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Color quantification in angioscopic video images

J.A. Oomen, C.J. Slager, K.G. Lehmann, J.C.H. Schuurbiers & P.W. Serruys
Thorax Center, University Hospital Rotterdam, The Netherlands

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Abstract

Colors in video representations of angioscopic images are up until now described by an human observer. Differences in settings of the monitor and the inherent poor ability of the human eye to classify colors objectively results in a very poor intraobserver as well as interobserver variability. A PC-based method is described to measure colors in a video image and to present the results in a novel C-diagram. Results with this method for standard calibrated colors are given. Possible sources of error are discussed and methods to minimize these errors are presented.

Introduction

In recent years it has become possible to obtain intraluminal images of coronary arteries by means of a small and flexible fiber optic viewing system connected to a standard color video camera [1, 2]. This intraluminal application is an extension of the longer existing technique of endoscopy, which also is capable of providing video color images from inner surfaces of the human body. These images are viewed on a video monitor and can be recorded using a commercially available (S)VHS recorder. One of the characteristic properties these systems open for investigation, is the color of the inner surfaces at its normal and diseased parts. However the ability of the human observer to distinguish between different colors in an objective way is relatively weak. Attempts at description of a color often result in vague terms like yellowish-white or whitish-yellow. This was confirmed by the observer panel of the European Working Group on Coronary Angioscopy [3]. Furthermore, if one wants to make use of color data in multicenter studies or longitudinal clinical trials the use of an objective and reproducible numeric description of color is highly preferred.

The color of an object can be precisely and unambiguously determined by measuring its relative reflectance at all visible wavelengths, a method called spectrophotometry. This spectroscopic method of quantifying color however is complicated, time-consuming and has to be performed in real time, because no easy method exists of storing all reflectance values for all elements of a picture on a recording medium. Furthermore, in the case of angioscopic material, the image consists of a color video picture, on which the spectrophotometric method is difficult to perform. The colorimetric properties of such a picture do not only depend on the viewed sample, but also on the colorimetric parameters of the color monitor and the settings of its 'saturation' and possibly 'hue' controls.

We have investigated the possibility of quantifying the different colors found in the angioscopic image of the endoluminal surface using standard video technology, which is based on the tristimulus colorimetry. Although almost all details of the reflectance spectrum are ignored by this simplified approach, it still may be very valuable as it objectifies the subjective human perception, allows for correction of common color deviations and easily adapts to daily clinical practice. If color is recorded on film or video tape, a standard human perception model is used to describe the color of the object as the relative contributions of three primary colors in accordance with the eye sensitivity curves for those colors. This paper describes the measurement technology, use of color correction algorithms and their respective accuracies.

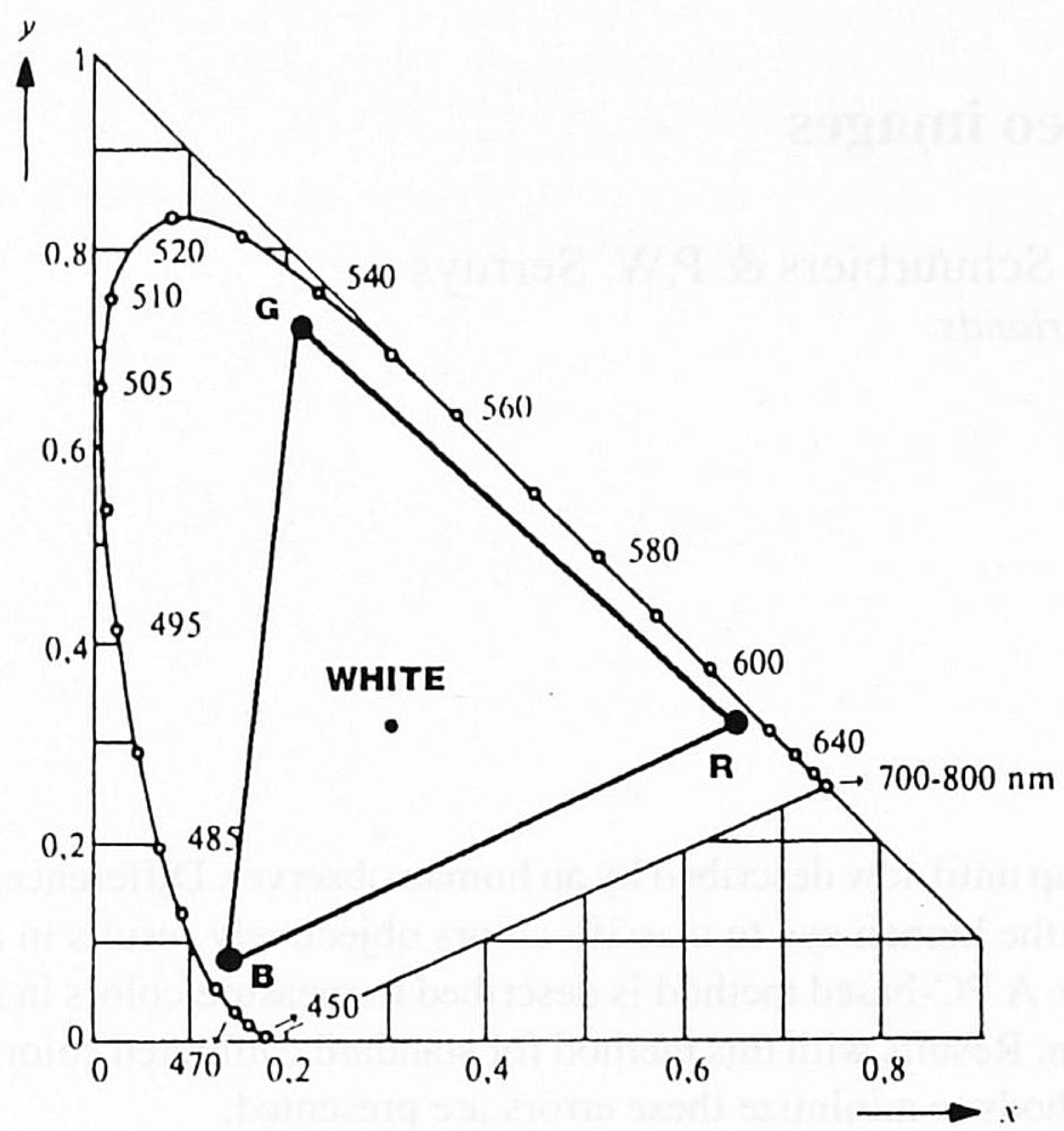

Fig. 1. The CIE chromaticity diagram. R, G, B defines the color triangle for video systems.

Color representation

A color video system achieves color reproduction by specifying the relative contribution of a well defined set of the primary colors red (R), green (G) and blue (B) to each of the picture elements (pixels) the image is composed of. Due to the nature of the color coding in video systems, only colors within the color triangle defined by R, G and B can be faithfully reproduced. The colors R, G and B are defined in the C.I.E. 1931 chromaticity diagram [4] as:

$$\begin{aligned} R &: x = 0.67\ y = 0.33 \\ G &: x = 0.21\ y = 0.71 \\ B &: x = 0.14\ y = 0.08 \end{aligned} \tag{1}$$

Figure 1 shows the CIE diagram and the triangle defined by R, G and B. Because a color video system reproduces color by the synthesis of the R, G and B components, extremely saturated colors, e.g. pure monochromatic colors cannot be reproduced. Such a saturated color however hardly appears in medical images. Commonly occurring colors fall within the R, G, B triangle and are coded within the video signal, and thus can be measured with suitable hardware (frame grabbers) and software aids.

The intensity of each of the colors R, G and B relates to the strength of the signal values S_R, S_G and S_B. In video systems the gain of the S_R, S_G and S_B signals is adjusted to produce equal values of S_R, S_G and S_B for a standard white surface [4]. It should be understood however, that the color values measured by a video system depend on the spectrum of the light used to illuminate the object. In order to correct for the color temperature of the illuminating light, most video cameras posses a 'white balance' adjustment. Setting of the white balance is performed by directing the camera onto a white object, illuminated by a possibly not pure white light, and then (automatically) adjusting the electronic gain of the R and B channels to achieve $S_R = S_G = S_B$.

The intensity of the illumination of an angioscopic image is not the same for all elements in the picture. However, the color of a surface does not depend on the absolute level of illumination, and thus video color can be specified by the signal strength (S_R, S_G or S_B) of two of the three primary colors normalized for total intensity ($S_R + S_G + S_B$). We specify color as a set of two numbers C1, C2, defined as:

$$C1 = S_R/(S_R + S_G + S_B) \tag{2 a}$$

$$C2 = S_G/(S_R + S_G + S_B) \tag{2 b}$$

where S_R, S_G and S_B represent the video camera output signals for red, green and blue respectively.

In this system the color white, defined as $S_R = S_G = S_B$ becomes:

$$C1 = C2 = 1/3 \tag{3}$$

The components S_R, S_G and S_B can be measured easily for any pixel in an image by using a frame-grabber board in a computer.

If C1,C2 is plotted on an orthogonal coordinate system a novel chromaticity diagram can be constructed, which will be referred to as the C-diagram, shown in Fig. 2. All measurable colors in this C-diagram will lie within the triangle Blue (0,0), Red (1,0), Green (0,1).

We defined the standard deviation (SD) of a set of C1,C2 points (i = 1 . . N) as

$$SD = \frac{1}{N-1}\sqrt{\sum_{i=1}^{N}(C1_i - \overline{C1})^2 + (C2_i - \overline{C2})^2} \tag{4}$$

where N = Number of samples
and $\overline{C1}$,$\overline{C2}$ = Mean value of C1 and C2 respectively.

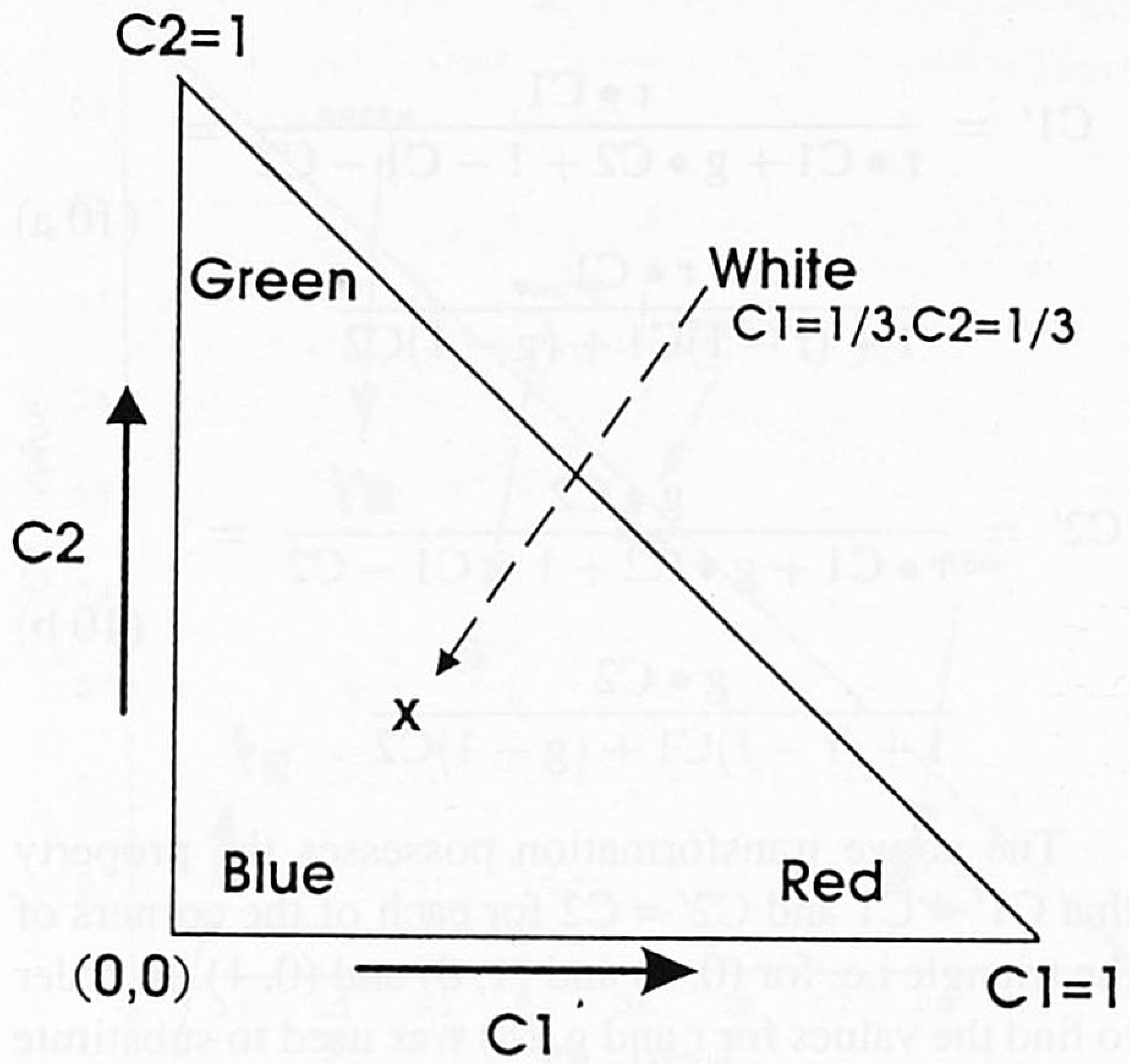

Fig. 2. The C-diagram. All colors reproducible by a color video system can be expressed with C-coordinates encompassed by this triangle.

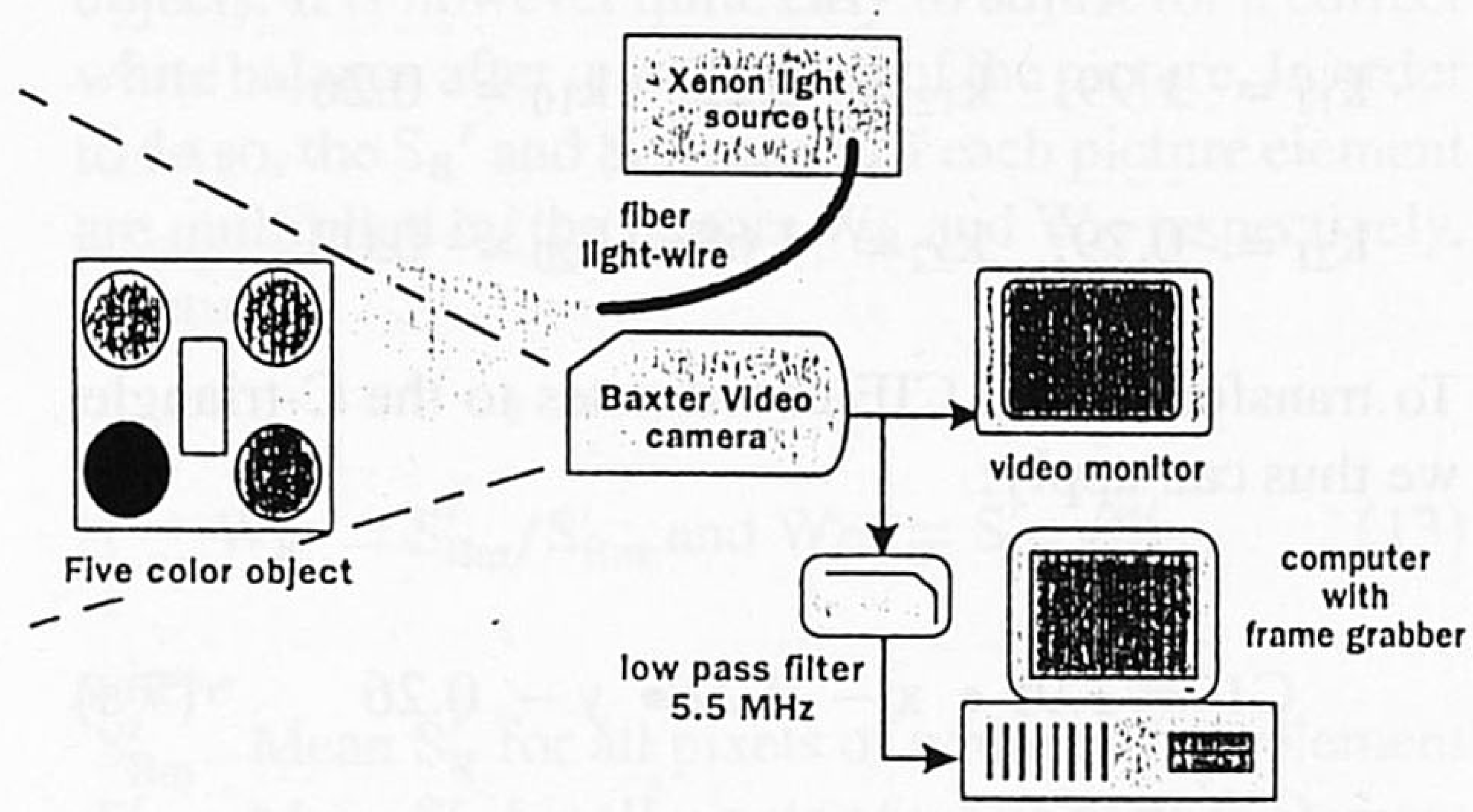

Fig. 3. Measurement setup to establish color rendition accuracy of the Baxter angioscope video camera.

Measurement setup

In this study the angioscope camera model 2075 from Baxter (Irvine, CA, USA) was used to establish the accuracy with which colors could be measured under varying intensities of ambient light. This camera delivers a PAL standard color video image. The set up is shown in Fig. 3. The standard lens of the video camera has been replaced with another one (Olympus f = 38 mm) and the camera is adjusted to record a picture of four standard color samples (Green, Red, Blue, Yellow) and a standard equal-energy white sample. The standard colors and the white sample are certified reflectance standards from Labsphere (North Sutton, NH, USA). Illumination of the samples is achieved with the Baxter xenon light source using the accompanying light transmitting fibers. The amount of xenon light is controlled through a mechanical shutter, so the color temperature is constant throughout the light intensity range. The relative amount of light falling on the sample was determined by a light sensitive photo-diode. White balance adjustment of the camera was performed on a piece of Labsphere standard white before each set of measurements.

Output from the video camera was fed to a video monitor and a PC/AT (Commodore 386SX-16), which has been provided with a frame grabber (IRIS) and image acquisition software (ColorVision 1) both from Cocoon Software, Oud Gastel, Netherlands. The video signal for the frame grabber was passed through a 5.5MHz low pass filter to prevent aliasing effects. Color quantification of the grabbed images was performed by the in-house developed ColMet software. Video signals were interconnected using y/c cabling.

Relation between CIE values and C1-C2 values

Introducing the C-diagram establishes a straightforward relation between the S_R, S_G, S_B-values measured by the frame grabber and the C1,C2 coordinates (expression 2a, b). In our case we had access to calibrated color samples, with the calibration being done according to the CIE1931/D65 standard. In order to predict the expected C-values of these samples, a relation had to be established between the CIE and C-values. The RGB-triangle in the CIE diagram can be shifted and rotated to the C-triangle by the linear transformation:

$$\begin{bmatrix} C1 \\ C2 \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{bmatrix} \times \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} k_{10} \\ k_{20} \end{bmatrix} \qquad (5)$$

Making use of the fact that red, green and blue as defined by (1) form the corners of the C1,C2 triangle, we arrive at the set of equations:

$$\begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} k_{11} & k_{12} & 0 & 0 & 0 & 0 \\ k_{21} & k_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & k_{11} & k_{12} & 0 & 0 \\ 0 & 0 & k_{21} & k_{22} & 0 & 0 \\ 0 & 0 & 0 & 0 & k_{11} & k_{12} \\ 0 & 0 & 0 & 0 & k_{21} & k_{22} \end{bmatrix} \times \begin{bmatrix} 0.67 \\ 0.33 \\ 0.21 \\ 0.71 \\ 0.14 \\ 0.08 \end{bmatrix} + \begin{bmatrix} k_{10} \\ k_{20} \\ k_{10} \\ k_{20} \\ k_{10} \\ k_{20} \end{bmatrix} \qquad (6)$$

Solving for the k's we find:

$k_{11} = 1.99; \quad k_{12} = -0.22; \quad k_{10} = -0.26$

$k_{21} = -0.79; \quad k_{22} = 1.68; \quad k_{20} = -0.02$

To transform from CIE coordinates to the C-triangle, we thus can apply:

$$C1 = 1.99 \bullet x - 0.22 \bullet y - 0.26 \quad (7\,a)$$

$$C2 = -0.79 \bullet x + 1.68 \bullet y - 0.02 \quad (7\,b)$$

One should keep in mind however that the color white is defined as C1 = 1/3 and C2 = 1/3. White in CIE/D65 is defined as x = 0.3127 and y = 0.3291 [4]. Using formula (7a, b) to compute the C-values for white CIE/D65 we find:

$$C1 = 0.2888 \text{ and } C2 = 0.2808 \quad (8)$$

White as defined by CIE and white as defined by the color video system do not coincide. This is to be expected, because the phosphor colors as defined in color video systems are chosen to be technologically feasible and are not necessarily equidistant from the point defined as white. In order to get agreement between the CIE white and the C-diagram white a second transformation is defined. This second transformation takes into account the fact that the relative contributions of the S_R, S_G and S_B signals to the intensity of the R, G and B color components are not necessarily equal. Therefore S_R, S_G are each multiplied with r and g respectively, while keeping the gain of S_B at 1. The value of the factors r and g now defines the setting of the 'white balance', a feature always present in color video cameras. Having introduced g and r, we now can write:

$$C1' = \frac{r \bullet S_R}{r \bullet S_R + g \bullet S_G + S_B} \text{ and} \quad (9\,a)$$

$$C2' = \frac{g \bullet S_G}{r \bullet S_R + g \bullet S_G + S_B} \quad (9\,b)$$

The color does not depend on the amount of illumination, so we may set the illumination at 1, leading to: $S_R + S_G + S_B = 1$. Using this expression and the definition of C1 and C2 in (2a, b) we arrive at:

$$C1' = \frac{r \bullet C1}{r \bullet C1 + g \bullet C2 + 1 - C1 - C2} = \frac{r \bullet C1}{1 + (r-1)C1 + (g-1)C2} \quad (10\,a)$$

$$C2' = \frac{g \bullet C2}{r \bullet C1 + g \bullet C2 + 1 - C1 - C2} = \frac{g \bullet C2}{1 + (r-1)C1 + (g-1)C2} \quad (10\,b)$$

The above transformation possesses the property that C1′ = C1 and C2′ = C2 for each of the corners of the triangle i.e. for (0, 0) and (1, 0) and (0, 1). In order to find the values for r and g, (8) was used to substitute for C1, C2 in (10a, b) and C1′ and C2′ where both replaced by 0.3333 in (10a, b). The Optimizer function from Quattro Pro V5.0 (Borland) was used to solve the resulting set of equations for r and g and it was found that:

$$r = 1.4906; \quad g = 1.5328$$

which leads to the following expression for the second transformation

$$C1' = \frac{1.4906 \bullet C1}{1 + 0.4906 \bullet C1 + 0.5328 \bullet C2} \quad (11\,a)$$

$$C2' = \frac{1.5328 \bullet C2}{1 + 0.4906 \bullet C1 + 0.5328 \bullet C2} \quad (11\,b)$$

So if for a color its CIE1931/D65 values are known, applying the transformations (7) and (11) in that order will give the corresponding C1,C2 values. We have used these transformations in order to find the locations of the standard Labsphere colors in the C-diagram (Fig. 4).

Black level offset

After digitizing the S_R, S_G and S_B signals from a camera with the aid of a frame grabber, it is found that the combination of camera and frame grabber introduces an offset in the S_R, S_G and S_B values. Stated otherwise, it can be said that the digitized S_R, S_G and S_B values are not zero for a black picture element. This aberration

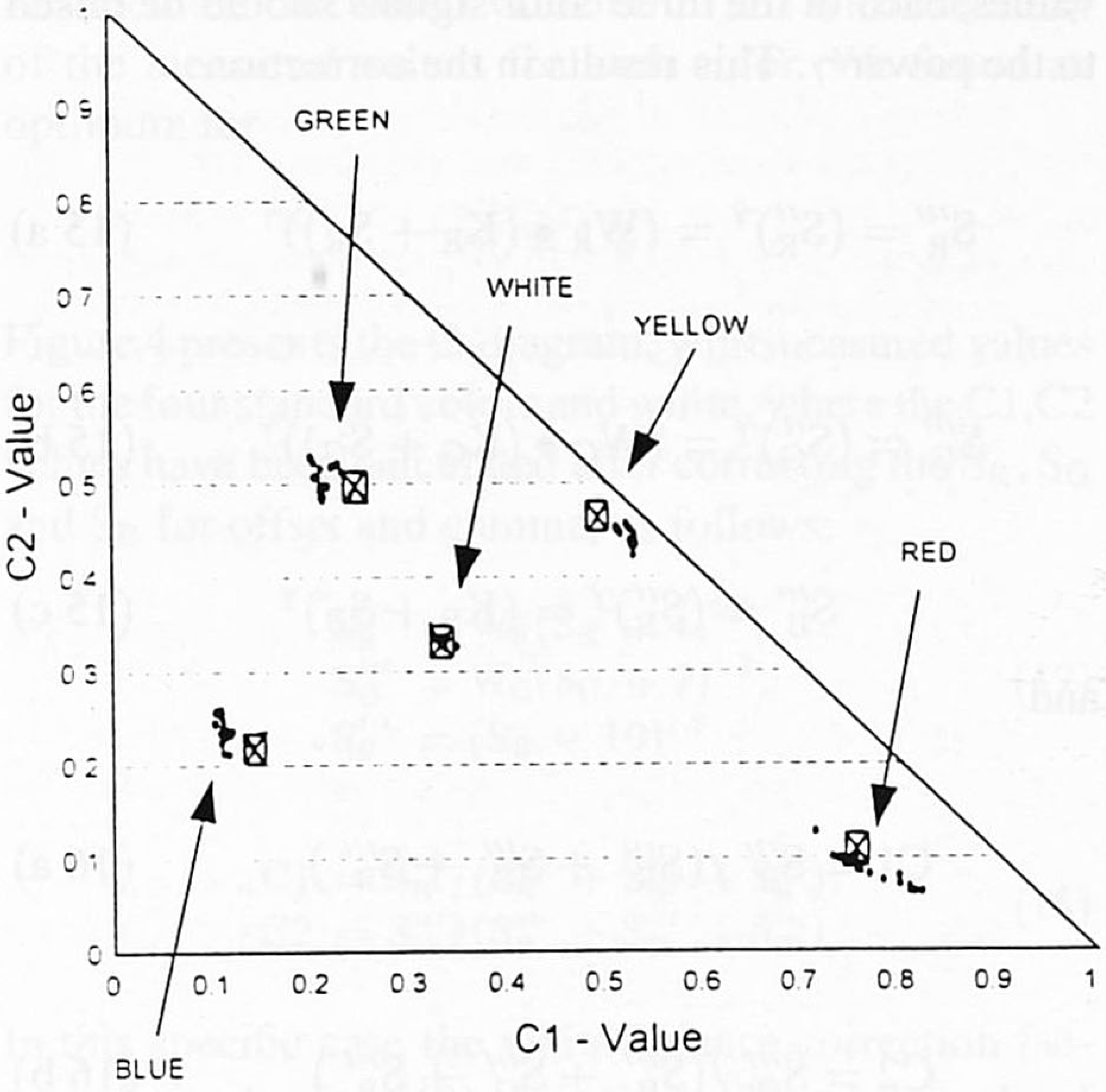

Fig. 4. Result of 24 measurements on 5 calibrated standard Labsphere colors. The boxed X marks the C1,C2 coordinates of the color samples as computed from the specified CIE1931/D65 values.

is allowed by the standard for digitized video images [6] and normally corrected on the video monitor by the 'brightness' setting. The result of this aberration is a tendency for C1 and C2 to move closer to white (less saturated colors) or away from white (more saturated colors) if the level of illumination ($S_R + S_G + S_B$) changes.

This error can be minimized by adding suitable correction constants (K_R, K_G and K_B) to each of the S_R, S_G and S_B values before further processing. These constants can be derived through a calibration procedure using a set of certified standard color samples. When the values of K_R, K_G and K_B are known, the measured color values S_R, S_G and S_B can be transformed to the black level corrected values S_R', S_G' and S_B' by:

$$S_R' = S_R + K_R; S_G' = S_G + K_G; S_B' = S_B + K_B \quad (12)$$

White balance

Although most cameras posses a white balance adjustment, which should result in $S_R' = S_G' = S_B'$ and thus $C1 = C2 = 1/3$ for an object indicated as white, possible gain errors introduced in camera and digitizing circuits result in values other than 1/3 for C1 and C2 for white objects. It is however quite easy to adjust for a correct white balance after quantization of the picture. In order to do so, the S_R' and S_G' values of each picture element are multiplied by the factors W_R and W_G respectively, where:

$$W_R = S'_{Bm}/S'_{Rm} \text{ and } W_G = S'_{Bm}/S'_{Gm} \quad (13)$$

where
S'_{Rm}: Mean S'_R for all pixels of white picture element
S'_{Gm}: Mean S'_G for all pixels of white picture element
S'_{Bm}: Mean S'_B for all pixels of white picture element
White balance correction is now applied to all pixels in subsequent pictures according to:

$$\begin{aligned} S''_R &= W_R \bullet S'_R = W_R \bullet (S_R + K_R) \\ S''_G &= W_G \bullet S'_G = W_G \bullet (S_G + K_G) \quad (14) \\ S''_B &= S'_B = S_B + K_B \end{aligned}$$

The white balance correction as described here can be performed before each set of measurements and it has been included as an integral part of the ColMet color quantification software package. This software package allows the operator to indicate a rectangular area containing the presumed white color. This area is subsequently used to derive $S_R{'}_m$, $S_G{'}_m$ and $S_B{'}_m$ and (13) is then applied to arrive at the correction factors W_R and W_G to be used throughout all subsequent measurements. In our measurement setup as depicted in Fig. 3 the equal energy white standard in the middle of the test pattern, with a relative illumination of 900 (Fig. 5) has been used for this white balance correction.

Gamma correction

The response of the Baxter camera for a white color sample is shown in Fig. 5. Immediately apparent is the fact that for sufficiently high levels of illumination the output signal is almost constant. This is expected and is a result of the automatic gain circuitry in the camera. Furthermore the first part of the curve, for lower light levels, is non-linear. This represents the inherent gamma operation on the signal. With video cameras the signal level as provided by the light sensitive element is customarily raised to the power $1/\gamma$, where γ is chosen to fall between 1.5 and 2.5. This is done to account for the non-linear transfer characteristic of the picture display tube (light out = signal in) at the end of the chain. So in order to linearize the S_R, S_G and S_B

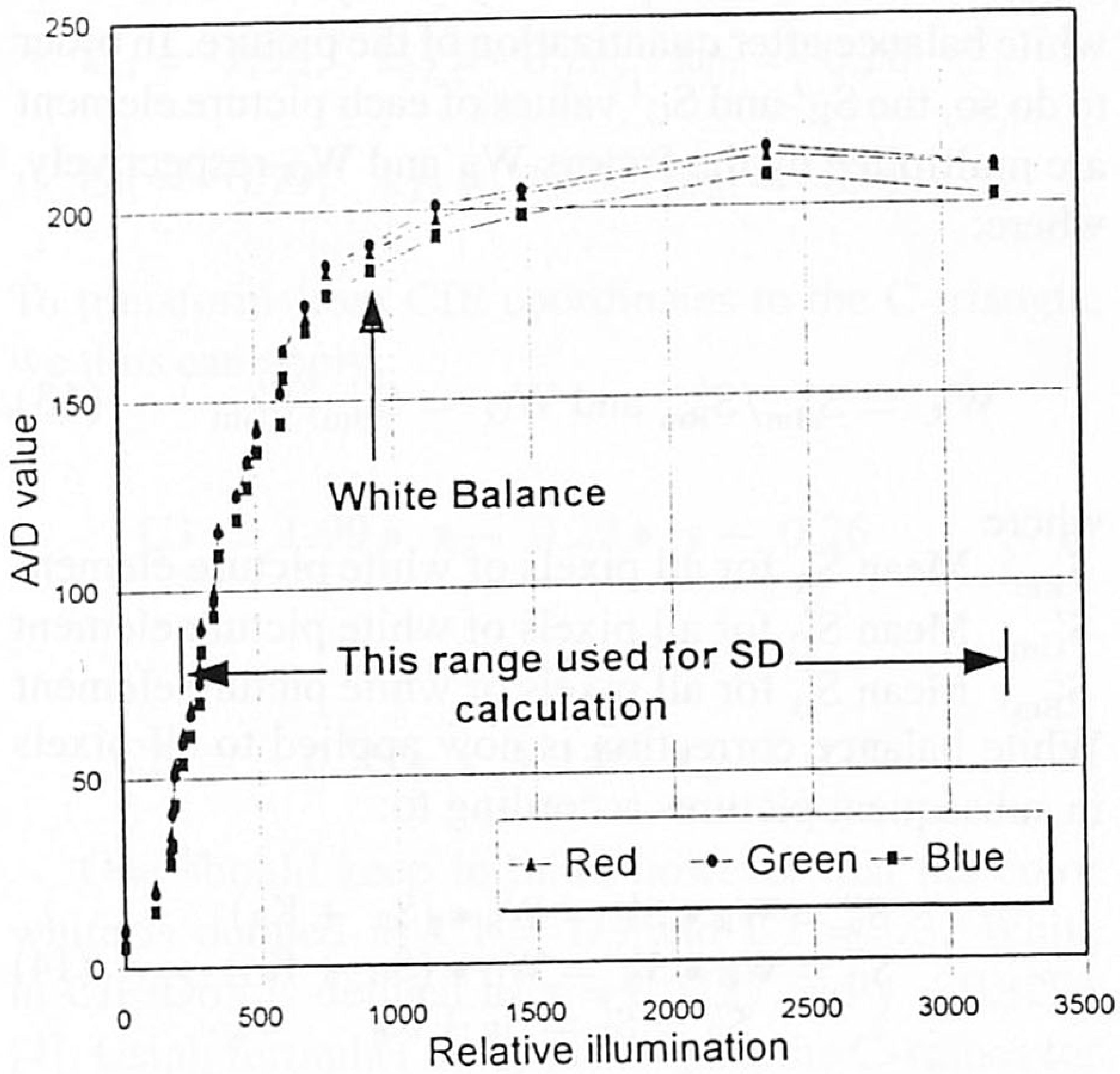

Fig. 5. Digitized value for each of the primary colors of the white object as a function of illumination intensity. Indicated in this figure are the level used for white balance correction and the range used for assessment of the standard deviation.

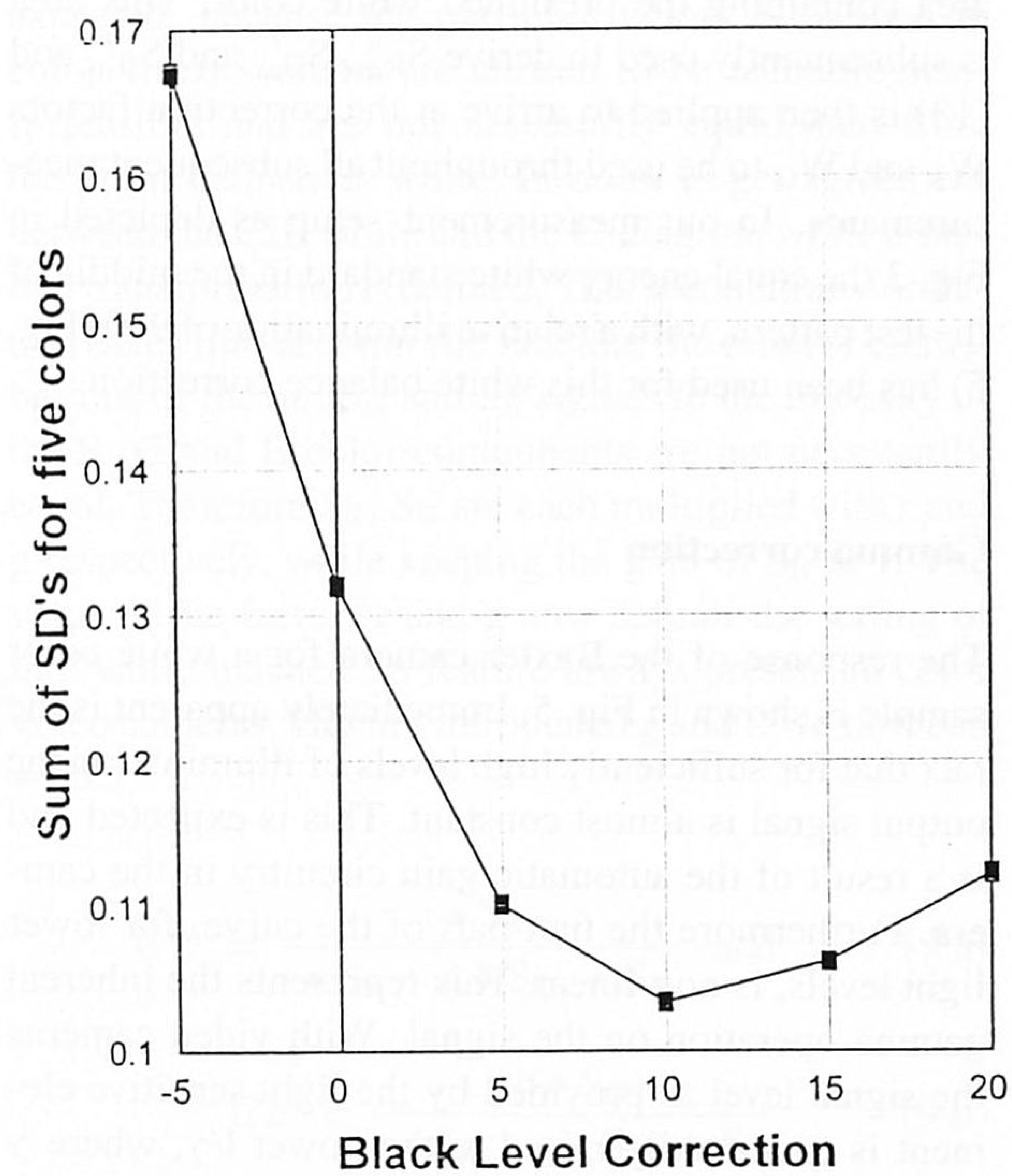

Fig. 6. Sum of standard deviations of C1,C2 for the colors white, yellow, green, red, blue as a function of black level correction with $K_R = K_G = K_B$.

values, each of the three color signals should be raised to the power γ. This results in the correction:

$$S_R''' = (S_R'')^\gamma = (W_R \bullet (K_R + S_R))^\gamma \quad (15\text{ a})$$

$$S_G''' = (S_G'')^\gamma = (W_G \bullet (K_G + S_G))^\gamma \quad (15\text{ b})$$

$$S_B''' = (S_B'')^\gamma = (K_B + S_B)^\gamma \quad (15\text{ c})$$

and

$$C1 = S_R''' / (S_R''' + S_G''' + S_B''') \quad (16\text{ a})$$

$$C2 = S_G''' / (S_R''' + S_G''' + S_B''') \quad (16\text{ b})$$

If $\gamma = 1$ then no gamma-correction takes place. If gamma increases from 1, it can be shown that this will influence the C1,C2 coordinates of a specific color in such a way, that these coordinates move away from the point white (1/3, 1/3). If the measured standard colors, with gamma = 1, are compared to the C1,C2 values computed using (7) and (11), it is found that the measured colors lie closer to white (1/3, 1/3) than their calculated equivalents. Increasing γ will result in a much closer agreement between measured and calculated C1/C2 values.

Results

To find the most suitable values for each of the K constants, the setup of Fig. 3 was used to measure five standard colors (red, green, blue, yellow and white) using different amounts of illumination. A spreadsheet (Quattro Pro) was used to introduce variable K constants according to (12). For each color the standard deviation (SD) of C1,C2 over all measurements for that color (N = 21) was computed. Finally, an optimization function was used to find the values for the K's which minimized the sum of the SD's for the five colors. We arrived at:

$$K_R = 4;\ K_G = 7;\ K_B = 10$$

To correct for the gamma of this particular camera we used the optimizer function in the Quattro Pro spreadsheet to establish the value of γ which most closely matched the calculated value of C1,C2 with the mean of the measured values for each color. We found an optimum for

$$\gamma = 1.8$$

Figure 4 presents the C-diagram, with measured values for the four standard colors and white, where the C1,C2 values have been calculated after correcting the S_R, S_G and S_B for offset and gamma, as follows:

$$\begin{aligned} S_R''' &= W_R(S_R + 4)^{1.8}; \\ S_G''' &= W_G(S_G + 7)^{1.8}; \\ S_B''' &= (S_B + 10)^{1.8} \end{aligned} \quad (17)$$

$$\begin{aligned} C1 &= S_R'''/(S_R''' + S_G''' + S_B'''); \\ C2 &= S_G'''/(S_R''' + S_G''' + S_B''') \end{aligned} \quad (18)$$

In this specific case the white balance correction factors, derived using (13) at a relative illumination level of 900, were found to be:

$$W_R = 0.9926 \; W_G = 0.9769$$

With SD as defined by (4), the following results where obained for an illumination range (Fig. 5) of 1 : 7.5

Color:	Green	Red	Yellow	Blue	White
SD:	0.017	0.036	0.011	0.017	0.006

Discussion

We present a method to transfer color coordinates from the well known CIE values to the novel C-diagram. This method, given by the transformations (7) and (11) is derived without any regard to the typical properties of a specific color video system. The only parameters used are the R, G and B coordinates in the CIE diagram (Fig. 1) and the fact that white in video systems is defined as $S_R = S_G = S_B$. The transformations therefore are generally valid and do not depend upon the type and quality of color video equipment in use with any particular experiment. Correction constants for black level offset (K_R, K_G and K_B) and gamma (γ) should be re-established for every new camera-frame grabber combination.

Apart from these corrections however, the ability of a video camera to truthfully separate a color in its S_R, S_G and S_B components might be less than perfect. Especially the so called 'one chip cameras' use a rather crude way to extract the primary colors [5]. The Baxter camera used in these experiments is based on a one chip design and although the registered colors might appear natural to the eye, subjecting them to a precise quantification as we have done, clearly shows its limitations in color rendition accuracy, as is apparent by the calculated standard deviation. Additionally, the frame grabber might introduce its own errors. Even with those residual errors the method presented here should be superior to color estimation by the unaided eye. This also holds if the human observer is equipped with a reference color chart, as the specific properties of the video equipment will influence the results, because the settings of the color monitor have a poorly controllable effect on the color rendition. Next to internal adjustments of color monitors, which might need readjustment with aging, the European PAL monitor has an user adjustable 'color intensity' setting, which influences the saturation of a color; the US. NTSC standard on top of that has a 'color hue' control, which strongly influences color appearance.

We introduced and described three corrections used with the Baxter camera coupled with a Cocoon frame grabber: Black Level Offset, White Balance and Gamma Correction. The black level correction we employed leads to a positive correction value, a surprising result because the literature [6, 7] states that digital video black should be set at 16 quantization levels. One would therefore expect a black level correction value around - 16 instead of the value of + 10 we arrived at. Figure 5 gives an indication of why our result is valid. For very low light levels (almost black), there is a sharp bend in the transfer curve. Because of their obvious aberrant behavior we did not take these low levels in account while optimizing the black level correction value. When approximated by a straight line, the part of the curve between 50 and 150 quantization levels clearly points to a y-axis intercept at negative y, around - 10 to - 20 units. Figure 6 shows the effect of the black level correction value on the sum of the standard deviation for the five standard color samples. For the sake of simplicity the same offset value is used for S_R, S_G and S_B. Figure 6 clearly shows the improvement in SD for small positive levels of offset correction. SD is not very sensitive to small changes, levels between 5 and 15 quantization units all seem satisfactory.

The white balance correction, using W_R and W_G as described by (14), is easy to implement and can be performed at the start of every set of measurements. It guarantees that $S_R = S_G = S_B$ for what the user indicates as standard white. Objects called 'white' might have slightly different colors, so we propose to use an 'equal energy white' object to be adopted as the standard.

Introduction of the gamma correction will not influence the reproducibility while using one camera, but it should result in better agreement between different cameras. When using a system different from our Baxter camera, one will be forced to establish the effective gamma for that camera. We propose defining the effective gamma as that value which results in the closest agreement between the measured and computed C1,C2 values of a standard, calibrated set of color samples, where the C1,C2 computation is performed using (7) and (11).

Conclusions

Quantification of colors recorded by standard video equipment is feasible and less prone to errors compared to estimation of colors on a video monitor by the naked eye. When using the appropriate transformations and corrections, good agreement exists between measured values and the calibration values given in CIE1931 coordinates. The C-diagram thereby is an easy-to-interpret and generally applicable vehicle for registering and comparing values measured in different pictures and with different systems. If care is taken to adjust the black level offset and gamma correction for each particular system, good agreement between measurements on different systems should be possible.

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