Color Error in the Digital Camera Image Capture Process

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Abstract The color error in images taken by digital cameras is evaluated with respect to its sensitivity to the image capture conditions. A parametric study was conducted to investigate the dependence of image color error on camera technology, illumination spectra, and lighting uniformity. The measurement conditions were selected to simulate the variation that might be expected in typical telemedicine situations. Substantial color errors were observed, depending on the measurement conditions. Several image post-processing methods were also investigated for their effectiveness in reducing the color errors. The results of this study quantify the level of color error that may occur in the digital camera image capture process, and provide guidance for improving the color accuracy through appropriate changes in that process and in post-processing.

Keywords Color error · Camera · Color difference · Color correction · Telemedicine

Background

The prevalence of computers and digital cameras, in conjunction with the wide availability of the internet, has stimulated strong growth of telemedicine [1]. The prominence of mobile devices appears to be accelerating this growth [2]. Telemedicine offers consultation and diagnosis opportunities to patients in

remote locations that they would normally not have readily available to them. However, the diagnosis can be affected by the quality of the image rendered to the viewer. In some fields, like telepathology and teledermatology, color information provides valuable clues for a quick and accurate diagnosis. Inaccurate color images can lead to longer diagnosis times [3], and potentially improper conclusions. Given the importance of color images in telemedicine, the entire digital image workflow needs to be critically evaluated in order to determine the error sources in the process.

A typical telemedicine workflow generally includes (a) the image capture of a colored object by a digital camera, (b) digital compression of the raw image, (c) transmission of the image to the diagnostic computer, (d) image processing of the image viewing software, and (e) the physical rendering of the image by a display. This investigation focused on the initial capture of the image using a color digital camera. It is a critical component in the workflow, since errors introduced at this step are likely to be propagated through the entire process. An investigation of the color error produced by the display, and the system as a whole, will be presented in a subsequent publication.

Experimental Method

In many telemedicine applications, the digital image capture is not well controlled, and often incorporates consumer devices that range in quality. The image may be acquired with a cell phone camera or single-lens reflex (SLR) camera, depending on the circumstance. Given the large number of possible scenarios, it was deemed necessary to first determine a baseline of what the color error would be for workflows under nominal conditions. Therefore, digital cameras were characterized in their fully automatic mode. Some image post-processing methods were also investigated in order to improve the image color accuracy.

A simulation of a typical image capture process was implemented by placing a color test chart (see Fig. 1) in a light booth with controlled illumination and taking an image of the chart

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Fig. 1 NIST CQS color test chart (left) and X-Rite Digital ColorChecker SG chart (right). Numbers were placed on the image to identify the colors. The numbers in the lower half of the Digital ColorChecker SG chart are added to this chart to label the flesh tone colors

with a digital camera. The NIST color quality scale (CQS) color test chart was created from a set of saturated colors (NIST CQS #1–#17) that sample the range of perceived hues (Fig. 2) [4]. The color patches are Munsell samples with a matte reflective surface, and are commercially available¹. Many of the colors lie within the standard sRGB color gamut rendered by most displays [5]. However, a few colors lie slightly outside this gamut, and served to stress the camera. In addition to the saturated colors, the NIST CQS color test chart (see Fig. 1) included a span of gray shades (NIST CQS #19–#24) to evaluate the white balance over a range of intensities. For medical applications, a reference chart with a range of human skin colors is also necessary. But there are limited commercial options. In this study, an X-Rite Digital ColorChecker SG was utilized as a color test chart for flesh tones, and as a reference color chart for color correction in an image post-processing procedure. Although flesh tone patches with a matte finish were preferred, the X-Rite color chart patches were only available with a semigloss reflective surface. The flesh tone colors are located in the lower half of this chart and are identified by numbers in Fig. 1 for data analysis purposes.

These color charts were placed in a light booth and individually illuminated in sequence by three types of lamps, each with a different correlated color temperature (CCT) [6]. The lamps included a daylight fluorescent lamp, a cool white fluorescent lamp, and an incandescent lamp with CCTs of 5,900, 3,900, and 2,700 K, respectively. These lamps were chosen to estimate the response of the telemedicine system to the outdoor, office, and home lighting environments where images may be captured. The normalized spectral distributions of these lamps are given in Fig. 3. The light booth normally illuminates the charts with the lamps positioned above. In order to improve the illumination

uniformity across the charts for the fluorescent lamps, a second set of fluorescent lamps was positioned at the bottom of the booth entrance. The lamps were allowed to warm up for at least 30 min to stabilize the illumination prior to the measurements.

The quality of the camera technology was expected to have a significant effect on the final color accuracy. Therefore, a cell phone camera, a mid-priced point-and-shoot camera, and a digital SLR camera were employed to sample the potential use cases (see Table 1). Since the cell phone and point-and-shoot cameras could only produce 8-bit per color joint photographic experts group (JPEG) files, all the cameras were evaluated based on this common format. Although it is expected that higher bit depth cameras capable of saving RAW image files would yield better results, this hypothesis was not investigated in this preliminary study. All cameras were operated in their fully automatic image capture mode (with flash off). The point-and-shoot and SLR cameras were positioned 1 m in front of the color chart and zoomed in to mostly fill the frame with the image of the color chart. The cell phone camera did not have an optical zoom, so that camera was positioned approximately 0.5 m from the chart in order to preserve ample chart resolution. Since the image capture process appeared to be inherently noisy, repeated image captures were taken over the course of 4 months in order to gather statistical data.

Once the images were captured, the colors encoded in the JPEG images were digitally extracted and evaluated for their color accuracy. Image processing software was used [7] to find the center location of each color patch in the JPEG image, and determine the average color (CIE XYZ tristimulus values [5]) of a 21 by 21 pixel area about the patch center. The size of the pixel area was selected to approximate the measurement area of the reference spectroradiometer. The image processing software was validated against values obtained from Adobe Photoshop CS5 software. A Bradford chromatic adaptation transform [8] was applied on the original image colors to shift them to a CIE D65 white point. Therefore, the images were transformed to how the colors would be perceived under standard daylight illumination.

¹ Certain commercial equipment, instruments, materials, systems, and trade names are photographically identified in this paper in order to specify or identify technologies adequately. Such identification is neither intended to imply recommendation or endorsement, nor is it intended to imply that the systems or products identified are necessarily the best available for the purpose.

Fig. 2 Range of colors used in the NIST CQS color chart when illuminated by a CIE D65 Illuminant [6]. The flesh tone colors in the Digital ColorChecker SG are also shown. The typical color span of monitors is indicated by the black sRGB triangle

This transformation does not negate the measured influence of a varying white point (and spectra) on the camera, but is a useful common reference, since in most cases, the displays will try to render these images to the viewer in the same sRGB color space and white point.

The color accuracy of the patches in each color chart was compared relative to spectroradiometer measurements. A Photo

Fig. 3 Normalized spectral distributions of the lamps used in the light booth compared to a CIE D65 Daylight Illuminant

Research PR-705 spectroradiometer was placed 1 m from the charts in the light booth, and laterally translated to measure the reflected spectrum of each color patch for a given illumination condition. A 0.5° measurement field angle and 5-nm bandwidth was used for the spectral measurements. After the spectral measurements of color patches were performed, a calibrated diffuse white reflection standard was placed in the light booth measurement area and also measured. The reflection standard provided a means for determining the illumination on the chart, and enabled the calculation of the spectral reflectance factor for each color patch. The spectral reflectance factor data was in turn used to calculate what the patch color would be when illuminated by a D65 illuminant [9], the sRGB color space white point. A perfect reflecting diffuser was used as the reference white point for the calculation of the spectroradiometer CIE L^* , a^* , and b^* values. The converted color data for each patch served as the reference for all the color accuracy analysis. Since the patch reflection data can be sensitive to the illumination geometry, separate reference color data was obtained for each light booth lamp (daylight fluorescent, cool white fluorescent and incandescent).

The color accuracy of each color patch in a digital image was evaluated by the CIELAB color difference ΔE_{ab}^* [6] between the encoded color in the image and the spectroradiometer reference color data. It is generally accepted that $\Delta E_{ab}^*=1$ produces a just noticeable difference between two colors. The color difference ΔE_{ab}^* is calculated as the geometric difference between two color points in the CIELAB three-dimensional color space as follows:

Table 1 Characteristics of cameras used in this study

Camera	Color depth	Number of pixels	White balance	Color space	Image format
Cell phone (Apple iPhone 4)	24-bit RGB	5 million	Auto	sRGB	JPEG
Point-and-shoot (Nikon Coolpix P100)	Not available (Presumably 24-bit RGB)	10.6 million	Auto	sRGB	JPEG
Digital SLR (Sony Alpha A100)	24-bit RGB	10.8 million	Auto	sRGB	JPEG

$$\Delta E_{ab}^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

Where each color is defined by its lightness (L^*) and hue (a^* and b^*) coordinates.

It is also useful to determine the CIELAB chroma C_{ab}^* , CIELAB chroma difference ΔC_{ab}^* , and lightness difference ΔL^* between two colors as follows:

$$C_{ab}^* = \sqrt{(a^*)^2 + (b^*)^2} \quad (2)$$

$$\Delta C_{ab}^* = C_{ab,1}^* - C_{ab,0}^* \quad (3)$$

$$\Delta L^* = L_1^* - L_0^* \quad (4)$$

A more recent formulation of the perceived color difference model was put forth by CIE DE2000 [6]. Although, this formulation is considered to be more appropriate for a CIE DE2000 color difference of $\Delta E_{00} \leq 5$.

In addition to characterizing the baseline color error of the acquired images, two color correction methods were investigated for their effectiveness. The X-Rite ProfileMaker 5 and research software from the University Hospital of Ghent [10, 11]. Both of these methods required the use of a reference color

chart. An image of the reference color chart was taken under the same camera settings and lighting conditions as the test target. The color correction software then evaluated the captured reference image and determined correction factors based on what the colors in the reference image should have been (per vendor measurements). The commercial color correction method used the common practice of creating color profiles, for the given measurement conditions, that conformed to the international color consortium (ICC) color profile specification standard [12]. This is a color correction methodology that is popular in the professional photography and print industry. An ICC compliant digital image viewing software can apply the ICC profile on the corresponding original test image to generate a color-corrected image. In contrast, the University Hospital of Ghent color correction software created new color-corrected JPEG images directly, without the use of ICC profiles.

Results and Discussion

This parametric study evaluated three main effects considered to be important factors that could influence the color accuracy of the image capture process as follows: the camera technology, the illumination spectra, and the target color chart

Fig. 4 Boxplot of CIELAB color difference for NIST CQS color patches captured by the point-and-shoot camera under the daylight fluorescent lamp

Fig. 5 Color error for point-and-shoot camera image taken of the NIST CQS color chart illuminated sequentially by a daylight fluorescent, cool white fluorescent, and incandescent lamp

position in the light booth (single chart in center or two charts side by side). In addition, interaction effects were also considered between the camera type and illumination spectra, camera type and chart position, and illumination spectra and chart position. The significance of the three main effects and three interaction effects was evaluated by performing an analysis of variance for each color patch [13] (a separate analysis of variance was completed for each color because of non-constant variance in the residuals of a combined color model). Among all 35 color patch models, only 19 of the 210 estimated effects were not significant at the 0.05 level.

Of these 19 nonsignificant effects, there were three interaction effects that were not significant among saturated colors and six interactions that were not significant among the flesh tones. The remaining nonsignificant effects were associated with position in the light booth for eight flesh tones and two saturated colors. Even though the position effect was not significant for some color models, the same models contained a significant position-by-camera interaction (if an interaction is significant, the associated main effects are usually included in the model as well, even if the main effects are not significant). For all colors, the analysis of variance results indicated that color error is sensitive to all three main effects (position in the light booth, camera technology, and illumination spectra); however, the interpretation of the main effects is very

complicated because of interactions. More information about the analysis is published elsewhere [14].

The image color accuracy of a typical point-and-shoot camera was initially evaluated using the NIST CQS color chart, with the chart centered in the light booth. Figure 4 shows a boxplot of the CIE LAB color difference ΔE^*_{ab} relative to the reference spectroradiometer data for each color patch in the chart under the daylight fluorescent lamp. Each color is labeled by a number, which was previously identified in Fig. 1. A rough color category (R=red, Y=yellow, G=green, C=cyan, B=blue, M=magenta, W=white, and shades of gray) was added to the label to assist in identifying the color region of each patch. Color patches 3-G, 5-C, 8-G, 13-B, and 17-C were slightly outside the sRGB color gamut (see Fig. 2) for the NIST CQS chart. However, these colors did not consistently produce the largest color errors. The boxplot identifies the span of color difference repeatability data for each patch, in addition to indicating the first and third quartiles, the median, and the mean (circle with cross-hair). The measurement error was dominated by the camera image capture process. The measurement reproducibility average over all the color patches was 1.8 in terms of ΔE^*_{ab} . This value was typical for most camera capture measurements. Although, the pooled chart color difference reproducibility ranged from 0.8 to 3.6, depending on the color chart, illumination conditions, and camera.

Table 2 Color error summary data from point-and-shoot camera images taken of NIST CQS and flesh tone color patches centered in the light booth under various lamp illumination

Lamp illumination	NIST colors mean ΔE^*_{ab}	NIST colors max ΔE^*_{ab}	NIST colors mean ΔE_{00}	Flesh tones mean ΔE^*_{ab}	Flesh tones max ΔE^*_{ab}	Flesh tones mean ΔE_{00}
Daylight fluorescent	12.4	26.3 (at 9-B)	7.0	14.7	15.8 (at 12-FT)	11.4
Incandescent	16.0	37.7 (at 15-Y)	9.1	17.7	24.4 (at 13-FT)	13.0
Cool white fluorescent	14.8	31.9 (at 13-B)	8.8	23.5	30.6 (at 1-FT)	18.8

Fig. 6 Color error for point-and-shoot camera image of flesh tone patches contained within the X-Rite Digital ColorChecker SG color chart when illuminated by a daylight fluorescent, cool white fluorescent, and incandescent lamp in the light booth

In order to simplify comparisons between different measurement conditions, the detailed color data for a given color chart was aggregated into several summary parameters. The data was summarized by calculating the chart mean color or lightness difference of all the patch mean ΔE_{ab}^* and ΔL_{ab}^* , the standard deviation (SD) between patch mean ΔE_{ab}^* within a chart, and the maximum color difference for the patches in a chart. The chart mean CIE DE2000 ΔE_{00} was also calculated to compare the color error values with this color difference formulation. The point-and-shoot camera yielded a NIST CQS chart mean $\Delta E_{ab}^* = 12.4$ (SD=8.0, Max=26.3 at color 9-R, mean $\Delta L_{ab}^* = 5.1$ and $\Delta E_{00} = 7.0$) for the daylight fluorescent lamp. The dependence of mean color difference on lamp illumination for each NIST CQS color patch is shown in Fig. 5. The pooled chart color difference results are summarized in Table 2. This data demonstrates that a typical point-

and-shoot camera can have significant color error encoded within the acquired color image. As illustrated in Fig. 4, the color error of an individual color patch can vary widely. In this case, the maximum patch color error was more than twice that of the chart mean error. For the point-and-shoot camera, the most severe color errors were in the red-yellow and blue regions, while the best results were for the gray shades.

Digital images of the X-Rite Digital ColorChecker SG color chart placed in the center of the light booth were also acquired using the point-and-shoot camera. The color difference ΔE_{ab}^* results for the flesh tone patches in that chart under different lamp illumination are shown in Fig. 6 and summarized in Table 2. The numbering for the flesh tone patches correspond to the patch numbers in the bottom section of the right chart in Fig. 2. The point-and-shoot camera seemed to have particular difficulty with the cool white fluorescent lamp illumination.

Fig. 7 Color error dependence on camera technology for NIST CQS color patches centered in the light booth under daylight fluorescent illumination

Fig. 8 Color error dependence on camera technology for flesh tone patches within an X-Rite Digital ColorChecker SG chart centered in the light booth under daylight fluorescent illumination

The chart mean ΔE_{ab}^* values for the flesh tones were also consistently worse than the more saturated colors in the NIST CQS color chart. These high values are especially concerning, since the human vision system is particularly sensitive to color errors of familiar objects, like human flesh tones.

The impact of camera technology on digital image color accuracy was investigated by comparing the point-and-shoot camera with a cell phone and digital SLR cameras. All cameras were operated in their full automatic image capture mode, and with the cell phone high dynamic range (HDR) function initially turned off. The color accuracy of the three cameras for the NIST CQS color patches and flesh tone patches under daylight fluorescent lamp illumination are given in Figs. 7 and 8. The summary results for the cell phone and digital SLR cameras using all three lamp illumination conditions are tabulated in Tables 3 and 4. The summary data for the NIST CQS in-gamut color patches were similar. The cell phone camera performed the worst in most cases. All cameras exhibited their best results under daylight fluorescent lamp illumination. The digital SLR produced excellent flesh tone accuracy for this illumination. However, this camera's performance was substantially degraded for the incandescent lamp illumination, matching the poor performance of the cell phone camera. Except for the digital SLR camera under daylight fluorescent illumination, all cameras had substantial flesh tone color

errors under the lighting conditions tested. If left uncorrected, most of these color errors would be propagated through the telemedicine workflow and rendered to the viewer.

The cell phone camera color error was also evaluated with the HDR function turned on. In comparing the HDR on versus HDR off condition, each color patch was identified as either saturated, flesh tone, or gray and analyzed according to those groups. Changing the HDR state proved to be statistically significant ($p < 0.05$) for each color group. The overall color error (ΔE_{ab}^*) difference between the HDR off and on states was on average 0.92 for the flesh tones, 3.09 for saturated colors, and -4.01 for the gray shades. Thus, turning on the HDR reduced the color error for flesh tones and saturated colors, but increased the error for gray shades. However, in practice, the cell phone camera image quality with HDR on was sensitive to mechanical and illumination intensity stability.

A common method used in the photography industry to improve the color quality of an image is to place a reference color chart next to the object of interest when capturing the image. Since the color properties of the reference color chart have been previously measured by the vendor, a vendor's color correction software can compare the colors obtained from the captured image of the reference chart to correct the color in the entire image. This process was simulated with the NIST CQS color chart as the test object, and the X-Rite Digital

Table 3 Color error summary data from cell phone camera images (with HDR off) taken of NIST CQS and flesh tone color patches centered in the light booth under various lamp illumination

Lamp illumination	NIST colors mean ΔE_{ab}^*	NIST colors max ΔE_{ab}^*	NIST colors mean ΔE_{00}	Flesh tones mean ΔE_{ab}^*	Flesh tones max ΔE_{ab}^*	Flesh tones mean ΔE_{00}
Daylight fluorescent	18.0	33. (at 13-B)	8.4	19.9	22.7 (at 2-FT)	14.5
Incandescent	23.9	49.9 (at 13-B)	11.0	23.7	31.0 (at 1-FT)	12.4
Cool white fluorescent	22.8	50.9 (at 13-B)	11.2	29.4	37.6 (at 9-FT)	22.8

Table 4 Color error summary data from digital SLR camera images taken of NIST CQS and flesh tone color patches centered in the light booth under various lamp illumination

Lamp illumination	NIST colors mean ΔE_{ab}^*	NIST colors max ΔE_{ab}^*	NIST colors mean ΔE_{00}	Flesh tones mean ΔE_{ab}^*	Flesh tones max ΔE_{ab}^*	Flesh tones mean ΔE_{00}
Daylight fluorescent	10.9	22.2 (at 13-B)	6.0	4.5	6.9 (at 2-FT)	3.1
Incandescent	22.4	48.4 (at 16-M)	12.4	26.5	29.9 (at 4-FT)	10.8
Cool white fluorescent	14.8	33.7 (at 13-B)	8.6	12.1	17.6 (at 9-FT)	9.3

ColorChecker SG color chart as the reference chart. The NIST CQS and X-Rite Digital ColorChecker SG charts were placed beside each other in the light booth (see Fig. 2) and illuminated with the three lamps in sequence. A smaller and more portable X-Rite Passport ColorChecker was also used as a reference chart. It had diffuse reflective color patches, similar in color to the 24 numbered patches in the upper section of the X-Rite Digital ColorChecker SG color chart (see Fig. 2).

Prior to evaluating color correction methods, a study was conducted comparing the relative color errors when all the charts are measured individually in the center of the light booth versus when the NIST CQS chart is placed beside the X-Rite Digital ColorChecker SG or Passport reference chart. Positioning the charts side-by-side offers a faster image capture process that is not subject to changes in the lighting environment. Therefore, this setup was used to evaluate the color correction software. However, the larger area required for the side-by-side configuration make it more sensitive to color errors introduced by lighting non-uniformity. The luminance non-uniformity in the light booth under incandescent illumination was up to 19 % over the X-Rite Digital ColorChecker SG color chart, and up to 20 % between the X-Rite Digital ColorChecker SG and the NIST CQS chart. An analysis of variance performed for each individual color patch indicated that the color error is sensitive to position (centered chart vs. side-by-side charts), but the configuration that produced smaller color errors depended on the type of camera and lamp illumination. Incandescent illumination exhibited the largest illuminance non-uniformity, and was used as a stress case.

The evaluation of color correction software was performed by placing the NIST CQS chart beside the Passport ColorChecker in the light booth under incandescent

illumination. Color images of both charts were taken with the point-and-shoot camera in full automatic mode operation, but flash turned off. Similar images were captured with the NIST CQS chart placed beside the Digital ColorChecker SG chart. All images were then processed by color correction software and saved as JPEG color-corrected images. Image color correction was first attempted using the process defined by the ICC color profile specification standard. X-Rite ProfileMaker 5 software was initially used to create an ICC profile by comparing the image of the reference chart in the light booth to internal color patch reference data measured by X-Rite. The ProfileMaker 5 software was set to create ICC profiles for a general purpose task, and a D65 illuminant destination white point (as required for the sRGB color space). Each uncorrected image, and its corresponding ICC profile, was then imported into Adobe Photoshop CS5 software. By assigning the ICC profile generated by the color correction software to the image, the Photoshop software produced a color-corrected rendering of the image. Photoshop was then used to convert the raw RGB data in the corrected image to values that would preserve the same perceived colors as viewed in the sRGB color space. The Photoshop image data conversion used relative colorimetry for the rendering intent, and applied Adobe's color engine Color Management Model to translate out of gamut colors into the sRGB color space. These color-corrected images were saved as JPEG files and further evaluated for their color accuracy using image processing software. Tables 5 and 6 summarize the percent reduction in color error obtained by this ICC profile process relative to the errors contained in the original images. The ICC profile color correction process implemented with the Passport ColorChecker reference chart produced a modest reduction in the color error. Whereas the Digital ColorChecker SG color reference chart had a factor of two better color error reduction. This improvement is presumably due to the larger sample of colors used to calculate the color correction, and the spatial distribution of white patches that could be used for compensating nonuniform illumination effects.

Although the use of the ICC profile process was demonstrated to reduce the color errors in the original image, its utility in telemedicine applications may be limited. The large size of the Digital ColorChecker SG chart may be impractical in field situations. This may be overcome by miniaturization of the reference chart, and/or advances in the color correction algorithms. The multistep ICC process is also cumbersome, and is

Table 5 Percent reduction in color error of the point-and-shoot camera images when using a Passport ColorChecker reference chart with incandescent lamp illumination

Color correction process	Percent reduction in color error		
	NIST colors mean ΔE_{ab}^*	NIST colors max ΔE_{ab}^*	NIST colors mean ΔE_{00}
Commercial ICC profiler	14 %	16 %	13 %
University Hospital of Ghent Process	44 %	22 %	53 %

Table 6 Percent reduction in color error of the point-and-shoot camera when using a Digital ColorChecker SG reference chart with incandescent lamp illumination. The flesh tone values were obtained from the color corrected image of the Digital ColorChecker SG chart

Color correction process	Percent reduction in color error					
	NIST colors mean ΔE_{ab}^*	NIST colors max ΔE_{ab}^*	NIST colors mean ΔE_{00}	Flesh tones mean ΔE_{ab}^*	Flesh tones max ΔE_{ab}^*	Flesh tones mean ΔE_{00}
Commercial ICC profiler	26 %	40 %	34 %	26 %	12 %	35 %
University Hospital of Ghent Process	53 %	35 %	61 %	72 %	40 %	69 %

difficult to implement in a clinical setting in its current form. In order for a color correction method to be successful, it must be easy to use.

Recent research on image color correction offers an alternative to the current ICC process. Researchers at the University Hospital of Ghent have developed a streamlined image correction process that is tailored for telemedicine applications. Their approach also uses the same reference color charts, but has the promise of eliminating the multistep image color correction by performing these functions automatically in the background. Their software was evaluated with the same set of images used in the ICC profile process. The two methods are compared for a Passport ColorChecker and Digital ColorChecker SG reference chart in Tables 5 and 6, respectively. The University Hospital of Ghent software produced substantial color error reductions, even for the smaller reference chart. This suggests that considerable improvements in color quality of the captured image can be obtained in future telemedicine systems.

Conclusions

The image capture process in a typical telemedicine image workflow was demonstrated to produce substantial color errors, depending on the setup conditions. If not addressed, these errors would be propagated through the digital image workflow to the viewer. Based on average chart color error, the smallest color errors were associated with the SLR camera under daylight illumination, at all positions, and for both flesh tones and saturated colors. In general, the cell phone camera produced the largest color errors. Overall, color errors for gray shades are small compared to errors for saturated colors and flesh tones. The errors can be somewhat reduced by using higher-quality camera technology and by performing the image capture under daylight illumination. Further details of this study are given elsewhere [14]. If the image capture must be done indoors, avoid incandescent lamps and provide uniform illumination on the object. When using the camera in its fully automatic mode, some of the color patches can be overexposed. The proper exposure time should be used, without resorting to the flash. Many higher-quality cameras also offer a white balance adjustment in an effort to improve the

color accuracy. Other valuable recommendations are offered by the American Telemedicine Association [15].

In many situations, the individual taking the image may have limited time and camera options. In that case, the use of a small reference chart placed next to the test object can be a valuable tool. The image can be processed at a later time with color correction software. It was demonstrated that color correction software is able to reduce the color errors in the image by more than half. In addition, efforts by researchers to automate the image color correction process would substantially improve the utility and acceptance of this capability to the image viewer.

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