Poster: Smartphone Colorimetry Using Ambient Subtraction: Application to Neonatal Jaundice Screening in Ghana

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ABSTRACT

A smartphone app to screen for neonatal jaundice has a large potential impact in reducing neonatal death and disability. Our app, *neoSCB*, uses a colour measurement of the sclera to make a screening decision. Although there are numerous benefits of a smartphone-based approach, smartphone colour measurement that is accurate and repeatable is a challenge. Using data from a clinical setting in Ghana, we compare sclera colour measurement using an ambient subtraction method to sclera colour measurement using a standard colour card method, and find they are comparable provided the subtracted signal-to-noise ratio (SSNR) is sufficient. Calculating a screening decision metric via the colour card method gave 100% sensitivity and 69% specificity (n=87), while applying the ambient subtraction method gave 100% sensitivity and 78% specificity (SSNR>3.5; n=50).

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CCS CONCEPTS

• **Human-centered computing** → **Ubiquitous and mobile computing systems and tools**; **Smartphones**.

KEYWORDS

colorimetry, neonatal jaundice, screening, smartphone

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1 INTRODUCTION

The accurate quantification of colour is important in a wide range of disciplines, including several scientific and medical applications. Context may add constraints as to how colour may be measured. In the least constrained case, a spectrophotometer can be used to measure the reflectance of an object with high spectral resolution, for example, in testing the colour reproduction quality of printed materials. In other cases, the target may be harder to measure if it is delicate, transient, or inaccessible. For example, the measurement of animal or animal habitat colours, which often must

be done *in situ*, under time pressure, and without disturbing the subject. In such cases, digital cameras have advantages of portability and rapid, contact-free measurement [1, 11].

Medical uses of colorimetry include screening for conditions such as anaemia and jaundice [4, 6–10, 13]. Jaundice is a potentially life-threatening condition that affects the majority of newborns [2]. It is caused by an excessive accumulation of bilirubin, which manifests as a yellow discolouration of the skin and sclera.

Existing approaches to screen for neonatal jaundice have significant limitations. The transcutaneous bilirubinometer (TcB) is a contact-based jaundice screening device that works by measuring the reflectance of the skin at various wavelengths. While effective, cost limits its use, especially in low-income countries. Subjective visual inspection is often the only available option in these settings, though it is not a reliable means of screening [2].

We aim to detect dangerous cases of jaundice using a smartphone camera measurement of the sclera colour. Unlike skin, the sclera does not contain melanin and haemoglobin chromophores, and so it is a more sensitive site to measure the yellow discolouration from jaundice [6, 8]. However, measuring the eye rules out contact-based colour measurement.

Jaundice can become severe days to weeks after birth, and so screening methods must be usable in a home environment. Jaundice-related disability and death is most common in Sub-Saharan Africa and South Asia, where it is estimated that three-quarters of the deaths occur [3]. This means there is a need for a low-cost approach. These additional constraints make the smartphone an ideal candidate for a screening tool. Not only do smartphones allow rapid, objective, and contactless measurement of colour, but they are also ubiquitous in low-income regions and in the domestic setting worldwide.

Some studies have shown promising results using a smartphone to detect jaundice [4, 10, 12]. Our *neoSCB* app (neonatal Scleral-Conjunctival Bilirubinometer) achieved a screening performance comparable to a modern TcB [10]. *BiliCam* is a smartphone app that has been validated in a sample of 530 newborns with impressive results [12]. *BiliCam* relies on a colour card to standardise a measurement of the skin, while *neoSCB* is based on sclera colour and uses a flash/ no-flash image pair to suppress the influence of ambient light.

In this work we evaluate an ambient subtraction (AS) method of standardising colour measurement using a smartphone and compare this approach to a colour card (CC) approach. To do this we analyse image data collected as part of a two-year study in Ghana, the purpose of which is to develop and test the *neoSCB* jaundice screening app.

2 THEORY

The sensor RGB values recorded by a digital camera depend on the illuminating light and the camera as well as the object properties. The prevailing ambient light varies depending on the image capture environment, and different smartphone devices do not have the same spectral responses. Accurate and repeatable colour measurement must be device- and ambient light-independent. This can be achieved by including a reference colour card with an array of patches of known colour (defined in a reference colour space such as the CIE 1931 XYZ colour space). The raw sensor RGB triplets recorded are mapped to XYZ values by a transform developed for that image. This simultaneously corrects for ambient light and camera variability.

The AS approach relies on taking two pictures in quick succession, one with an LED flash and one without. By subtracting the raw RGB values of the ambient-only image from the flash-and-ambient image, the RGB values as they would appear under only the LED flash are estimated. This standardises the lighting environment, but the measurement is still device-specific, as camera sensors and LED flashes vary between smartphones. A colour card transform is used to achieve device-independent XYZ values. The advantage of AS is that this transform need only be developed once per device rather than in each new capture instance.

The camera signal post-subtraction may have a low signal-to-noise ratio if the ambient light dominates the smartphone flash. To quantify this, we introduce the subtracted signal-to-noise ratio (SSNR). The noise is approximated as shot noise, given by the square root of the number of photon counts, I, for channel k, k={R,G,B}. Noise is added in quadrature between the flash (ambient-plus-flash) and no-flash (ambient-only) images to give Equation 1 for the SSNR.

$$SSNR = \frac{sub.\ signal}{sub.\ noise} = \frac{I_k^{ambient-plus-flash} - I_k^{ambient-only}}{\sqrt{I_k^{ambient-plus-flash} + I_k^{ambient-only}}} \quad (1)$$

3 METHODS

The *neoSCB* app was used to capture flash/ no-flash image pairs of the sclera of 87 newborns in the Greater Accra Regional Hospital. The smartphone device was a Samsung S8. An X-Rite ColorChecker Classic colour card was included in each image. The images were taken to coincide with a routine blood test for total serum bilirubin (TSB) concentration, the gold-standard for jaundice diagnosis. Ethical approval for this study was obtained from the Institutional Review Board, College of Health Science, University of Ghana, the Ghana Health Service Ethics Review Committee, and the UCL Research Ethics Committee. All data processing was performed using MATLAB R2018a.

In this work, all RGB-to-XYZ transforms are developed using a least-squares linear mapping based on measurements

of the 24 colour patches of the ColorChecker Classic. The patch XYZ values were measured using an X-Rite ColorMunki Photo. Equation 2 shows how the transformation matrix **M** is a function of 24x3 matrix of colour card XYZ values **H** and a 24x3 matrix of recorded raw camera RGB values **R**.

$$\mathbf{M} = (\mathbf{R}^T\mathbf{R})^{-1}\mathbf{R}^T\mathbf{H} \quad (2)$$

Ambient Subtraction (AS) Method

Corresponding sclera regions of interest (ROI) were manually drawn in the flash and no-flash images. The median RGB values were subtracted in linear raw space to arrive at an estimate of flash-only RGB sclera values. These were converted to XYZ values using a device-specific transform developed for the Samsung S8 by imaging the X-Rite ColorChecker under its flash illumination.

Colour Card (CC) Method

The no-flash image was used to attain sclera XYZ values using the CC method. The colour card was segmented automatically using ColorChecker Finder [5], and the raw RGB values of the card were extracted. From these an image-specific mapping to XYZ was developed and applied to the median raw RGB sclera values.

Scleral-Conjunctival Bilirubin (SCB) Calculation

In each case, the XYZ values were used to calculate xy chromaticity values: $x = X/(X+Y+Z)$; $y = Y/(X+Y+Z)$. A multiple linear regression of TSB against x and y produced our TSB estimation model, the output of which we call the scleral-conjunctival bilirubin (SCB), in analogy with the output from a transcutaneous bilirubinometer (TcB).

4 RESULTS

Chromaticity Error

In comparing the chromaticity values from the AS approach to the established CC approach, we calculated the Euclidean distance in the two-dimensional chromaticity space as our error metric. Figure 1 plots the SSNR against the chromaticity error. The correlation is -0.41 (p<0.01).

A laboratory experiment determined an empirical SSNR threshold of 3.5 above which chromaticity error did not decrease further (tested on 148 patches from the Macbeth ColorChecker DC card). Applying this threshold, which eliminated 37 of the 87 data points, decreased the mean chromaticity error by 34%.

TSB Prediction

Figure 2 shows the correlation between TSB and SCB. The correlation is higher for the CC method (r=0.79; p<0.01) than the AS method (r=0.50; p<0.01). However, when the SSNR threshold is used to discard image pairs with SSNR below 3.5, the correlation becomes comparable between the two methods for the remaining 50 subjects.

Figure 1: Scatter plot of subtracted signal-to-noise ratio (SSNR) against chromaticity error.

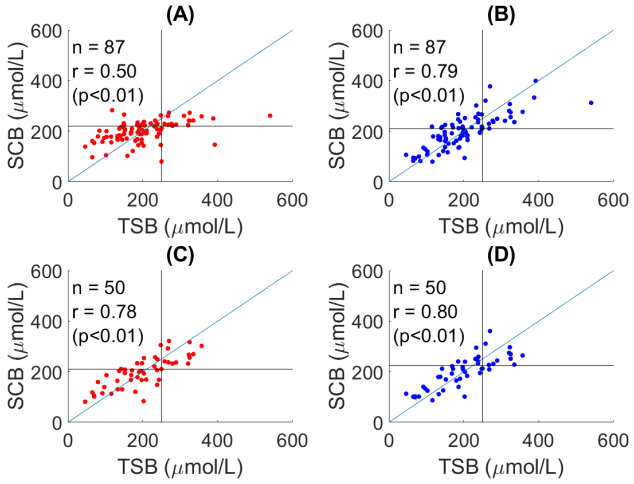

Figure 2: Correlation between scleral-conjunctival bilirubin (SCB) and total serum bilirubin (TSB). Horizontal and vertical lines are decision and screening thresholds used, respectively. (A) Ambient subtraction method; (B) Colour card method; (C) Ambient subtraction method, where SSNR<3.5; (D) Colour card method for same subjects as in (C).

Table 1 shows the screening performance in identifying neonates with TSB levels above 250μmol, the NICE-recommended threshold for blood test referral in term infants [2]. The CC method and AS method have area under curve (AUC) values for the receiver operating characteristic curve of 0.91

Table 1: Results for ambient subtraction (AS) and colour card (CC) methods in predicting total serum bilirubin from sclera chromaticity. Screening performance statistics are given for a screening threshold of 250μmol, with decision thresholds set to maximise Youden's Index. *p<0.01.

	All subjects, n=87		SSNR>3.5, n=50	
	AS	CC	AS	CC
Correlation, r	0.50*	0.79*	0.78*	0.80*
Sensitivity	0.84	1.00	1.00	0.85
Specificity	0.81	0.69	0.78	0.81
AUC	0.82	0.91	0.93	0.89

and 0.82 respectively. Again, when only the high SSNR data are considered, the performance of the AS method increases greatly. For the n=50 sample the AS method has a higher AUC (0.93) than the CC method (AUC=0.89).

5 DISCUSSION

Our results show that a sclera colour-based jaundice screening tool using ambient subtraction can deliver comparable screening performance to one using a colour card, provided signal-to-noise in the post-subtraction signal is sufficient.

Ambient subtraction has some advantages over a colour card method in the context of jaundice screening. Colour cards are not cheap and must be kept pristine to be useful. Distribution and maintenance of colour cards may represent a barrier to adoption, particularly in low-income countries. Furthermore, especially when imaging the sclera rather than the skin, it is not trivial to capture an image that includes a sufficiently large sclera ROI as well as the entirety of the colour card. A colour measurement protocol based on subtraction requires only a one-time calibration.

A limitation of the ambient subtraction approach is that it can fail if there is movement between the first and second captures. The capture sequence takes less than one second so this problem only affects a minority of cases. In future, for robustness, *neoSCB* will require several estimates to agree before providing a result, and automatically recommend moving to a less bright area if SSNR is below the required threshold.

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