Fingerprint imaging from the inside of a finger with full-field optical coherence tomography

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Abstract: Imaging below fingertip surface might be a useful alternative to the traditional fingerprint sensing since the internal finger features are more reliable than the external ones. One of the most promising subsurface imaging technique is optical coherence tomography (OCT), which, however, has to acquire 3-D data even when a single en face image is required. This makes OCT inherently slow for en face imaging and produce unnecessary large data sets. Here we demonstrate that full-field optical coherence tomography (FF-OCT) can be used to produce en face images of sweat pores and internal fingerprints, which can be used for the identification purposes.

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1. Introduction and background

The most commonly used fingerprint sensors today are based on frustrated total internal reflection (FTIR), which produce fingerprint images by reflecting light from only those parts of the skin-glass interface that are not in contact [1]. However, sensors often fail to produce adequate fingerprint images for the identification purposes when a finger has creases, is dirty, scarred or too wet/dry [2]. In addition, certain occupations and old age are associated with flattened fingerprints that produce poor quality fingerprint images. Nevertheless, papillary junction, a layer of skin inside a finger, has the same topographical features as the surface (external) fingerprint [3]. This internal layer, which we call here the internal fingerprint, serves as a ‘master template’ from which the external fingerprint regrows and, therefore, is believed to be less affected by the damages sustained on the surface. Thus, imaging internal fingerprint can be a more accurate way of fingerprint imaging. In addition, other internal structures of a finger, such as sweat pores [4] and microvascular structure [5] might be used for the identification purposes because they follow the same fingerprint pattern as the external fingerprint. Another problem in fingerprint sensing is fingerprint spoofing – traditional sensors can be tricked by an accurate imitation of the fingerprint structure made from low-cost materials and techniques [6]. New imaging solutions that would allow imaging below finger surface and enable discrimination between real and fake fingerprints are thus highly desirable. Currently, there are not many different types of sensors on the market that are able to gather information from the inside of a finger. One of those techniques, called multispectral fingerprint imaging [7], works by reconstructing a fingerprint image from multiple images.
collected at different wavelength, illumination and polarization settings [8]. Another
 technique that works by detecting transmitted infrared light through a finger is able to image
finger veins [9]. However, none of those techniques can acquire optically sectioned images
from specific depths in a finger. In contrast, optical coherence tomography (OCT) possesses
optical sectioning capability and is able to image deep in tissue. One of the first applications
of OCT in fingerprint imaging was its use to differentiate between real and artificial
fingerprints by a single A-scan acquisition (signal signature along optical axis) [10, 11].

Point-by-point raster-scanning of A-scan builds a 3-D data volume, which can be used to
reconstruct a single en face 2-D image at a specific depth. This way en face OCT images of
internal fingerprints [12], sweat pores [13] and even blood microcirculation [14, 15] were
demonstrated. Since the first demonstrations there has been quite a few further studies to
evaluate OCT technology for finger subsurface imaging [16–18]. Nevertheless, fast standard
OCT techniques, such as swept-source OCT (SS- OCT) are not very efficient in recording
en face images, as it requires the acquisition of 3-D data volume from which a single 2-D image
of a skin layer of interest is reconstructed. In addition, imaging a finger with sufficient field of
view and resolution typically results in data sizes approaching 1 Gb. In contrast, full-field
OCT (FF-OCT) [19] can acquire a single en face image without having to acquire 3-D data
set, and therefore, produce much smaller image size (a few Mb) and potentially can be faster.
FF-OCT uses a 2-D detector (camera) instead of a point detector (or a spectrometer and a line
scan camera in case of spectral-domain (SD) OCT) and a conventional, spatially incoherent
light source instead of a laser source or a super luminescence diode (SLD). The fastest OCT
system reported to date utilized Fourier domain mode locked (FDML) [20] laser with sweep
rate of 5.2 MHz that provided acquisition of 4.5 GVoxels per second and sensitivity of < 100
db, in four beam scanning configuration [21]. However, FF-OCT system with a fast camera
(10000 frames per second) can provide up to 10.5 GVoxels per second [22], albeit at lower
sensitivity. Nevertheless, some applications, such as shear wave imaging [22], do not require
high sensitivity and ability to image deep in tissue. For such cases FF-OCT can be used to
acquire en face images of 1024 × 1024 pixels in 0.2 msec, whereas the FDML-based OCT
takes around 200 msec. Moreover, Adimec is currently releasing an inexpensive (<10k$)
camera (Q-2A750/CXP) that is able to acquire images of 1440 × 1440 pixels at 750 Hz frame
rate and with pixel’s full well capacity (FWC) value of 1.5 Me-. FF-OCT system with this
camera would be a couple of times less expensive than the FDML-based OCT system but
would have specifications approaching those of fast FDML-based OCT systems - the
acquisition speed of 0.7 GVoxels/s and expected sensitivity of 90 db. In addition, such FF-
OCT system would be able to achieve better axial resolution (~1 µm) due to its ability to use
conventional broadband sources and would not require complex data acquisition schemes and
heavy processing.

FF-OCT has been mostly used for high resolution diverse biomedical applications, such as
imaging skin [23], brain tissue [24] and gastrointestinal wall [25], to name a few. For
fingerprint imaging applications, FF-OCT has been used to differentiate between real and fake
fingerprints [26] and to acquire surface fingerprint images [27]. A similar technique, called
full-field swept-source OCT, which utilized a spatially coherent swept-source for
illumination, has been used to acquire latent fingerprint images imprinted on a coverslip [28].
However, none of the above full-field OCT techniques demonstrated imaging below the
surface of a finger, except one study [29], where authors, by reporting on a wide-field OCT
system with an ultrahigh-speed camera and SLD, showed images of sweat pores and also
images of what seems to be the internal fingerprints. However, the images had to be spatially
averaged with a 10 × 10 spatial averaging filter in order to increase the contrast that
effectively reduced spatial sampling to 100 dots per inch (dpi), which is at least 5 times lower
than that necessary for fingerprint imaging applications [2]. Furthermore, the use of ultrafast
camera is prohibitively expensive and SLD increases cross talk between adjacent pixels in
camera, which is mostly eliminated by the use of spatially incoherent light sources in FF-
OCT.
Here, we demonstrate that FF-OCT can be used to image below surface of a finger by using a system constructed of a fiber-bundle-coupled halogen light source, Michelson interferometer and InGaAs camera. We use NIR illumination (1.3 µm) to achieve better penetration and improved imaging depths. We ultimately show that images of sweat pores and internal fingerprints can be acquired in less than a second.

2. Materials and methods

2.1 FF-OCT

FF-OCT system for fingerprint imaging below the surface of a finger is shown in Fig. 1. A halogen bulb (150 W, 3200K color temperature) is coupled into 5 mm diameter fiber bundle and delivered to the system, shown in Fig. 1. Köhler illumination is implemented as follows. Output of the fiber is imaged with a collector lens onto the aperture diaphragm that controls the illumination numerical aperture (NA). The next lens images the aperture to the infinity. A field diaphragm is inserted at the focal plane of the collector lens that can be used to control the illumination field of view (FOV) and also helps to reduce scattered light in the system. Light is divided into the reference and sample arms by a non-polarizing beamsplitter with the equal splitting ratio of 50:50. A finger is pressed against a 5 mm thick glass window in order to flatten it out and stabilize mechanically. An identical window is inserted in the reference arm to match the dispersion between the two arms. A 3 mm thick OD6 neutral density filter, that has reflectivity of ~0.04 in the infrared region, is used as the reflector in the reference arm. Light coming back from the reference and the sample arms is recombined by the same beamsplitter and reimaged onto an InGaAs camera with a 1:1 magnification by a 2-lens system in 4f configuration. Each of the lens system contains a pair of achromatic doublets (f = 10 cm) arranged in the Plösl configuration for the better off-axis performance [30]. The InGaAs camera (Xeva 640, Xenics) acquires images of 640 × 512 pixels at 25 Hz (pixel size – 20 μm, FWC – 2 Me).

![Fig. 1. FF-OCT fingerprint sensor. The system is shown in an oblique imaging configuration (with tilted reflector). Fiber-bundle delivers light from a halogen lamp source (not shown) to the system, where it goes through the Köhler illumination and is divided into the reference and sample arms by a beamsplitter (BS). Scattered light (gray) and reference beam (red) is recombined and imaged onto an InGaAs camera. Piezo actuator in the reference arm is used to modulate the interference on the camera. A motor is used to select the imaging depth in the finger. Note that in the diagram only one beam path is traced, which originates at the center of the fiber bundle. Insets (a): a magnified view of the reference and sample coherence gates with the exaggerated reference beam tilt. Δ – FOV that is limited due to the narrow coherence gate overlap in case of imaging a flat reflector or a very thin specimen. Inset (b): a magnified view of the reference coherence gate and a sample with the exaggerated reference beam tilt. The FOV is not limited due to the thick specimen but the coherence gate tilt slices it at an oblique angle that is defined by the reflector’s tilt.](image-url)
The system images large FOV (of 1.02 × 1.28 cm) with the spatial sampling of 1270 dpi. The beams form an interference image on the camera if the optical path length difference (OPLD) is within the temporal coherence length of the light source. A piezo actuator can move the reflector to introduce OPLD between the reference and the sample beams. The interference image will change upon the piezo movement but the background signal, coming from the outside the coherence gate, will stay the same. Subtracting images, recorded at different piezo positions (and different OPLDs), will get rid of the background light, and thus, produce an optically sectioned image. Four images acquired with $\lambda/4$ OPLD in between them are commonly used, where $\lambda$ is the central wavelength. A single FF-OCT image is reconstructed by calculating a square root of $(I_1 - I_3)^2 + (I_2 - I_4)^2$, where $I_1$, $I_2$, $I_3$, and $I_4$ are the images acquired at $0^\circ$, $90^\circ$, $180^\circ$ and $270^\circ$ phase difference between sample and reference arm, respectively. A few FF-OCT images are averaged in order to improve the signal to noise ratio (S/N), resulting in acquisition time of typically around 1 sec. In high-resolution FF-OCT systems [31, 32], a motor is used to move a specimen along z-axis in order to acquire images at different depths. In low numerical aperture (NA) cases, however, like here (NA =0.05), the reflector in the reference arm can be moved instead since the depth of field is relatively large and the coherence gate can be kept within the confocal gate over at least a millimeter. The broadband light provided by the halogen lamp covers the whole detection range of the camera, and therefore, the optical sectioning (the axial PSF) provided by the coherent gating is around 1.5 µm. However, signal from such a thin slice needs to be averaged over many images to increase the signal-to-noise ratio (S/N), which is not compatible with the live fingerprint imaging applications. Therefore, to increase OCT signal, we filter the broadband source with 1300/30 nm filter that resulted in a wider coherence gate and, subsequently, in axial resolution of 25 µm. Sensitivity of such system was measured to be of 85 db when 5 images are averaged (total acquisition time of less than a second). The measure can be improved by a better control of incoherent (stray) light in the system.

2.1 Oblique FF-OCT

In order to capture a single en face image of, for example, the internal fingerprint the depth at which it is located inside a finger needs to be known. For example, previous studies have shown that the internal fingerprint layer can be found in the range of 220 – 550 µm below the surface [12]. One can acquire a full 3-D image stack from which a layer of interest can be located. However, it is time consuming approach and not realistic for live fingerprint imaging applications. Here we propose to use, what we call oblique FF-OCT (o-FF-OCT), which enables recording all the layers in one image from which the distances to the surface of each layer can be determined. The principle of o-FF-OCT is depicted in Fig. 1 and is as follows. Tilting the reflector in the reference arm shifts the reference beam position on the pupil plane from its center towards its edge. This makes the coherence gate of the reference beam tilted and form an angle with respect to the camera’s plane and that of the coherence gate of a sample beam (Inset (a) in Fig. 1), which stays parallel to the camera’s plane because of the scattering that light experience in the sample. When an object, be it biological tissue or a grating, scatters beam that is normal to the object, it keep the coherence gate parallel to the scattering (object) plane regardless of the scattering angle. Therefore, the coherence gate of the sample is not tilted even when the sample beam follows the same path as the reference beam. When imaging a very thin object or a flat reflector, the FOV is limited because of the narrowed overlap between the coherence gates of the reference and the sample beams (Inset (a) in Fig. 1). However, in thick scattering specimen, such as biological tissue, the whole-FOV image will be acquired but at the oblique angle (Inset (b) in Fig. 1). The angular tilt of the reflector defines the angle at which o-FF-OCT image is recorded in a specimen (the angles are the same in 1:1 imaging case), and therefore, can be chosen such that it contains the images of the external fingerprints, sweat pores and the internal fingerprints. The maximum imaging depth that can be achieved with o-FF-OCT is limited by the depth of field of the detection optics, and therefore, can be approximated to $\lambda/2NA^2 = 1.3\mu m/0.05^2 =500 \mu m$. A distance of each layer from the surface can be worked out if the tilt and the depth of the image
are known. Subsequently, the reflector can be tilted to the *en face* imaging condition and moved to the determined depth to image a layer of interest, all of which can be done automatically.

3. Results

Two different experiments were carried out. In the first one a volunteer’s finger, pressed against the window, was imaged over the depth of 1 mm with the axial step of 5 µm. Each FF-OCT image was recorded in 0.16 sec and subsequently 10 of those images were averaged, resulting in the total acquisition time of 1.6 sec per image in the stack. Figure 2 shows images of sweat pores and the internal fingerprint extracted from the 3-D data stack by averaging over a few images in the stack. The FF-OCT images are compared to the external fingerprint image, shown in Fig. 2(a) that was acquired with the commercial fingerprint sensor (MSO300, Morpho), which is based on FTIR principle. We can see that the FTIR image of the external fingerprint is very similar to the FF-OCT image of the internal fingerprint, shown in Fig. 2(b). An image of the sweat pores, in Fig. 2(d), follows the same pattern as the external and the internal fingerprints. This demonstrates that images of the internal structures in the finger can serve for the identification purposes. Figure 2(e) shows an oblique image acquired from the finger with α-FF-OCT, which had the reflector tilted by 280 µm from the *en face* imaging condition. Knowing the tilt and the image depth at which the oblique image was acquired, it can be calculated that the most intense signal in the internal fingerprint layer is at 300 µm below the surface.

![Fig. 2. Fingerprint images acquired with FTIR and FF-OCT sensors. (a) FTIR image of the external fingerprint, (b) FF-OCT image of the internal fingerprint, (c) FF-OCT axial image of the fingerprint. Sweat pores (sp) and the internal fingerprint (int) are visible. Strong reflections at the finger-glass interface dominate the signal at the top of the image. Bar scale 0.5 × 2 mm, (d) FF-OCT image of sweat pores, (e) α-FF-OCT image containing sweat pores and the internal fingerprint, f) A sum of image (e) along its x-axis, which shows the location of a plane with the strongest signal in the internal fingerprint.](image-url)
It is important to be able to scan fingerprints fast enough so that finger movement during the acquisition would not compromise the quality of fingerprint image. To this end, we performed the second experiment where we demonstrated that FF-OCT images of sweat pores and internal fingerprints, shown in Fig. 3, could be recorded in under a second. However, the overall time to record the internal fingerprint image would be longer because of the need to first acquire o-FF-OCT image for the distance determination purposes. The system can also be used to scan the external fingerprints, the image of which is shown in Fig. 3(a). However, in this particular configuration, the image is saturated at the window-finger interface because of specular reflections occurring at the interface despite the window’s anti-reflection coating. The image is, therefore, recorded 50 µm away from the window, where the effect of the reflections are weaker. In the future we plan to use dark-field FF-OCT [33] configuration to reject the reflections, which also should increase the imaging depth through the increased sensitivity.

Fig. 3. Fast fingerprint imaging (0.8 sec.) with FF-OCT. (a) external fingerprint (0 µm), (b) internal fingerprint (300 µm) and (c) sweat pores (200 µm).

4. Discussion and conclusions

Here we demonstrated that FF-OCT could be used to image inside a finger, and thus, capture images of sweat pores and internal fingerprints. Those images might be used for a more reliable way to identify a person. We demonstrate that the images can be captured under a second, which is adequate for live fingerprint imaging applications. Nevertheless, we expect that the time can be further reduced by implementing a ( × 5) faster InGaAs camera that is readily available on the market. A particularly promising approach is to use Adimec’s fast silicon camera that is currently being released. Furthermore, we have proposed a method, which we call o-FF-OCT that is able to determine the depth of each skin layer by acquiring an oblique image. This technique might be a convenient way to quickly determine the depth of each skin layer of interest since it vary from person to person and from finger to finger. o-FF-OCT can also be useful in applications similar to those that benefit from oblique imaging techniques, such as ones reported in refs [34, 35]. The FF-OCT system developed here can also be of a more general interest due to its ability to image deep under skin, and therefore, we expect to use it to study and monitor various skin diseases and conditions [36].

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