Accuracy of the skin model in quantifying blood and epidermal melanin

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Abstract. *Quantifying different skin parameters may help the specialists to detect skin cancers. A new method of skin imaging developed by Cotton and Claridge [1] produces quantitative images of the main components of the skin. This paper evaluates the accuracy of the new skin imaging method in quantifying the levels of epidermal melanin and blood supply in the normal skin and in thin skin lesions. Theoretical analysis shows that the method is capable of detecting small changes in melanin level (less than 5%). Changes in blood supply can typically be assessed to within 20%. Correlation with measurements Sciteusing Mexameter is excellent for melanin ($r = 0.985$) and moderate for blood ($r = 0.621$), with $p < 0.001$ for both.*

1 Introduction

A new method of skin imaging developed by Cotton and Claridge [1, 2], uses an optical model of the skin to relate the distribution of skin colours in a 3-dimensional colour space to the skin structure and composition. For normal skin, colours form a 2D surface whose principal axes can be calibrated in units related to the level of two main skin pigments, melanin and blood. Any colour deviating from this surface by a given amount represents a quantifiable change in the skin structure, such as the descent of melanin into the dermis or change in the thickness of the papillary dermis, both diagnostically important. Using the model, skin colours can be interpreted in terms of quantitative parameters related to the skin histology.

This paper presents an analysis of the accuracy of the skin imaging method in quantifying the levels of epidermal melanin and dermal blood, in the normal skin and in the presence of a thin layer of melanin in the dermis. Change in pigmentation associated with the appearance of a new "mole" (a skin lesion), change in pigmentation within an existing lesion, and increase in blood supply around a lesion, can all be indicative of an incipient malignancy. As the early detection can lead to a complete cure, the ability to detect subtle changes is important. Only if the system's accuracy is well understood, its results can be reliably interpreted.

To assess the system accuracy, theoretical analysis was carried out first. Using the optical model of the skin, changes in the histological parameters were related to the changes in skin colouration. Theoretical detectability threshold was then determined assuming a particular noise level for a CCD camera used to acquire images. Further, experimental validation was performed by comparing the levels of melanin and blood returned by our system with those obtained with Mexameter, a commercial device used to assess skin colouration.

2 Sensitivity measure

The colour space of the skin model uses Red (R), Green (G) and Blue (B) primaries. Given an (r,g,b) triplet for an unknown sample of the normal skin, its levels of blood and melanin are returned through reference to the histologically parametrised model of the skin colouration. The accuracy of the returned parameters depends on (1) the nature of changes in each primary w.r.t. changes in a histological parameter value; and (2) the noise level in imaging system (e.g. a CCD camera), which has variance $\sigma = 0.5$ for the camera used in this work.

The measure of accuracy was taken to be detectability threshold, DT, the smallest detectable increment in the magnitude of a given parameter. This can be defined as the minimum increment in the parameter value, x, which results in the increment in the value of a measured primary, y, by 2σ. $DT(x) = \Delta x / \Delta y = \Delta x / 2\sigma$. Value of DT is thus a measure of error and these two terms will be used as synonyms in the remainder of the paper. Sensitivity is the inverse of detectability threshold and, in the limit, is proportional to a partial derivative of the measured primary with respect to a parameter value. If the value of the derivative is greater than 2σ, each single increment in the value of a primary is error free.

3 Analysis for normal skin and for thin lesions

Two skin models were considered, one representing the normal skin structure, the other representing an early stage of invasive melanoma where a thin layer of melanin ($0.01mm$ thick) is present in the dermis, adjacent to the dermal-epidermal junction. In both cases the model generates colours spanning the full range of melanin (0-0.02) and blood (0-700), for the nominal level of papillary dermis thickness of ($0.2mm$). The increment was set equal to $1/30$ of the maximum amounts of blood and melanin [3]. For reference, the Caucasian skins normally show melanin levels below 0.006.

The initial analysis was carried out independently for each primary, followed by calculation of the overall detectability. We first consider the normal skin model. Figure 1 shows the variations in each primary (R, G and B) for a normal range of blood and melanin concentrations, as computed by the model. It can be observed that the R primary shows a steady decrease as the level of melanin increases and that it is effectively independent of blood concentration. The decrease in levels of G and B primaries is exponential for both, blood and melanin. This behaviour can be related to their optical properties as shown by the absorption coefficients [4]. Blood has the highest absorption level in the spectral region of Blue primary ($300 - 500nm$ wavelength). This indicates that a small change in blood level affects the blue primary more than the others. From the melanin absorption spectrum it can also be concluded that the blue primary should be most affected by change in melanin level. However, the high absorption in blue will result in early saturation of this primary and, consequently, contribute to lower sensitivity. This behaviour is confirmed by the behaviour of the blue primary in Figure 1.

Following the discussion in Section 2, let us consider partial derivatives (the gradients) of R, G, and B primaries with respect to the change in blood and melanin levels; the higher the level of the gradient versus the parameter, the more sensitive the system to the parameter.

$$\frac{\delta(Primary)}{\delta(Blood)} \qquad \text{and} \qquad \frac{\delta(Primary)}{\delta(Melanin)} \tag{1}$$

The gradient of each primary is computed using (1) and compared with the sensitivity of a CCD camera for two different noise levels, $2\sigma = 1$ and $2\sigma = 2$. Figure 2 shows the gradient with respect to melanin concentration; two flat surfaces show the two levels of camera noise. The gradient of R primary is higher than 2 for the whole range of melanin levels in the epidermis. The overall gradient for B and G primaries is higher than for R, but it drops below the camera noise level in the regions where the levels of these primaries get saturated due to high melanin concentration. Whereas R and G primaries are error free, B primary shows an increase in error where melanin level is higher than 0.016 (very dark pigmentation). Similar analysis was applied to the gradient of each primary with respect to blood (figures of gradients not included). It showed that blood level measurements have significantly lower accuracy, especially where the melanin level is high. The B primary performs best, but only where melanin level is low (below 0.015). The R primary performs worst. For higher levels of melanin, G primary shows the lowest error, mainly because of moderate absorption level for both blood and melanin levels.

System sensitivity in the presence of thin skin lesion was performed by considering the surface of skin colouration with two extreme levels of dermal melanin concentration. The gradient of each primary versus epidermal melanin and blood were computed using (1). The gradients were then compared against the camera noise level. Figure 3 shows the gradient plots for R, G and B primaries. The highest gradient is shown by B primary where melanin and blood concentration are low. As a result of high absorption coefficient in the blue spectral region, the B primary is saturated very rapidly resulting in lower sensitivity to change in melanin concentration. G primary starts with high gradient and it maintains its level above the camera noise level. Both, B and G primaries, show gradient lower than the camera noise level where melanin concentration in the dermis is high. In contrast, R primary shows moderate gradient, between 1.5 and 3.5, which is higher than camera noise level for the whole normal range of melanin concentration in epidermis. Blood level measurement analysis for thin lesions showed sensitivity very similar to that of the normal skin, demonstrating that the blood level in thin lesions can be measured with similar accuracy as in the normal skin.

4 Overall detectability threshold

Overall detectability thresholds for blood and melanin measurements were computed by combining the thresholds derived for individual primaries using ℓ_2 norm. Figure 4 shows the contours of equal detectability thresholds for

melanin and blood in the normal skin. The threshold for melanin detection is very low for most of the parameter range. The threshold for blood detection shows an increase when the level of melanin increases. The figure also shows an increase in the detectability threshold level where the level of blood increases. To increase the sensitivity of the system, either the most reliable primary should be used individually or a higher quality camera with lower noise level should be employed. The overall detectability threshold for blood and melanin measurement in thin skin lesions shows similar behaviour but with decreased sensitivity, as shown in Figure 4.

5 Validation

Ideally, validation should compare measurement results with "the gold standard" representing true quantities. The quantification *in vivo* of the absolute levels of melanin and blood is not practicable. *In vitro* measurements of the pigment levels were validated for the LIR method (Logarithm of Inverse Reflectance) [5]. The agreement for low concentrations of blood was to within 2%, rising to the underestimate of 17% for higher concentrations. For melanin the error was negligible. Estimates obtained for LIR in vivo indicated 8% underestimation for melanin.

Practical validation of our method was done in the first instance by comparing its measurements with LIR indices. This was carried out using Mexameter, a commercial device based on LIR. The assessment of melanin and blood levels was carried out using both systems on a range of subjects from a broad ethnic range. 73 subjects took part in the study. Correlation analysis was carried out to compare the results. For melanin measurements correlation coefficient was $r = 0.985$ ($p < 0.001$) and for blood, $r = 0.621$ ($p < 0.001$). Relatively low correlation for blood measurement was partially due to a very small range of blood concentration levels present in normal skins (even with the use of the Tourniquet). We plan to extend this part of the study by taking measurements on skin conditions where abnormally high blood supply is present. However, in the light of the theoretical analysis above, showing that blood measurements can have significant error margin, correlation for blood is likely to remain lower than that for melanin.

6 Conclusion

The new skin imaging method can reliably detect very small changes (less than 5%) in melanin level for almost entire range of skin pigmentations. For very high melanin contents the detectable increment reaches approximately 20% of the maximum concentration. There is an excellent correlation with Mexameter measurements of melanin level. Changes in blood concentration can be detected with less sensitivity. For the normal Caucasian skin a typical detectable increment is around 20% of the maximum level assumed and slightly less in the presence of thin lesions. This can be improved by a careful selection of primaries and is the subject of current work. There is moderate correlation with Mexameter measurements. As our method uses three spectral values of measurement of both pigments, its accuracy is likely to be superior to that of Mexameter. This will be investigated in future work.

Quantitative sensitivity analysis exploiting the model of image formation demonstrates theoretical capabilities of the imaging system and can give valuable insights for its further improvement. The availability of the detection thresholds as a function of the skin parameters will enable critical evaluation of the parametric images produced by the new skin imaging method and will give confidence in their interpretation.

7 Acknowledgement

This work is supported by EPSRC grant GR /M53035.

References

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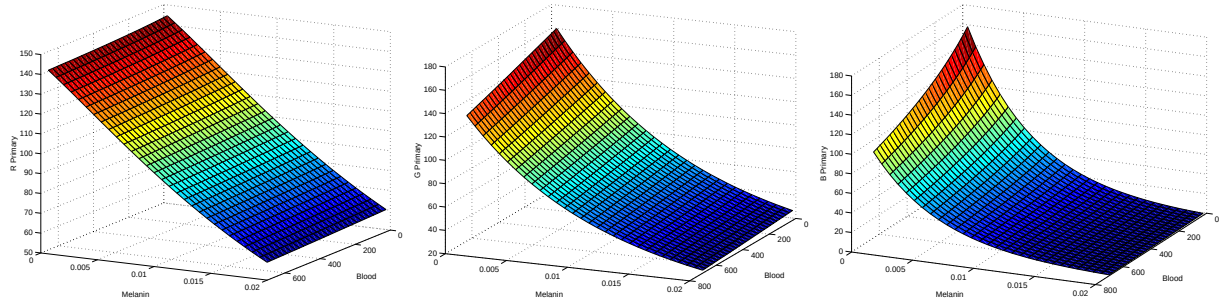


Figure 1. Red (R), green (G) and blue (B) primaries for a normal skin with different levels of epidermal melanin and blood concentration.

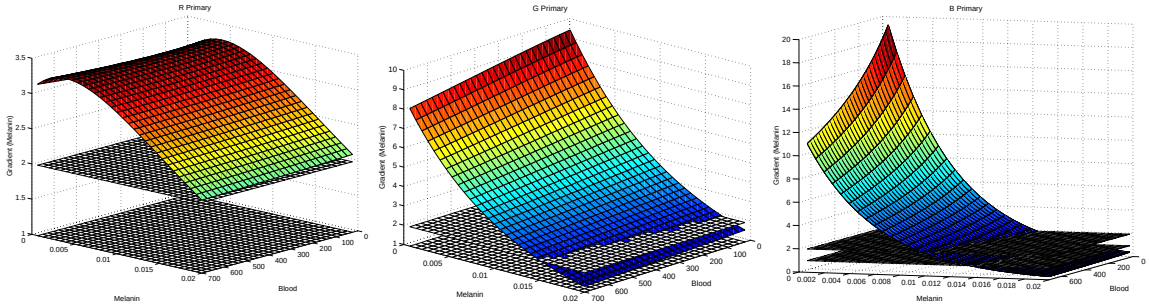


Figure 2. Absolute value of the gradient of R, G, and B primaries with respect to melanin concentration.

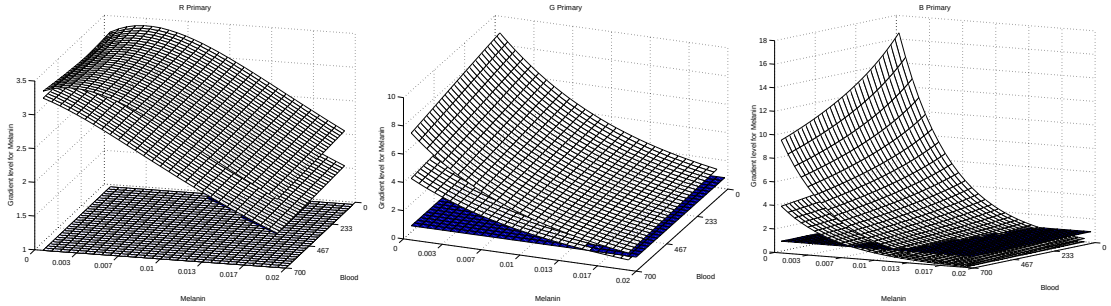
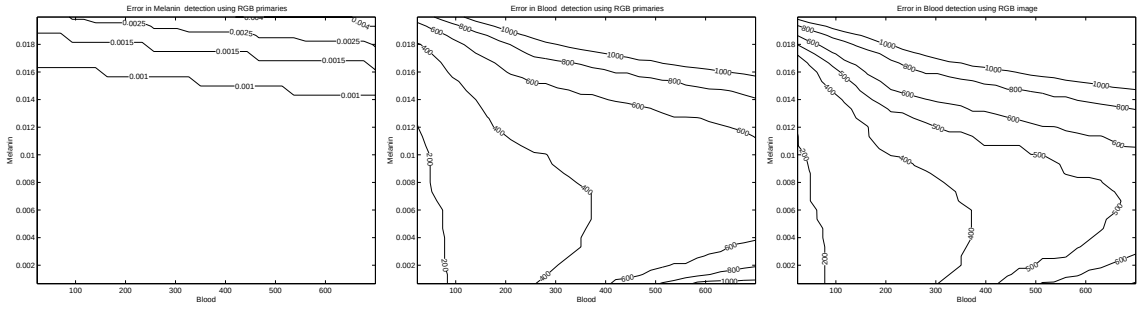


Figure 3. Absolute value of the gradient of R, G, and B primaries with respect to melanin concentration, for the two different concentrations when the thickness of melanin is 0.01 mm.



(a) (b) (c)

Figure 4. Detectability thresholds for measuring (a) melanin and (b) blood concentration in normal skin, and (c) blood concentration in skin lesion with a thin layer of dermal melanin. The thresholds are computed for a CCD camera with uniform noise level, $\sigma = 1$.