Perspective

Molecular basis of fingerprint pattern formation

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Abstract: The fingerprints are an individual's genetically determined unique epidermal ridge patterns that remain constant throughout life. For centuries, man has used fingerprints for fortune-telling and as proof of a person's identity. Glover et al., [1] recently published an interesting article that aims to understand the developmental basis of fingerprint pattern formation and variation. The fingerprint ridges undergo a trun-cated hair follicle developmental program with differential gene expression and signaling of molecular players. Cell proliferation in several spreading waves initiated at variable sites delivers uniqueness to each fingerprint. Here, I present an overview of the historical background, a concise review of the molecular mechanisms and the implications of fingerprinting technology.

Keywords: fingerprints, genes, epidermal ridges, signaling, patterning

Citation: Ramachandra N. B.; . *Awareness*, 2 (1): 4-7

Academic Editor: Dr. B. K. Thelma

Received: Aug. 24, 2024

Revised: Dec. 04, 2024

Accepted: Dec. 19, 2024

Published: Jan. 14, 2025

1. Introduction

Fingerprinting captures the unique impression of ridges on an individual's palms, digits, and soles. The ridges on the skin surface enhance grip and discriminate texture. The most common types of fingerprint ridge patterns are loops (65 %), whorls (30 %) and arches (5 %) (Figure 1). Loops are ridges that curve only on one extremity of the pattern. The ridges that encircle a core are the whorls in an anticlockwise or clockwise. The arch is the simple ridge passing from one digit margin to another. Fingerprints are not the same in both hands and persist lifelong unless the dermis is damaged. The likelihood of seeing identical fingerprints was 1 in 64 million. The fingerprint is unique for an individual be-cause the epidermal ridges are genetically determined, and their patterns remain con-stant throughout life. Nongenetic factors may also influence the inheritance of fingerprint patterns [2-3].

For centuries, man has used fingerprints for fortune-telling and as proof of an individual's identity. The history of skin ridges and their applications was reviewed by Galton [4]. In 1929, Harold Cummins and Charles Midlo published the remarkable book "Fingerprints, Palms and Soles" [5]. In 1976, Schaumann and Alter published a book titled "Dermatoglyphics in Medical Disorders". Li et al., [6] reported that limb development genes underlie variation in a human fingerprint pattern. Glover et al., [1] recently published exciting articles on the developmental basis of fingerprint pattern formation and variation. Here, I summarize the key findings of Glover et al., [1] highlighting the molecular mechanisms involved in the fingerprint pattern.

2. Molecular mechanisms in fingerprint patterning

Glover et al., [1] demonstrated the developmental basis of fingerprint pattern formation and variation using fetal specimens, cell lines and mice as experimental materials, employed several staining methods, in situ hybridization, single nucleus RNA sequencing, ridge and hair placode markers, skin organoids, fibroblast and ex vivo skin cultures, qPCR, atomic force microscope for cell density, primary ridge morphology and proliferation analysis, mouse digit ridge and flexion crease analysis as well as mathematical simulations. The following paragraphs provide an overview of notable findings on fingerprint patterning.

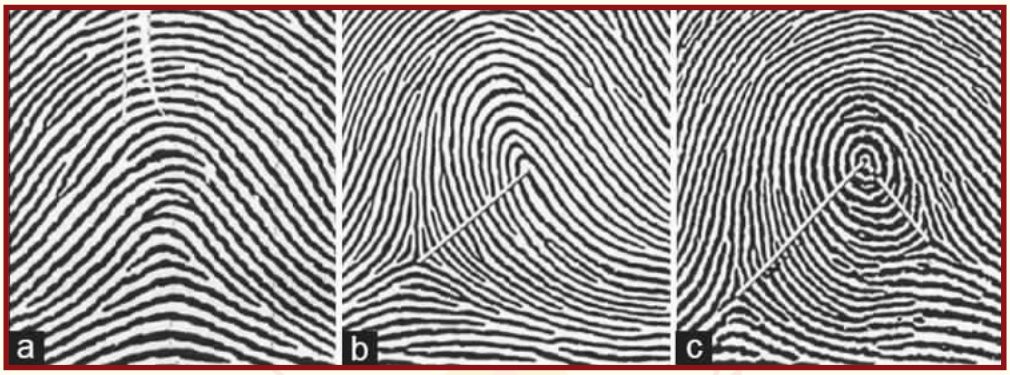

Figure 1. Common types of ridge pattern. a) Arch, b) Loop, and c) Whorl [7].

The early fingerprint ridges are epithelial buds molecularly analogous to hair placodes. The human body carries hair follicles (HF), which express EDAR and WNT pathway genes during embryonic development as circular epithelial placodes. Each placode recruits a dermal condensate by emitting an FGF20 signal and undergoes extended tubular down growth driven by SHH signaling. The volar (hairless) skin from week 8 carries a series of flexion creases across the palm and digit. The expression of EDAR, FGF20, and BMP2 proteins is identical across all the creases, indicating that crease epithelium remains competent to undergo patterning with normal epidermal polarity and organization [8].

The volar epithelium is the first on the body to differentiate into a keratinized, stratified epidermis with lower WNT activity to form a dermal condensate and for aggregation responses to FGF20 signals. In the deepest part of the ridges, FGF20 promotes mesenchymal cell adhesion with the highest WNT/b-catenin activity and retains EDAR and LEF1 expression throughout their proliferative down growth. The primary digit ridges express the early markers as that of HF like EDAR, FGF20 and BMP2, but not the specific HF markers SHH6, SOX2 and DKK1, indicating that primary ridges undergo truncated hair placode development. Single-cell expression profiling identifies LMX1A, TGFA, MYB, and MEGF11, the selective markers as-sociated with ridge and sweat glands, but not HF. High levels of BMP signaling and expression of ENGRAILED in the ridges contribute to the suppression of HF formation in volar skin.

The fingerprints initiate in weeks 12th to 13th when cells in the middle basal layer of the skin start growing faster than the inner or outer layers of the skin. These extra cells are responsible for forming the skin to fold into ridges at the tips of the digits. EDAR expression in the ventral digit epithelium is uniform at week 12 and localized, with high expression at weeks 13 and 14 to the nascent ridges into bands and diminishing in inner ridges. This makes the boundaries at the nail bed and dorsal-ventral boundary of digit skin. By week 15, the primary ridges form the arch, loop, or whorl pattern by interaction with anatomical landmarks. By week 17, the primary ridges carry periodic down growths of sweat glands with higher expression of TGFA and become flanked by smaller secondary ridges, resulting in parallel ridges and grooves of the skin surface.

In volar skin, higher BMP activity was detected throughout the ridge and interridge basal epithelium. The expression of EDAR and WNT signaling is responsible for partitioning the epithelium into ridges and interridges by banded proliferation. Elegant experiments involving inhibition of WNT and ablation of EDAR signaling

confirmed that EDAR is required for normal ridge patterning, and its effects on the size, spacing, and shape of the digit ridges indicate the operation of a spatial patterns and diffusion system in defining their arrangement. The high WNT signaling promotes and drives cellular proliferation and the emergence of morphological ridges and binding to BMPs in interridges to prevent BMPs from binding to their receptors on the cell surface. This indicates that BMP is responsible primarily for patterning signals, and WNT signaling activates cell cycle progression in progenitor and stem cells, defining the spacing interval between ridges. Thus, the interacting WNT and BMP signalling defines the spacing interval between ridges. It is evident that development is complete by the 21st week. One can reproduce the major pattern types of arch, loop, and whorl by manipulating the in-itiation sites' relative timing, location, and angle. The operation of a simple patterning system that reads distal limb geometry to trigger initiation events and the subsequent collision of spreading patterning waves is capable of generating many different types of human fingerprint patterns.

In conclusion, fingerprinting ridges are developmentally abbreviated ectodermal appendages. The early fingerprint ridges are epithelial buds molecularly analogous to hair placodes. The fingerprint ridges do not recruit mesenchymal cells or express late HF markers. Several common and specific molecular signaling are responsible for the development patterning of fingerprints. The interacting WNT and BMP signaling defines the spacing interval between ridges. Further, the ridge initiations from anatomically variable sites determine fingerprint pattern type.

Even though a substantial amount of experimental data has been generated, a more comprehensive presentation of the findings would have enhanced the clarity of gene activity cascades and signaling.

3. Limitations of the study

Although extensive experiments have been carried out, there are many limitations to the current study. Ridge inhibitory factors other than BMPs have yet to be explored and may act in the patterning process. Secondly, the small size of the mouse digit prevents the elaboration of complex ridge patterns in understanding mechanisms defining ridge-to-ridge periodicity. Thirdly, in vivo experiments in humans to understand fingerprint patterning are not possible. To address this issue, longer-term culture methods or organoids that specifically model volar skin formation must be developed. These limitations should be addressed in future studies.

4. Implications of fingerprinting technology

Currently, biometrics is being used widely across the globe for accurately identifying and authenticating an individual. It has various applications ranging from personal devices to corporate security systems, making everyday transactions safer and adaptable to diverse environments. The types of biometrics are fingerprints, ears, iris, and retinal identification, DNA matching, hand geometry, voice, facial, signature and body recog-nition. The patterns of ridges found on the fingertips of humans are the most prominent and widely accepted biometric traits due to their uniqueness, permanence, storability, high indispensability, universality, collectability and performance. Medical uses of fingerprinting aim to solve patient matching, identification and diagnosis of genetic abnormalities. Fingerprinting is also used to identify criminals, trace the drugs ingested, improve security and many more. With the advent of technology, the automated fingerprint identification computer system was developed and implemented on a large scale to improve and expedite the process of maintaining, searching and matching fingerprints in computerized databases. Fingerprint verification technology has become critical in our daily lives as an access key for everything from smartphones and computers to bank accounts, offices, and even health records. Most of the world's population owns Smartphones with built-in biometrics capabilities. In many fields, such as airlines, airports, hotels, telehealth, mobile payments, online retail, e-commerce, and hospitality, companies are integrating mobile biometric authentication into their identity verification processes to enable seamless, secure services and amenities.

Although Smartphone biometrics provides robust security, they are only partially foolproof. Biometric data can be manipulated using high-resolution photos or sophisticated 3D-printed replicas. To address the challenges in mobile biometric authentication, robust encryption, continuous improvement in accuracy, and user education are crucial. Manufacturers are continuously improving their algorithms to combat such attacks.

Author Contribution: The entire article was conceptualized and written by Dr. Rama-chandra.

Supplementary Materials: No supplementary materials.

Funding: No funding was received for this article.

Institutional Review Board Statement: Not applicable

Informed Consent Statement: Not applicable

Data Availability Statement: Not applicable

Acknowledgement: I thank DAE for the Raja Ramanna Chair grant, and the University of Mysore for providing me the place of work.

Conflicts of Interest: None.

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