Exploring the EarMetrics Concept: The Bony Ear Canal as a Non-Pigmented Site for Photoplethysmography

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Abstract: Photoplethysmography (PPG) is a well-established form of physiological sensing, but persistent challenges include skin-tone-dependent variations in performance and trade-offs between performance and acceptance factors in site selection. We propose that the inner, bony portion of the ear canal may offer several advantages over established sites, including reduced sensitivity to skin tone. We support this position through a combination of anatomical analysis, colorimetry, and the first examples of PPG data collected from the bony ear canal, including pulse oximetry calculations during voluntary breathholds. Colorimetry revealed no statistically significant differences in lightness, chroma, or hue of the bony canal between subjects with lighter versus darker external skin tones. The commonly used ratio-of-ratios (R) method for pulse oximetry was sensitive to de-oxygenation from breathholds, showing statistically significant correlation with breathhold duration. Our results show that the bony ear canal is not pigmented, and that PPG signals can be obtained from this site, even in the presence of idiosyncracies such as earwax and myringosclerosis.

1 INTRODUCTION

Photoplethysmography (PPG) is a well-established form of physiological sensing. It is widely used for measurements including heart rate, pulse oximetry, and - increasingly - blood pressure, due to advantages such as its low cost, ease of miniaturisation, and richness of information content. However, persistent challenges include skin-tone-dependent variations in performance (Nowara et al., 2020; Martin et al., 2024), movement artefact (Ismail et al., 2021), and the trade-offs between performance and acceptance factors in site selection (Seifi et al., 2018; Longmore et al., 2019).

Numerous prior works have demonstrated the potential of the ear canal as a site for PPG sensing, but in virtually all cases the focus has been on the outer, cartilagenous portion of the canal. In this paper, we propose that the inner, bony portion of the ear canal may offer several advantages over the cartilagenous portion, including reduced sensitivity to skin tone. We provide evidence to support these assertions through a combination of anatomical analysis, colorimetry, and the first examples of PPG data collected from the bony ear canal, including pulse oximetry calculations during voluntary breatholds.

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2 LITERATURE REVIEW

2.1 Photoplethysmography (PPG)

2.1.1 Basic Principles

PPG is a non-invasive optical technique that measures blood volume changes in the microvascular bed of tissue. It is based on the principle that light absorption by blood is different from that of surrounding tissue, and that the absorption varies with the volume of blood in the illuminated area. When light is shone on the skin, some of it is absorbed by the underlying tissue, and some portion of the unabsorbed light can be detected by a photodetector. PPG devices are

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typically categorised as ‘transmission’ or ‘reflection’ devices, depending on whether the light source and photodetector are on opposite sides of the tissue or on the same side. Most PPG devices make use of light sources and one or more photodetectors in direct contact with the skin. However, it is also possible to capture PPG signals remotely, often using ambient light sources, cameras, and advanced algorithms to focus the measurement on a suitable region-of-interest, as recently reviewed by Pirzada et al. (2024).

Arguably the most common application of PPG is heart-rate monitoring, where the pulsatile component of the signal is used to detect the heart rate. PPG signals can also be used to estimate other physiological parameters, such as blood pressure, respiratory rate, and oxygen saturation.

2.1.2 Pulse Oximetry

Pulse oximetry is a specific application of PPG that measures the oxygen saturation of arterial blood. It is based on the principle that oxygenated and deoxygenated blood have different absorption spectra as a function of wavelength, and that the ratio of these two components can be used to calculate the oxygen saturation of the blood. Pulse oximetry is widely used in clinical settings, and is also increasingly being used in consumer devices for continuous health monitoring.

The most common method for calculating oxygen saturation from PPG signals is the ratio-of-ratios method, using PPG signals captured at two different wavelengths of light, typically red (e.g. 640 nm) and infrared (e.g. 940 nm) (Nitzan et al., 2020). These two signals are each decomposed into a pulsatile ‘AC’ component and a non-pulsatile ‘DC’ component. The AC/DC ratio is then calculated for each wavelength, and the ratio of these two ratios is used as a proxy for oxygen saturation, which can be determined from a device-specific calibration curve.

In recent years there has been increasing evidence of racial bias in pulse oximetry, with darker-skinned individuals being more likely to be victims of ‘occult hypoxaemia’, in which blood oxygenation is low enough to warrant clinical attention but the oximeter indicates a reading within healthy bounds (Sjoding et al., 2020; Nowara et al., 2020; Martin et al., 2024).

2.1.3 In-Ear PPG

Various studies from as early as 2007 (Vogel et al., 2007) have demonstrated the potential of the ear canal as a site for PPG sensing. As reviewed by Azudin et al. (2023), potential advantages include ease of integration with earbud devices, robustness to peripheral blood perfusion changes (e.g. in hypothermia), reduced exposure to changing environmental variables (e.g. ambient light and temperature), and reduced motion artefact.

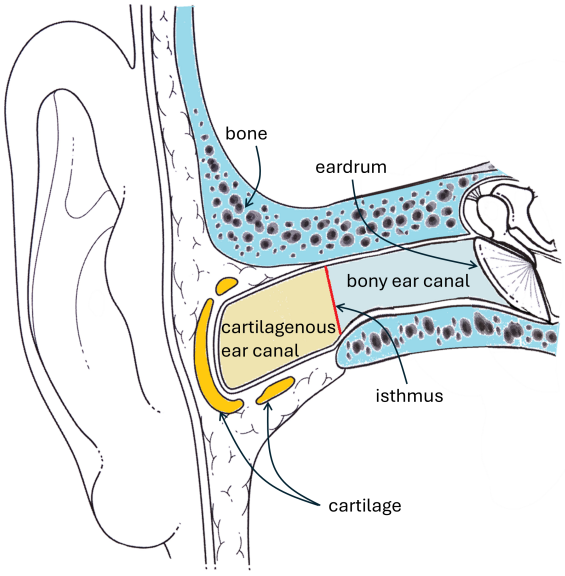

Figure 1: A cross-sectional drawing of the ear canal. The outer third can be seen to be surrounded by cartilagenous tissue, while the inner two thirds is surrounded by bone. Adapted from Descouens (2009).

Prior in-ear devices typically focus on the external ear (e.g. concha or tragus) or the cartilagenous outer third of the ear canal (Azudin et al., 2023). However, we propose that a stand-off sensor targeting the inner, bony portion of the ear canal, rather than the outer cartilagenous portion, can offer distinctive advantages.

2.2 Anatomy of the Ear Canal

The ear canal (external auditory meatus) is divided into two portions: the outer, cartilagenous portion, and the inner, bony portion. The bony-cartilagenous junction is at the isthmus, the narrowest part of the canal, positioned approximately one third of the distance from the outer opening to the eardrum (Stinson and Lawton, 1989). The cartilagenous portion is the outer third of the canal, and produces hairs and cerumen (earwax), which the bony portion does not. Furthermore, it is tacit knowledge among many physicians that the bony ear canal is not pigmented, while the cartilagenous portion is. However, we are not aware of any published work that confirms this, prior to the evidence provided in this paper.

The skin lining the bony ear canal is much thinner that that of the cartilagenous portion: approximately 0.1 mm vs. 1.0-1.5 mm respectively (Perry and Shelley, 1955). This thinner medium may of-

fer improved inter-individual repeatability by reducing wavelength-dependent variations in path length. Simulations by Ash et al. (2017) demonstrate that the relative intensity of light penetrating to a depth of 1mm increases by an order of magnitude as wavelength increases across the visible and near-infrared spectrum. Thus the effective path length from light source to sensor is dependent on both wavelength and the relative configuration of source, sensor, and anatomy. Device-specific calibration curves are typically used to account for this, but cannot compensate for inter-subject anatomical variations (Yossef Hay et al., 2018; Moço et al., 2016). In the thinner skin of the bony ear canal, although much of the light may penetrate into the underlying bone, the absorption coefficient of bone is relatively consistent across the visible and near-infrared spectrum (Genina et al., 2008). Hence we propose that greater consistency of path lengths between wavelengths may result in reduced inter-individual variations in calibration curves for a device targeting the bony ear canal compared with fleshier sites.

3 EXPERIMENTAL METHOD

In this section we describe experiments conducted to provide proof-of-concept for bony ear canal as a viable site for pulse oximetry.

3.1 Cohort

We set out to recruit a cohort of healthy adult volunteers with a range of skin tones, as measured by the Fitzpatrick scale. This scale is a widely used classification system for human skin colour, based on the skin's appearance and response to sun exposure. Although it has recognised limitations (Monk, 2023; Tian, 2024), suitable alternatives were not well established at the start of our study, and it allows our work to be easily compared with prior art, in which it is used widely. Prospective participants were excluded if they had any known history of circulatory disorder such as Raynaud's Syndrome, thrombosis, hypertension, or heart disease.

Thirty-three subjects were recruited from the general population after pre-screening based on self-assessment of skin-tone against the Fitzpatrick scale to ensure broad representation. Of these, two subjects were excluded due to excessive earwax in both ears, to conservatively avoid the risk of study instruments compacting the wax against the eardrum.

As shown in Fig. 3, the cohort was well-distributed across the Fitzpatrick scale. Although none of our participants self-identified as Fitzpatrick type VI (the darkest category), we were able to recruit participants from all other types, including ten from type V.

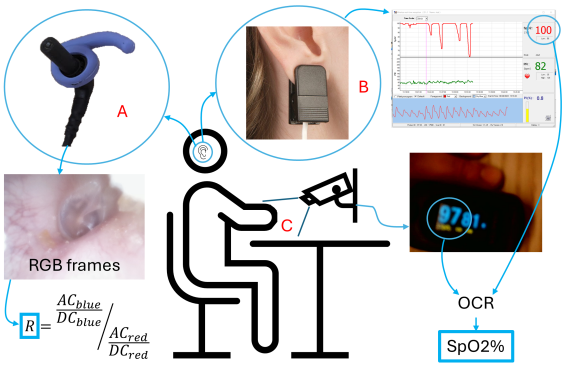

Figure 2: The configuration of equipment used in this study. A = Prototype EarMetrics® device, which was positioned inside the ear canal, capturing RGB images at 30 frames-per-second (fps). B = Earlobe pulse oximeter, transmitting data via bluetooth to the experiment manufacturer's Oximeter Manager software, from which screenshots were captured at 1 fps. C = Finger pulse oximeter, monitored by a camera mounted above the hand at 1 fps. For B and C, optical character recognition (OCR) software was used to extract SpO2 values.

3.2 Equipment

The configuration of equipment used in this study is shown in Fig. 2.

3.2.1 EarMetrics®

The in-ear sensor used in this study is a prototype EarMetrics® device, developed by Earswitch Ltd. The concept of non-contact, stand-off or remote spectroscopy (including PPG) from the inner ear canal has been termed EarMetrics® and has patent granted (UK) (Gompertz, 2023) and pending internationally by EarSwitch Ltd. The EarMetrics concept developed from the EarSwitch concept, in which detection of ear-drum movement mediated by voluntary control of middle ear muscles is used as an assistive switch for individuals with motor neurodisabilities, including motor neurone disease (MND/ALS) (Hoyle et al., 2024). The EarMetrics experimental device studied consisted of CMOS camera module with 4 white light LEDs mounted within a cylindrical metal barrel. The CMOS camera module was mounted in a 3D printed barrel component, within an adjustable ear worn device allowing alteration of angle and depth of the camera module within the wearers ear-canal. Soft elastomer outer earbud components were provided to

fit the individual in small/medium/large and left/right configurations.

The EarMetrics camera module was wired to a MIPI-to-USB conversion PCB. This was plugged via USB cable to the research laptop for data acquisition. The data from the CMOS camera was collected on the research laptop synchronously with the data recording from the reference devices.

3.2.2 Reference Devices

For comparison with the EarMetrics device, we used two reference devices approved for medical use. Data from both devices was captured using the same experiment PC using custom software in order to synchronise the data streams.

- Finger: a Creative PC-60B1 finger oximeter was worn on the index finger of the right hand. Readings were captured using a camera connected via USB to the experiment computer and mounted over the hand, facing the on-device display. Captured frames were timestamped by our custom software, and the SpO2 and pulse rate values were extracted from the display using optical character recognition (OCR).
- Earlobe: a Creative SP-20 pulse oximeter was worn on either the left or right earlobe (chosen to avoid interference with the EarMetrics device and any jewellery). Readings were transmitted wirelessly to the experiment computer via Bluetooth and displayed using the manufacturer's software, such that screenshots could be captured and timestamped by our custom software. Readings were extracted by application of optical character recognition to relevant sections of these screenshots.

This approach enabled efficient, approximately synchronised data capture from multiple conventional devices. The accuracy of synchronisation is dependent on the lag in each device between signal acquisition and display/transmission. Informal experiments with deliberately induced motion artefacts (tapping the sensors) indicated that these delays were consistently less than 3 seconds, hence only time differences greater than this may be considered non-negligible.

3.3 Protocol

Each participant sat in a chair as the devices were applied. They were then allowed five minutes of settling time, making slow movements of their head and hands to ensure comfort and stability of the devices. Next, they performed four breathholds, each lasting as long as they could manage without excessive discomfort. The first and third were performed after inhaling (i.e. with lungs full) and the second and fourth after exhaling (i.e. with lungs empty). In each case, the researcher provided a 10-second countdown after which the the participant began the breathhold at the next appropriate point in their breathing cycle. The researcher used a button in the custom software interface to approximately timestamp the start and end of each breathhold based on visual observation. A minimum of 60 seconds was allowed between breathholds to allow the participant to recover; a previous study with finger and in-ear oximetry during breathholds (Davies et al., 2020) provides evidence that this is sufficient for SpO2 levels to return to baseline, and this was corroborated in our own data.

3.4 Analysis

3.4.1 Colorimetry

To test the conjecture that the bony ear canal is not substantially pigmented, we extracted a frame from the end of the settling period (before breathholds) for each participant. An arbitrary pixel was manually selected from the canal wall, near the tympanic membrane (to conservatively avoid the cartilagenous outer canal), avoiding visually apparent blood vessels. The brightness values of the three colour channels (RGB) were extracted and converted to the CIELAB-based 'LCh' colour space for more perceptually uniform interpretation (Weatherall and Coombs, 1992; Tian, 2024). In this space, L* represents lightness, C* represents chroma (saturation), and h* represents hue.

3.4.2 Oximetry

Custom software was used to extract mean RGB brightness values (three colour channels) across all pixels of each frame from the EarMetrics®device. The specific parameters of this algorithm were determined heuristically to optimise visually perceived signal quality and robustness to artefacts. Each of the three resulting time series was split into AC (pulsatile) and DC (baseline) components by applying a 10th-order zero-phase Butterworth highpass filter with a cut-off frequency of 0.25 Hz, then subtracting this highpass-filtered signal from the original to obtain the DC signal. The high-pass filtered signal was low-pass filtered at 8 Hz to remove high-frequency noise. Peaks were detected in this signal to identify individual heartbeats. To exclude sections corrupted by artefact, beats of abnormal length were excluded using the following heuristically determined thresholds: $< 50\%$ or $> 150\%$ of median beat interval, or

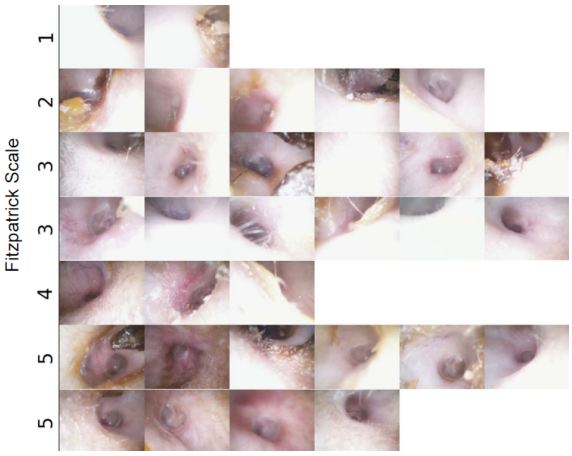

Figure 3: Images captured using the EarMetrics®device showing the ear canal of participants. The precise field of view and light distribution vary between participants. Hence, the cartilagenous outer ear canal may be visible in outer portions of some images, evidenced by the presence of hair and/or cerumen. The tympanic membrane is seen as a dark central region in most images. The canal wall surrounding this is considered to be the bony ear canal.

$< 80\%$ or $> 120\%$ of the previous interval. The AC signal was then calculated as the peak-to-peak amplitude of the high-pass filtered signal within each valid beat. The 'ratio-of-ratios' R was then calculated as the ratio of the AC/DC values between the blue and red channels, providing an uncalibrated proxy measure of SpO2. No R values were calculated for abnormal beats, identified as described above.

For each breathhold, the resting value of R (for the EarMetrics®device) or SpO2 (for the reference devices) was calculated as the median in the window from 15 to 5 seconds before the start of the breathhold. The depleted value was calculated as the minimum in the window from 20 seconds before to 30 seconds after the end of the breathhold. The effect of the breathhold was calculated as the difference between the depleted and resting values.

4 RESULTS

4.1 Pigmentation of the Bony Ear Canal

As shown in Fig. 4, the LCh values sampled from the bony ear canal portions of the sample images in Fig. 3 show no clear separation by external skin tone. For statistical analysis, Fitzpatrick scales I-III and IV-V were combined to form two groups. Two-tailed heteroscedastic T-tests were performed to compare the L*, C*, and h* values between these groups, revealing no statistically significant differences ($p > 0.1$).

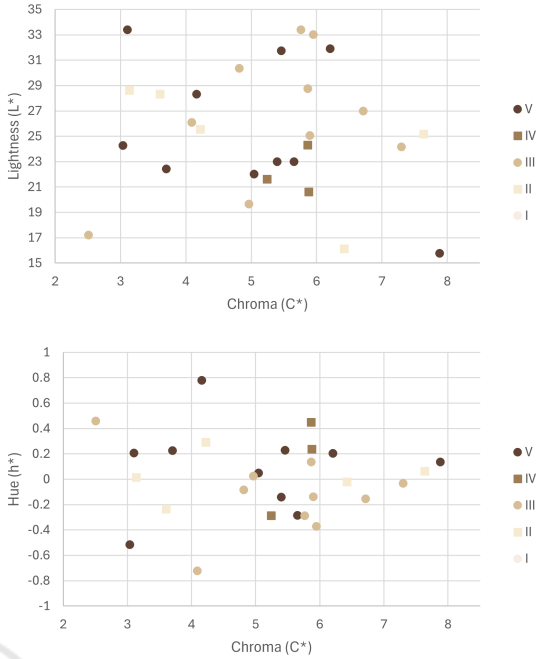

Figure 4: Colorimetry values sampled from the bony ear canal (images presented in Fig. 3) show no clear separation by external skin tone (Fitzpatrick scale, colour coded as shown in the legend). The 3-dimensional LCh colour space is represented across two 2-dimensional scatter plots.

4.2 Example Breathhold Data

As shown in Fig. 5, the R metric from the EarMetrics®device is sensitive to changes in oxygen saturation during breathholds. Although the duration of breathhold and the extent of de-oxygenation vary substantially between participants, there is a statistically significant correlation between the two ($R^2 = 0.06$, $p = 0.015$). Fig. 6 shows an example of the data collected from a single participant during a breathhold. The R value from EarMetrics®device shows a clear response to the breathhold, and appear to descend earlier and begin to recover earlier than the SpO2 values from the reference devices.

5 DISCUSSION

From the presented results, we draw the following key insights:

- The bony ear canal is not pigmented (Fig. 3, Fig. 4). It may therefore offer a more equitable target site for PPG sensing. Limited other non-pigmented external sites exist, such as the nail beds or the lips, but these are less conveniently accessible, especially for continuous monitoring.

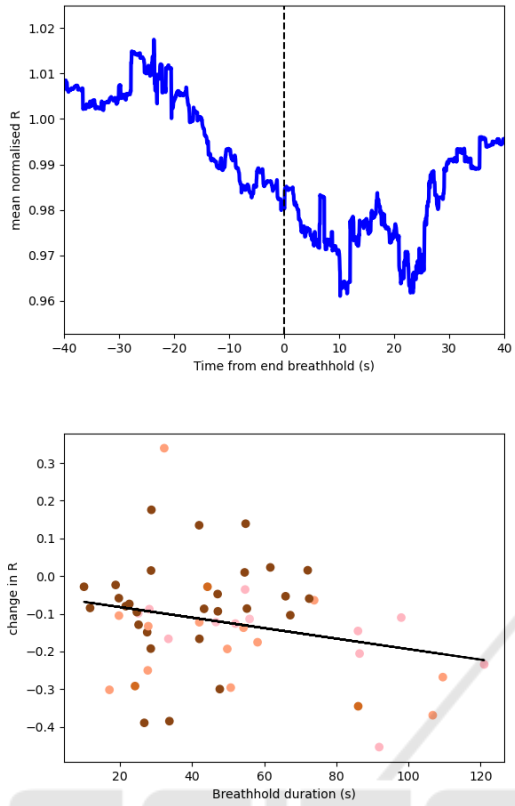

Figure 5: Upper panel: The normalised R value from the EarMetrics®device across all breathholds from all subjects, synchronised to the end of the breathhold. Lower panel: The change in R (depleted - baseline) was significantly correlated with the breathhold duration ($R^2 = 0.07$, $p = 0.029$). Data points are coloured according to the subject's Fitzpatrick skin type.

- Pulse oximetry at this site is sensitive to deoxygenation from breathholds (Fig. 5), and may offer insights distinctive from the more commonly targeted outer portion of the ear canal, owing to the difference in vascularization and skin thickness (Section 2.2). The delayed and muted response of the finger device relative to the earlobe is consisent with observations in prior studies (Lindholm et al., 2007), and is attributable to the greater distance between the finger and the heart. The earlier response of the EarMetrics®device (Fig. 6) is possibly indicative of a more central blood supply, as described in Section 2.2, or protection from effects of vascular autonomic function or peripheral vasoconstriction. Hence it is possible that pulse oximetry from the bony ear canal may provide advantages in the speed of response to changes in central blood oxygenation, e.g. during apnoeic episodes.

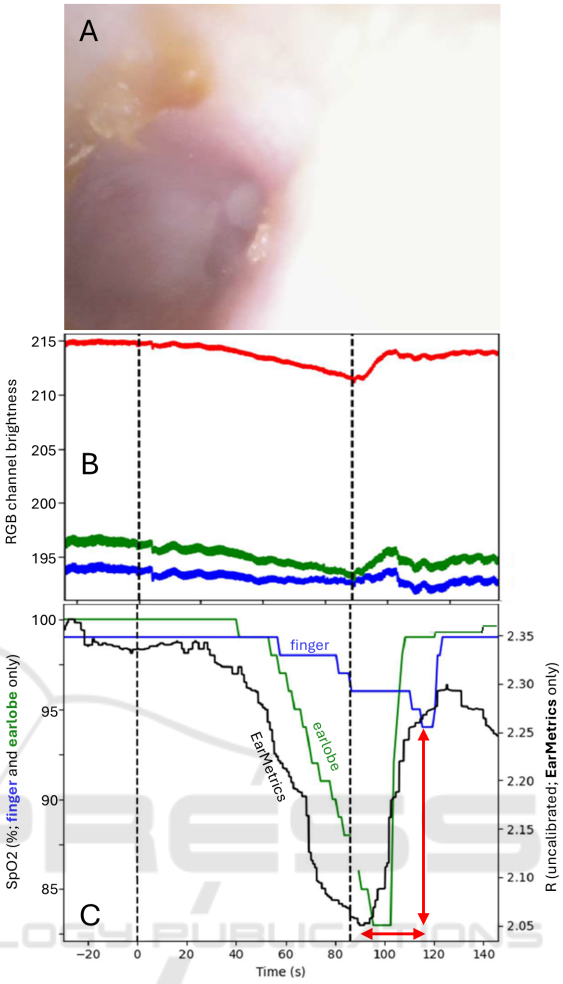

Figure 6: Example data from a single participant during a breathhold. Panel A shows a single frame captured from the EarMetrics®device; in which several idiosyncracies are apparent: presence of earwax, myringosclerosis (white patches on the eardrum), and wide variation in light distribution. Panel B shows the average channel brightness in each of the three colour channels (red, green, blue) across all frames. Dashed vertical lines indicate the start and end of the breathhold. Pulse waveform (i.e. AC) amplitude is discernible from the thickness of the lines. Variations in both AC and DC components are apparent during the breathhold. Respiratory frequency oscillations are visible even during the breathhold, reflecting ongoing autonomic fluctuations modulating cardiovascular properties as observed in prior studies (Western, 2012; Hanson et al., 2012). Panel C shows the variations in SpO2 readings from the reference devices (left vertical axis) and the R metric (uncalibrated SpO2 proxy) from the EarMetrics device (right vertical axis). As highlighted by the red arrows, EarMetrics readings appears to descend earlier and begin to recover earlier than the SpO2 values from the reference devices, and the finger sensor is relatively insensitive to the transient deoxygenation.

- PPG signals can be obtained from the bony ear canal, even in the presence of idiosyncracies such

as earwax and myringosclerosis (Fig. 6). Although a small number of participants were excluded from our study due to earwax, in deployment the device may be usable with only occasional or one-off removal of earwax.

The above insights warrant further development and evaluation of the EarMetrics®concept. However, several limitations of the current study should be noted:

- The use of breathholds yields only transient changes in oxygen saturation and presents substantial inter-subject variability, for example in the duration of voluntary breathholds. As can be seen in Fig. 5, our dataset lacked examples of participants with darker skin tones (Fitzpatrick type IV-V) achieving long breathholds ($>$ 70 seconds) and the associated substantial de-oxygenation. Furthermore, the physical response (e.g. gasping) to resumption of breathing presents challenging conditions for the extraction of clean PPG signals during the brief peak in de-oxygenation. More rigorous experiments could be achieved by using a controlled hypoxia chamber, using a rebreathing apparatus to induce more consistent and substantial de-oxygenation, or working with participants with chronic deoxygenation confirmed by gold-standard methods.
- The reference devices used have notable limitations in accuracy (Olive et al., 2016). They are both likely to perform differently for different skin tones. Furthermore, although the finger site is typically less pigmented than the earlobe, its distal location makes it less responsive to transient changes in central blood oxygenation (Lindholm et al., 2007). The gold standard for SpO2 measurement is arterial blood gas analysis, which is invasive and impractical for repeated measurements except where dictated by clinical necessity.
- The colorimetric measurements were taken from the EarMetrics®device itself, rather than from a dedicated colorimeter, which might offer more optimal lighting and calibrated sensing, but may not be suitable for targetting the bony ear canal. A single pixel was sampled from each image, but in further work a larger sample could be taken to account for variations in anatomy and lighting.
- Our study made use of the Fitzpatrick scale as a proxy for skin tone, which has recognised limitations in its suitability for capturing the full breadth of human skin tones. Future work should consider more sophisticated methods for characterising skin tone, such as the recently developed Monk Skin Tone Scale (Monk, 2023).
- Despite proactive recruitment, our cohort did not include any participants self-identifying as Fitzpatrick type VI, the darkest category. Nonetheless, the second darkest category, type V, included more participants than any other.
- PPG signals were extracted from the full frames captured by the EarMetrics device. Performance could be improved through more sophisticated signal processing or computer vision techniques to focus on the most informative regions of the image and focus more exclusively on the bony ear canal.

6 CONCLUSIONS

This paper provides evidence to support anecdotal accounts that skin in the human bony ear canal is not pigmented; colorimetric analysis showed no statistically significant differences in lightness, chroma, or hue of the bony ear canal between subjects with lighter versus darker external skin tones. It should therefore be considered as a target site for optical sensing modalities, such as photoplethysmography (PPG), that are sensitive to the variable influence of pigmentation. We further support this position with evidence that clear PPG signals can be obtained from this target site, even in the presence of idiosyncracies such as earwax and myringosclerosis. Pulse oximetry at this site is sensitive to de-oxygenation from breathholds, as indicated by the statistically significant correlation with breathhold duration. This site may offer insights distinctive from the more commonly targeted outer portion of the ear canal, owing to the difference in vascularization.

Further work should be conducted to evaluate the potential of the bony ear canal as a racially equitable, sensitive, reliable, and convenient target site for pulse oximetry and other physiological sensing. This work should include validation against gold-standard arterial blood gas analysis and evaluation of user acceptance for both long-term usage and acute monitoring applications.

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