Material preparation, data collection, and formal analysis were performed collectively by all authors (Edouard Raynaud, Laudine Bertrand, Frederic Flament, Jennifer Bourland, Emmanuelle Tancrède-Bohin, Tao Li, and Hussein Jouni). Edouard Raynaud wrote the first draft of the manuscript, and all authors provided critical revisions on previous versions. All authors have read and approved the final manuscript.

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Data Availability. The data that support the findings of this study are not openly available owing to reasons of sensitivity and confidentiality. This contains proprietary data which belongs to L'Oréal Research & Innovation. Data can be available upon reasonable request; please contact the corresponding author (Hussein Jouni).

Declarations

Conflict of interest. Hussein Jouni, Laudine Bertrand, Frederic Flament, Tao Li, Jennifer Bourland, and Emmanuelle Tancrede-Bohin are employees of L'Oréal. Edouard Raynaud works as a consultant dermatologist for L'Oréal.

Ethical Approval. Given the strictly non-interventional nature of this study, in which no products were applied to the volunteers, formal ethics committee approval was not required. Written informed consent authorizing the use of their images for research and scientific publication was obtained before the study from all participating volunteers. Furthermore, to ensure strict anonymity and protect privacy, the photographs presented in this manuscript have been heavily cropped.

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