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Contrast-Gain-Based Visual Tone Mapping for Digital Photo Prints

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Abstract. *With the popularization of digital photo printing, there is a demand for print image quality that approaches the quality of silver halide photographs. One way to achieve this is through automatic correction of image luminance/tone. The conventional approach based on spatially invariant mapping often causes undesired luminance changes when enhancing contrast; moreover, luminance changes are also accompanied by changes in contrast. This paper proposes a novel algorithm for the enhancement of the contrast and lightness using spatially variant mapping to achieve high-quality printing of images photographed using digital cameras. First, we define a "contrast-gain" function to quantitatively evaluate the visual contrast that results from tone mapping. Based on this function, the proposed tone mapping algorithm enables independent control of the lightness and contrast through spatially variant processing. Next, we formalize a "shadow-up tone curve," which produces an effect similar to auxiliary lighting during photography. Our contrast-gain-based visual tone mapping method, which uses the shadow-up tone curve in the algorithm, has none of the unnaturalness that arises with a conventional single tone curve. Furthermore, it provides an extremely natural effect similar to that in images photographed by a professional photographer using auxiliary light provided by a reflection board. © 2006 Society for Imaging Science and Technology.* [DOI: 10.2352/J.ImagingSci.Technol.(2006)50:5(458)]

INTRODUCTION

With the rapid popularization of digital cameras and their broadening user base, users are switching from viewing images saved on a personal computer to viewing printed hard copy images such as conventional silver halide photographs. Users expect more options from digital cameras than merely the convenience of viewing photographed images at the shooting location; they also desire outstanding image quality comparable to that of photographs taken by professionals. In fact, one complaint regarding the image quality of photo prints is that the principal subject (such as a person) appears different in the prints and while shooting. The image is often dark and lacks contrast; this, together with blurring caused by the shaking of the camera, is a chronic problem that typifies poor photographs. One way to rectify this is by automatic image correction. This approach seeks to adjust automatically the luminance and contrast according to the expectations of the photographer. In an actual situation, shooting information in the exchange image file format[1,2] tag stored in the file header of the image taken by a digital camera is accessed, and the type of shot is determined (i.e., whether landscape or portrait). The camera or printer then determines the tone curve most likely to meet the photographer's expectations. However, it is difficult to consistently and automatically determine the optimal tone mapping conditions; hence, the result often fails to meet user expectations.

The various types of tone mapping algorithms are broadly classified into two categories: (1) spatially invariant and (2) spatially variant mappings. Spatially invariant mapping uses a position independent single tone reproduction curve (TRC) for the entire image while spatially variant mapping uses a position dependent tone reproduction operator (TRO) that changes with the spatial position of the pixels in the image.[3,4] Recently, the spatially invariant point process has been evolving into the spatially variant process.

Spatially invariant mappings include a simple linear conversion with gain/offset, nonlinear γ correction,[5] and histogram equalization[6,7] with the TRC determined by the tonal distribution in the image. Further, Tumblin et al. have proposed a dynamic range compression technique[8] that

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maintains the visual brightness of a high dynamic range (HDR) image based on the concept of human vision. Larson et al. have proposed a technique[9] that is based on models of display capabilities and human vision and uses histogram equalization on a HDR image. In all these techniques, the shape of the tone curve is first determined by extracting global features from the entire input image; high-speed processing is then performed via point operations using the TRC. In images where bright and dark regions can be clearly separated, this method results in good dynamic range compression. However, with this kind of spatially invariant mapping, the TRC must be a monotonically increasing function in order to prevent the processing from causing tone inversion. For example, when the image of a person against a dark background is lightened, the background lightens further and the contrast decreases. Therefore, it is impossible to apply a strong correction in many images, and a significant improvement cannot be expected. Another serious problem with spatially invariant mapping is that contrast and brightness cannot be controlled independently.

On the other hand, spatially variant mappings apply a position dependent variable TRO to different parts of an image to realize a flexible tone mapping. Fattal et al.[4] indicated that it is important for the tonal rendition to preserve the local image contrast, i.e., the luminance ratio of a pixel to its local surround. Chiu et al.[10] addressed the problem of global visibility loss by scaling luminance values based on a spatial average of luminances in pixel neighborhoods. Values in bright or dark areas would not be clipped but would be scaled according to different values based on their spatial location.

A different TRO approach is the retinex theory[11] that was proposed by Land as a technique for effectively using spatial information. This theory has been developed into the single-scale retinex (SSR),[12–16] which uses a center-to-surround model where the peripheral visual field is taken as an average by a single-scale Gaussian function. The SSR has been extended to a multiscale retinex[17–19] which integrates multiple-scale SSRs. Kotera has proposed a linear multiscale retinex modle[20] by introducing an adaptive scale-gain function for each center-to-surround-based SSR. These retinex techniques recover the reflectance image under unbiased uniform illumination by considering the luminance ratio of center to surround in the input image. Since the center pixel gain is automatically controlled to get lighter in the dark surround and, *vice versa*, darker in the light surround, the average retinex output tends to concentrate near medium luminance. As a result, shadow visibility is dramatically improved. However, most of the up-to-date retinex models have drawbacks, for example, output image quality is considerably affected by the empirical selection of "clipping points"[21] and the lightness and contrast tend to be corrected too strongly. The major aim of this paper is to improve further high quality raw images that are, nevertheless, insufficient in the shadow area as compared with those taken by professional photographers.

For the dynamic range compression of HDR images using a spatially variant concept, Jobson et al. have extended their retinex model,[22] and Pattanaik et al. have advocated a multiscale approach.[23] Monobe has proposed a local contrast range transform algorithm[24] that aims to maintain the local contrast between input and output after passing through a given TRC. This technique estimates the center to surround change due to the TRC through linear approximation in logarithmic space and emphasizes local contrast to compensate for this change. The technique has been successfully applied to a video camera to improve the highlight contrast that is limited by the knee characteristics; it has also been applied to an image projector to improve the visual contrast under ambient light. These spatially variant mapping algorithms are region-based algorithms that have a degree of freedom in changing the conversion characteristics for each region based on the spatial and local information surrounding the pixel in question. Thus, they can overcome the limitations of spatially invariant mapping.

It is empirically known that while printing an image photographed with a camera, the subject is sometimes printed darker than it appeared when seen directly during shooting. For this reason, professional photographers use the technique of photographing the subject by selectively directing auxiliary light onto the parts of the subject in shadow by using a reflection board (or similar techniques), thereby producing a finished image print with the desired lightness. To achieve a similar effect using the TRC, we realized a desirable shadow-up TRC that selectively lightens only the dark areas without changing the light areas. However, such shadow-up TRCs are difficult to operate because they have an inflection point with a strong nonlinearity. If they are used in a spatially invariant mapping, the dark areas will become lighter; however, there will be an extreme drop in contrast for parts with medium darkness, and the reproduced image will be extremely unnatural. Further, if a highly nonlinear curve of this type is used with the Monobe technique (which allows local contrast to be maintained), the tones will undulate due to errors in estimating the extent of contrast correction, and tone inversion may occur.

This paper proposes a new region-based visual tone mapping method. This method aims to achieve natural photo prints that closely resemble the image seen at the time of shooting—similar to the results obtained when a professional photographer directs light onto dark areas using a reflection board. The proposed method uses a shadow-up TRC that is difficult to operate in the conventional TRC or TRO; however, it enables the local contrast for an arbitrary type of TRC to be maintained. The first step is to define a contrast gain (*Cgain*); it uses the input/output ratio of the Weber contrast for the quantitative assessment of visual contrast changes due to tone mapping. Using *Cgain*, we measured changes in visual contrast for the well-known histogram equalization method and for a typical shadow-up TRC technique. The results show that *Cgain* is effective as a measure of the change in visual contrast due to tone mapping. Next, a new spatially variant mapping algorithm that enabled independent control of lightness and contrast was derived by applying *Cgain* to spatially variant mapping. The proposed algorithm can achieve a natural improvement in the lightness of dark areas while maintaining the local contrast of the input image. It also resolves the previously mentioned drawbacks in retinex when applied to professional digital photography and yields stable natural effects similar to those obtained by actually focusing light on the parts in shadow using a reflection board.

CONTRAST-GAIN (CGAIN)

A new criterion, *Cgain*, is introduced to evaluate the changes in visual contrast between input and output through the TRC. The following have been proposed as definitions of contrast:[25,26]

$$\text{(A) Simple contrast } (C_R) \quad C_R = \frac{L_{MAX}}{L_{MIN}}, \tag{1}$$

$$\text{(B) Michelson contrast } (C_M) \quad C_M = \frac{L_{MAX} - L_{MIN}}{L_{MAX} + L_{MIN}}, \tag{2}$$

$$\text{(C) Weber contrast } (C_W) \quad C_W = \frac{\Delta L}{L}, \tag{3}$$

where L_{MAX} and L_{MIN} are the luminances in the brightest and darkest parts.

Simple contrast is called the contrast ratio and is principally used to represent the dynamic range of a display. Michelson contrast defines a modulation transfer function on a periodic striped pattern of light and darkness. Further, when the difference between the light and dark is narrowed, the following relations are assumed: $L_{MAX}+L_{MIN}\rightarrow 2L$ and $L_{MAX}-L_{MIN}\rightarrow 2\Delta L$. This definition then agrees with the definition of the Weber contrast, which is visual contrast based on the visual differential luminance threshold (ΔL) relative to luminance (L) in accordance with Weber's law. It is also a function of the luminance level and is suitable for evaluating the contrast for each tone level.

Cgain is defined here as a function for evaluating visual contrast changes due to tone mapping. When defined as the ratio of the Weber contrast $Cwg(x,y)$ of the output level $g(x,y)$ to the Weber contrast $Cwf(x,y)$ of the input level $f(x,y)$, it is given by the following partial differential equation:

$$Cgain(x,y) = \frac{Cwg(x,y)}{Cwf(x,y)} = \left[\frac{dg(x,y)}{g(x,y)} \Big/ \frac{df(x,y)}{f(x,y)} \right]. \tag{4}$$

Let $F(x,y)$ and $G(x,y)$ be $f(x,y)$ and $g(x,y)$ converted to logarithmic space, then Eq. (4) is rewritten as

$$Cgain(x,y) = \frac{dG(x,y)}{dF(x,y)}. \tag{5}$$

This signifies the slope when input and output are viewed in logarithmic space.

If the tone mapping function $P(t)$ is denoted as

$$g(x,y) = P[f(x,y)], \tag{6}$$

then Eq. (4) is given by the following equation:

$$Cgain(x,y) = \frac{f(x,y)}{P[f(x,y)]} \cdot \frac{dP[f(x,y)]}{df(x,y)}. \tag{7}$$

Further, consider the case where the input and output are gamma-corrected (normally, camera gamma $\gamma = 1/2.2$) luminance signals $f_g(x,y)$ and $g_g(x,y)$,

$$f_g(x,y) = f(x,y)^{\gamma}, \tag{8}$$

$$g_g(x,y) = g(x,y)^{\gamma}. \tag{9}$$

Letting $P_g(t)$ be a tone mapping function with a gamma-corrected scale, we obtain

$$g_g(x,y) = P_g[f_g(x,y)]. \tag{10}$$

The relationship with the linear scale tone mapping function $P(t)$ is now derived from Eqs. (6) and (8)–(10) as follows:

$$P[f(x,y)] = P_g[f(x,y)^{\gamma}]^{\frac{1}{\gamma}}. \tag{11}$$

Cgain with a gamma-corrected scale then resembles Eq. (7),

$$Cgain(x,y) = \frac{f_g(x,y)}{P_g[f_g(x,y)]} \cdot \frac{dP_g[f_g(x,y)]}{df_g(x,y)}. \tag{12}$$

See the Appendix (Appendix available as Supplemental Material on the IS&T website, www.imaging.org).

Evaluation of TRCs Using Cgain

Owing to its definition, *Cgain* can be applied to tone mapping regardless of whether the mapping is spatially invariant or variant; thus, it can be used to compare the characteristics of the two approaches. This section evaluates two types of typical TRCs used for spatially invariant mapping as examples and focuses on contrast enhancement and lightness conversion characteristics.

Evaluation of Tone Mapping for Contrast Enhancement

First, *Cgain* is applied to evaluate histogram equalization[6,7] as a typical form of tone mapping intended for contrast enhancement. The tone curve $P_g(t)$ that equalizes the histogram $h_g(t)$ for a gamma-corrected luminance scale is given by

$$P_g[f_g(x,y)] = \int_0^{f_g(x,y)} h_g(t)dt. \tag{13}$$

Cgain for this is

$$Cgain(x,y) = \frac{f_g(x,y) \cdot h_g[f_g(x,y)]}{\int_0^{f_g(x,y)} h_g(t)dt}, \tag{14}$$

where t represents the tone level.

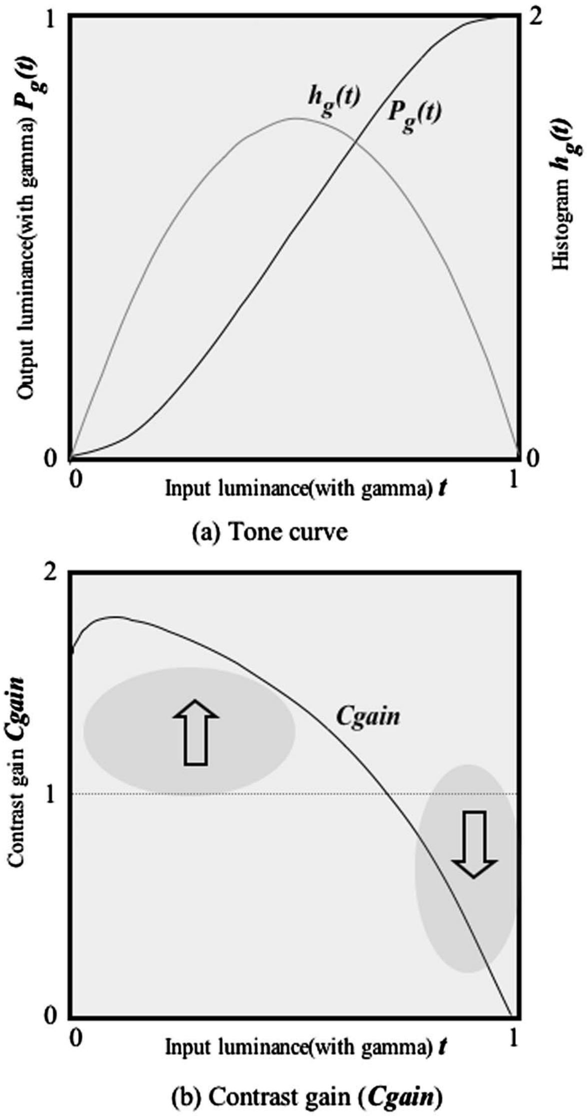

Figure 1. Tone curve and contrast gain (*Cgain*) for histogram equalization.

Figures 1(a) and 1(b) show an example of a TRC and its *Cgain* for a typical histogram $h_g(t)$, where tonal levels are concentrated in the middle range. In this case, $P_g(t)$ for the tone conversion curve is an S curve. As can be seen in the figure, *Cgain* takes a value higher than 1.0 over the wide range of shadow to upper middle range with increasing contrast but drops abruptly in the light areas with decreasing contrast.

Evaluation of Tone Mapping for Luminance Conversion

In conventional silver halide photography, the shadow areas are often printed darker than they actually appear during shooting. This is especially true for photography under backlighting conditions. Professional photographers obtain the desired brightness by using a technique where they selectively focus auxiliary light on parts of the subject in shadow by using a reflection board (or a similar technique).

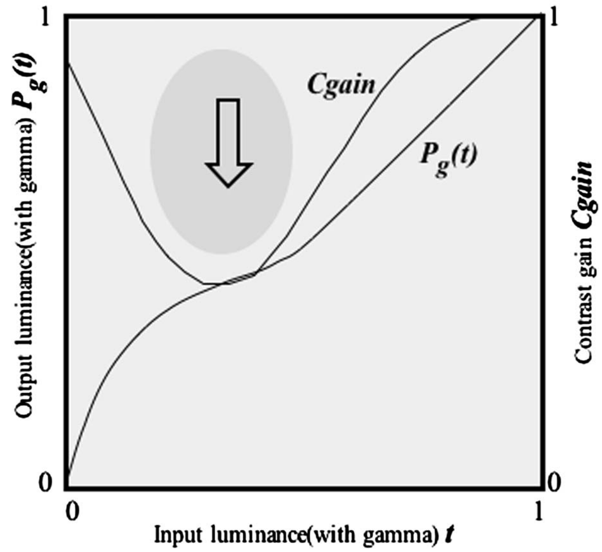

Figure 2. Tone curve and contrast gain (*Cgain*) using shadow-up TRC.

If an attempt is made to achieve a similar effect by tone curve manipulation, a TRC that selectively lightens only the shadow regions should be selected.

Here, the term "*stone*" refers to an example of such a shadow-up TRC.

$$P_g[f_g(x,y)] = stone[f_g(x,y)]. \tag{15}$$

From Eq. (12), *Cgain* in this case is

$$Cgain(x,y) = \frac{f_g(x,y)}{stone[f_g(x,y)]} \cdot \frac{dstone(f_g(x,y))}{df_g(x,y)}. \tag{16}$$

Figure 2 shows *Cgain* for *stone*. It drops to less than 1.0 in almost all ranges except the upper range, and a particularly extreme drop in *Cgain* is evident in the tones of areas with medium darkness that are slightly above the maximum shadow. This extreme drop in visual contrast at the region of medium tone (which is critical for image quality) is thought to be the reason for the resulting images that are extremely unnatural (See Figs. 10, 14(b), and 15(b), and Fig. 16(b) later).

In addition, a TRC that selectively lightens only the shadow regions results in an unnatural image—this fact is empirically known with regard to normal retouching. Thus the approach of lightening only the shadow regions is abandoned, and instead, a TRC such as gamma correction is used for lightening. However, although such a smooth curve causes the overall contrast to decrease, an unnatural image can be avoided because there is no contrast decrease for specific tones. Thus, it is clear that the cause of unnatural images is the extreme contrast decrease in specific tone ranges (due to tone conversion that lightens shadow ranges).

As illustrated in the above examples, the evaluation using *Cgain* agrees with our empirical experience in the selection of the TRC.

METHOD

Cgain-Based Spatially Variant Mapping Algorithm

Using spatially variant tone mapping employing the local contrast concept based on a center to surround model, the output image level $g(x,y)$ is determined by the ratio of the luminance $f(x,y)$ of the center pixel to the luminance $f_{ave}(x,y)$ of the surround. If we call this transfer function "tsf" then

$$g(x,y) = \mathrm{tsf}[f(x,y), f_{ave}(x,y)]. \tag{17}$$

The global change in the tone when tsf applies to the overall image can be regarded as a change in tone over a region broader than the local region. As the global TRC is denoted by $P(t)$,

$$\mathrm{tsf}[f_{ave}(x,y), f_{ave}(x,y)] = P[f_{ave}(x,y)]. \tag{18}$$

The average surrounding luminance $f_{ave}(x,y)$ of the pixel in question is calculated using the following Gaussian-filter

$$f_{ave}(x,y) = \langle W(x,y) \otimes f(x,y) \rangle, \tag{19}$$

where $\otimes$ denotes the convolution integral. Further,

$$W(x,y) = K \exp\left\{ \frac{-(x^2+y^2)}{\sigma^2} \right\}, \tag{20}$$

where

$$\int\int W(x,y)dxdy = 1. \tag{21}$$

Cgain for a spatially variant mapping is a function of $f_{ave}(x,y)$ and not merely $f(x,y)$, depending on the local contrast at the pixel location (x,y),

$$Cgain(x,y) = \frac{f(x,y)}{\mathrm{tsf}[f(x,y), f_{ave}(x,y)]} \cdot \frac{d\mathrm{tsf}[f(x,y), f_{ave}(x,y)]}{df(x,y)}. \tag{22}$$

Equation (22) is converted to integral form as follows:

$$\int \frac{1}{\mathrm{tsf}[f(x,y), f_{ave}(x,y)]} d\mathrm{tsf}[f(x,y), f_{ave}(x,y)] = \int \frac{Cgain(x,y)}{f(x,y)} df(x,y). \tag{23}$$

Solving Eq. (23), we obtain

$$\log \mathrm{tsf}[f(x,y), f_{ave}(x,y)] = Cgain(x,y) \cdot \log f(x,y) + c1, \tag{24}$$

where $c1$ is a constant of integration and

$$c2 = e^{c1}.$$

Hence,

$$\mathrm{tsf}[f(x,y), f_{ave}(x,y)] = c2 \cdot f(x,y)^{Cgain(x,y)}. \tag{25}$$

Further, from Eq. (18), we obtain

$$c2 = \frac{P[f_{ave}(x,y)]}{f_{ave}(x,y)^{Cgain(x,y)}}. \tag{26}$$

Therefore, the spatially variant mapping algorithm based on *Cgain* can be expressed using the following equation:

$$g(x,y) = \frac{P[f_{ave}(x,y)]}{f_{ave}(x,y)^{Cgain(x,y)}} \cdot f(x,y)^{Cgain(x,y)}. \tag{27}$$

The above equation shows that $P(t)$ and *Cgain* can be set independently with this algorithm.

Spatially Variant Contrast Enhancement Without Changing Lightness

As a simple application of the spatially variant mapping algorithm derived in the previous section, this section considers contrast enhancement for uniformly enhancing visual contrast over the entire tone range without changing the lightness sensation.

Cgain is defined as the constant β ($\beta > 1$),

$$Cgain(x,y) = \beta. \tag{28}$$

To maintain the overall luminance of the image after passing through a TRC, the following condition should be fulfilled:

$$P[f_{ave}(x,y)] = f_{ave}(x,y). \tag{29}$$

Substituting the above conditions in Eq. (27), we obtain a contrast enhancement based on a spatially variant mapping; it emphasizes the local contrast β times

$$g(x,y) = \frac{1}{f_{ave}(x,y)^{\beta-1}} \cdot f(x,y)^{\beta}. \tag{30}$$

From Eqs. (8) and (9), the output in the luminance scale using camera gamma is

$$g_g(x,y) = \frac{1}{f_{ave}(x,y)^{\gamma \cdot (\beta-1)}} \cdot f_g(x,y)^{\beta}. \tag{31}$$

A diagram plotting the family of tone conversion curves $g_g(x,y)$ with β=1.5 is shown in Fig. 3. When $f_{ave}(x,y)$ is small, i.e., when the surround of the pixels in question is dark, a high gain TRC is selected. When the surround is lighter, a low gain curve is selected.

As compared with histogram equalization described in the preceding section, the enhancement of contrast by spatially variant mapping has several advantages as follows:

- it provides a consistent effect without being influenced by the bias in luminance distribution;
- it does not change the overall luminance of the image; and
- it provides a consistent contrast emphasis for all tones.

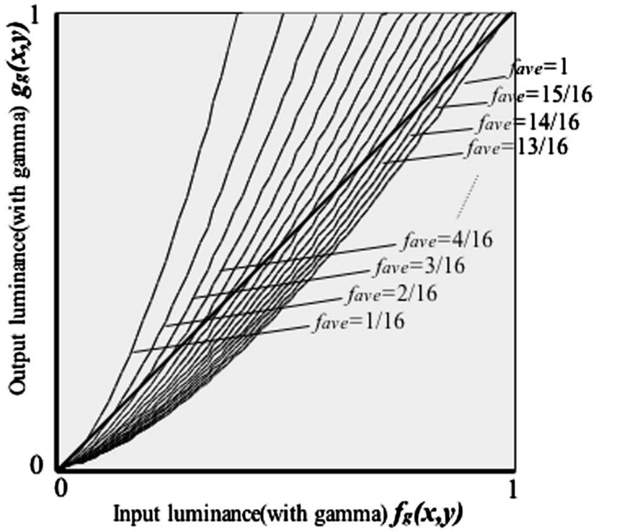

Figure 3. Tone conversion function of a contrast enhancement ($Cgain$=1.5) for each luminance level of the surroundings.

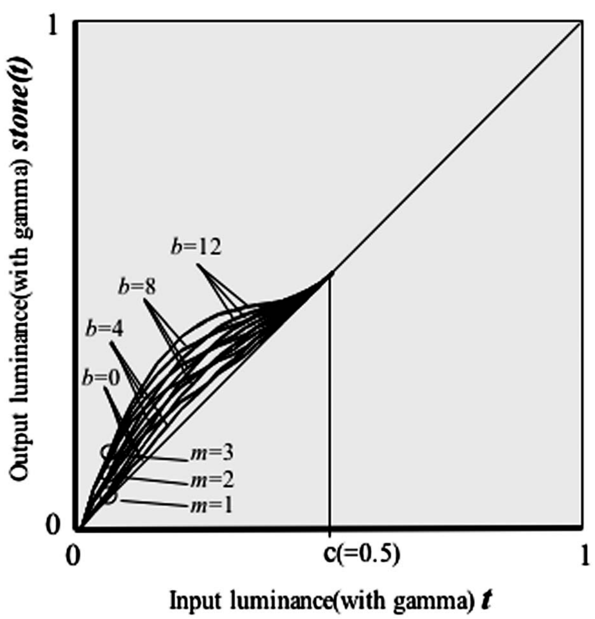

Figure 4. Shadow-up TRC (*stone*).

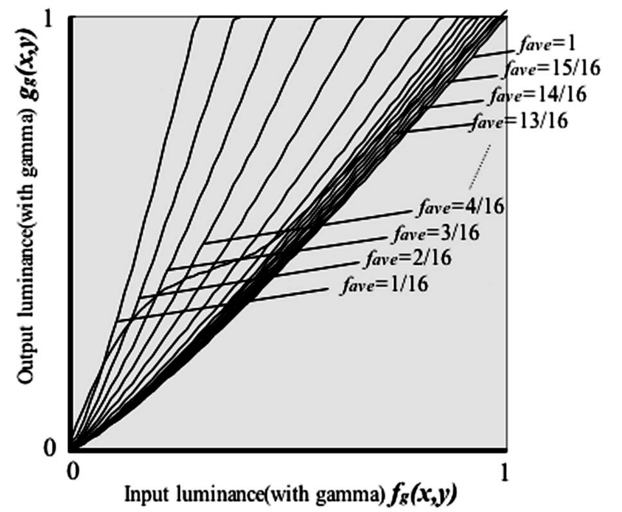

Figure 5. Tone conversion function by proposed method with shadow-up TRC for each luminance level of the surroundings ($Cgain$=1.2).

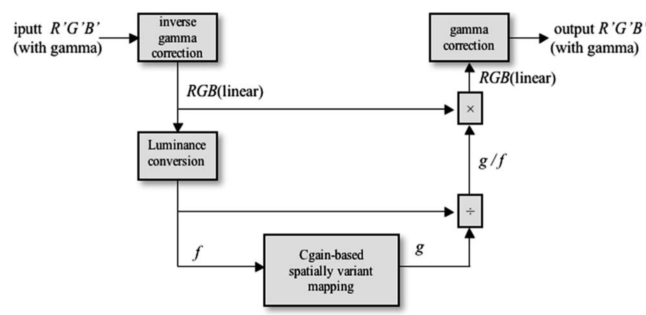

Figure 6. Procedure for applying proposal method to a color image.

Spatially Variant Shadow-Up Mapping Without Changing Contrast

This section describes an application of the spatially variant mapping algorithm for lightness conversion. Here we use the previously mentioned shadow-up TRC referred to as *stone*. First, *stone* is parametrized using the following equations. Here, t is luminance level determined using camera gamma

$$stone(t)=\begin{cases}(a(t-c)^3+b(t-c)^2+1)\cdot t & (t\leqslant c)\\ t & (t>c),\end{cases} \quad (32)$$

$$stone'(0)=m, \quad (33)$$

where c is the upper limit when increasing the luminance in shadow areas and m is the gain in deep shadow areas. The *stone* function monotonically increases from the onset with the condition that areas are not darkened

$$stone(t)\geqslant t. \quad (34)$$

Thus

$$a=\frac{bc^2+1-m}{c^3}, \quad (35)$$

$$b\geq 0. \quad (36)$$

This function allows control by means of the three coefficients b, c, and m. Figure 4 depicts the function when b and m are changed.

With regard to the tone conversion, the condition that only shadow ranges using the shadow-up function are lightened is given by Eq. (10) as

$$P[f(x,y)]=stone[f(x,y)^{\gamma}]^{\frac{1}{\gamma}}. \quad (37)$$

Let the contrast enhancement condition be $Cgain(x,y)=\beta$.

From Eq. (18), we obtain the spatially variant tone mapping function for selectively lightening the shadow areas as

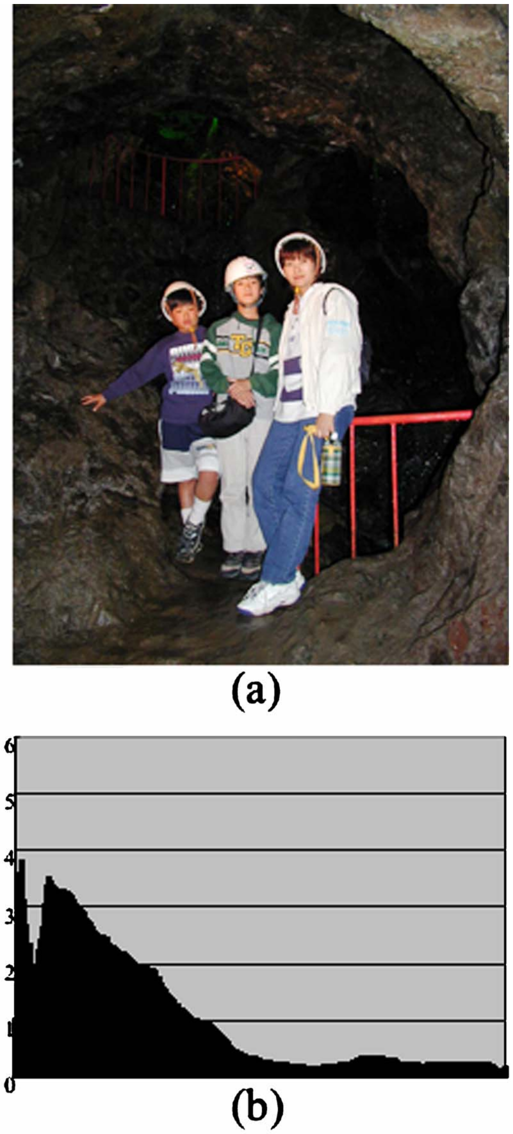

Figure 7. Original image (a) and histogram (b).

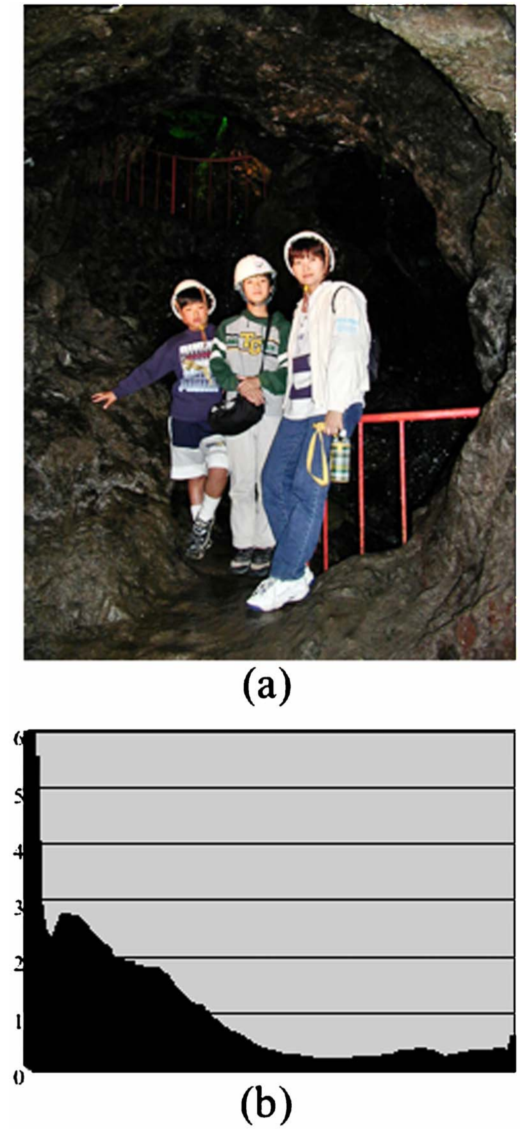

Figure 8. Image by the proposed contrast enhancement: (a) (*Cgain* =1.5) and histogram (b).

$$g(x,y) = \frac{stone[f_{ave}(x,y)^{\gamma}]^{\frac{1}{\gamma}}}{f_{ave}(x,y)^{\beta}} \cdot f(x,y)^{\beta}. \quad (38)$$

Finally, with Eqs. (8) and (9), the enhanced luminance output with camera gamma is described by

$$g_g(x,y) = \frac{stone[f_{ave}(x,y)^{\gamma}]}{f_{ave}(x,y)^{\gamma \cdot \beta}} \cdot f_g(x,y)^{\beta}. \quad (39)$$

This represents a *Cgain*-based spatially variant shadow-up function with $Cgain=\beta$.

The proposed function when $\beta=1.2$, $c=0.5$, $m=3$, and $b=0$ is shown in Fig. 5.

EXPERIMENTS

The procedure for applying the proposed *Cgain*-based tone mapping to a color image is illustrated in Fig. 6. A linear *RGB* image is transformed into the luminance image *f* through *RGB* to *YCC* conversion after applying inverse gamma correction to a camera signal. Only this single luminance channel is processed using the proposed method to obtain the output luminance image *g*. The output linear *RGB* image is generated by multiplying the ratio of luminance levels before and after processing with the input *RGB*. Following this, the output *RGB* image is obtained by applying a gamma correction to display it on an *sRGB*-calibrated device. Further, the changes in hue and saturation are suppressed by an inverse transform from *YCC* to *RGB* using the output luminance image *g* without changing the *CC* components.

First, we compare the proposed method (spatially variant contrast enhancement) with the conventional technique (histogram equalization) in terms of contrast enhancement.

Figure 7(a) shows an original image taken with an elec-

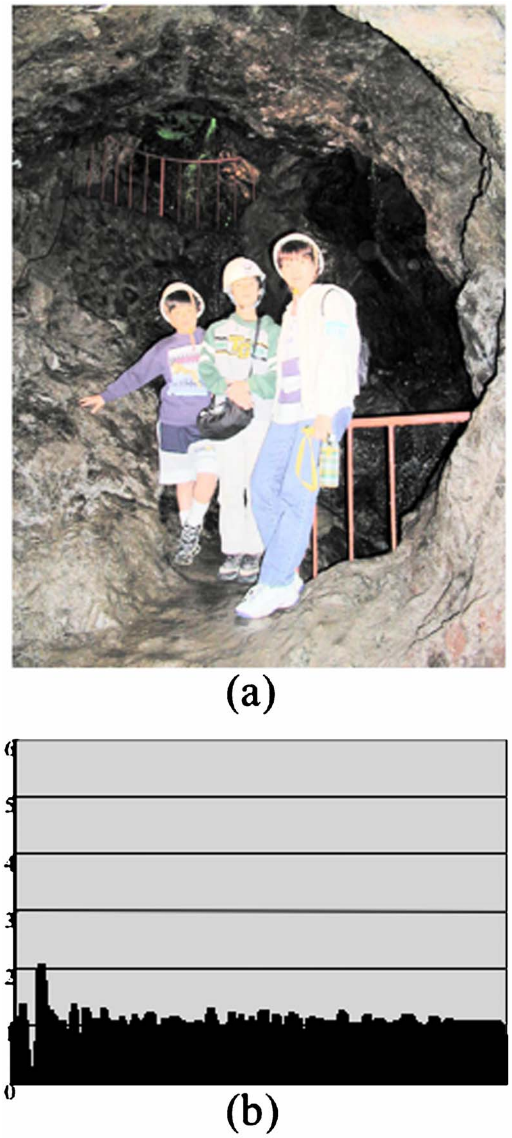

Figure 9. Image by the conventional histogram equalization (Adobe PhotoShop™ Ver.7) image (a) and histogram (b).

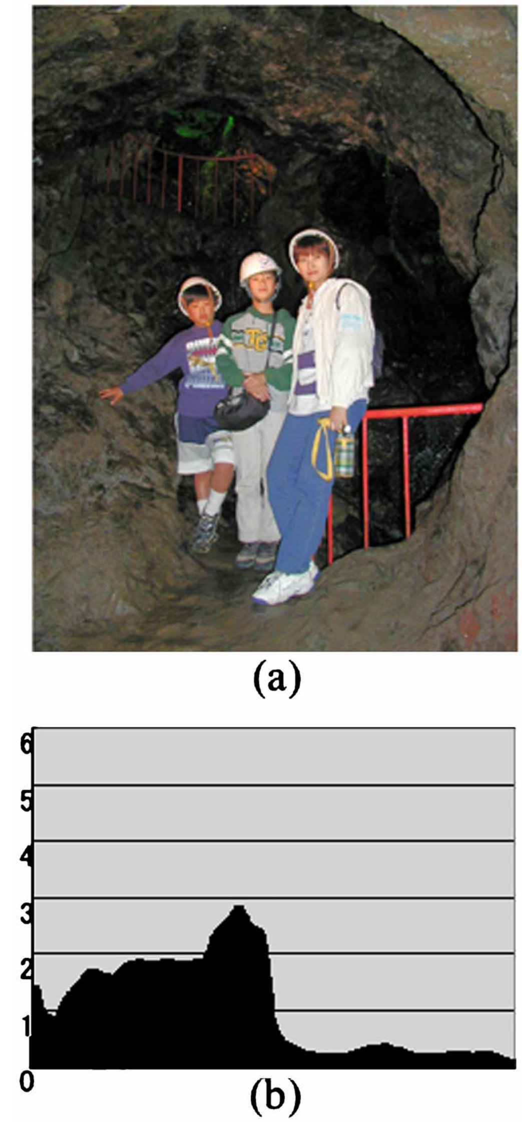

Figure 10. Image by the conventional method using shadow-up TRC (a) and histogram (b).

tronic flash in a dark cave. Since more light from the flash has fallen on the foreground than on the background, only the main subjects are brightly lit in a small area. In contrast, the background is dark and covers a broad area. Figure 7(b) shows a luminance histogram of this image.

Figure 8 shows (a) an image with visual contrast enhanced 1.5 times by the proposed method based on Eq. (30) without changing the lightness and (b) the resultant luminance histogram. Figure 9 is an image in which contrast is enhanced using the histogram equalization process in Adobe PhotoShop™ 7.0. In Fig. 9, the contrast is enhanced by equalizing the tonal distribution (the shadow ranges are extended toward lighter regions); however, the main photographic subject is extremely light and contrast decreases. On the other hand, the proposed method maintains the histogram in almost its original shape and enhances the contrast without changing the visual impression of the photograph or its overall lightness. Next, we present the experimental results of lightness correction using the previously mentioned shadow-up TRC *stone*.

Figure 10 is an image processed using *stone* as a conventional single TRC. In histogram (b), the distribution of the shadow ranges is shifted to the right as compared with the original image, and thus, the dark rock surface becomes brighter. However, there is a significant drop in contrast and therefore, the image is unnatural. In addition, features such as the subject's hair become brighter, and the contrast is lost. On the other hand, in Fig. 11, in which *stone* is used by setting *Cgain* to 1.0 in the proposed technique, the shape of the histogram is almost the same as in Fig. 10; the overall lightness of the image is also the same. As expected, the contrast in the original image is maintained even at the rock surface which has become brighter. An image quality with

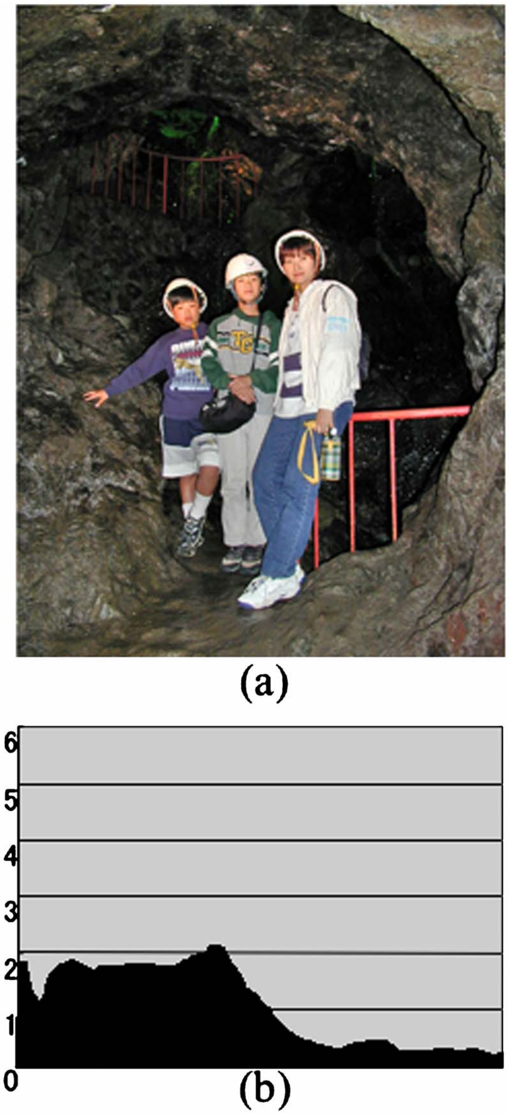

Figure 11. Image by the proposed method using shadow-up TRC (a) and histogram (b).

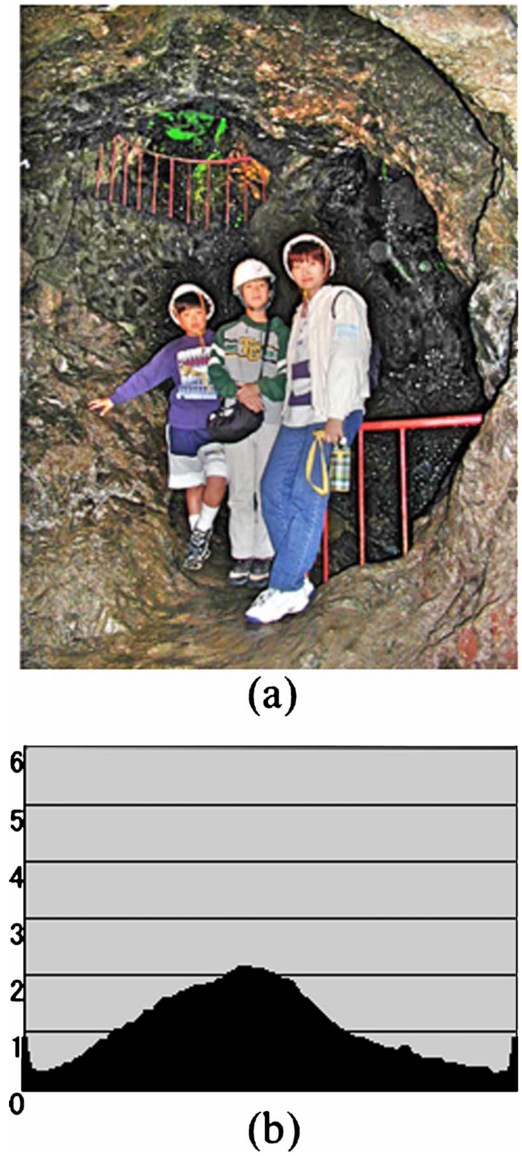

Figure 12. Image by retinex of Kotera (a) and histogram (b).

the expected impression is obtained; i.e., there is a naturally illuminated effect as would have been obtained if the background in the original image was lit with auxiliary light. Figure 12 is an image processed using the retinex model described by Kotera. Due to its elimination of the nonuniformity of illumination, the image becomes brighter up to the depths of the cave and contrast is also enhanced excessively. A tendency toward the formation of clusters in the center is also evident in histogram (b).

Since it is hard to differentiate between Figs. 10 and 11 based on the shape of the histogram, the difference is evaluated using *Cgain*.

In Fig. 13, (a) is the original image, (b) is an image obtained by using a spatially invariant shadow-up TRC, (c) is an image obtained by using the proposed *Cgain*-based spatially variant shadow-up mapping (with $Cgain=1.0$), and (d) is an image obtained by using the proposed method (with $Cgain=1.2$). Further, from the top of the figure, (1) is the image and (2) is a graph indicating the luminance value of the horizontal line at the center of the image. The light gray traces in these graphs of (b), (c), and (d) present the luminance values of the original image for the purpose of comparison; (3) is the *Cgain* value for the same position as (2). From the *Cgain* graph (b2) for the image using a TRC, Cgain is less than 1.0 in most parts of the image. In addition, the points with decreasing *Cgain* are the same as the unnatural parts of the image. With the proposed technique (c), the global lightness of the image using *stone* is the same as in (b); however, *Cgain* is almost constant at 1.0 and the visual contrast agrees with that of the original image. In (d), *Cgain* is maintained at almost 1.2 and visual contrast is enhanced as compared with (c).

Figures 14–16 show four more images for evaluation. They are (a) the original image, (b) an image processed us-

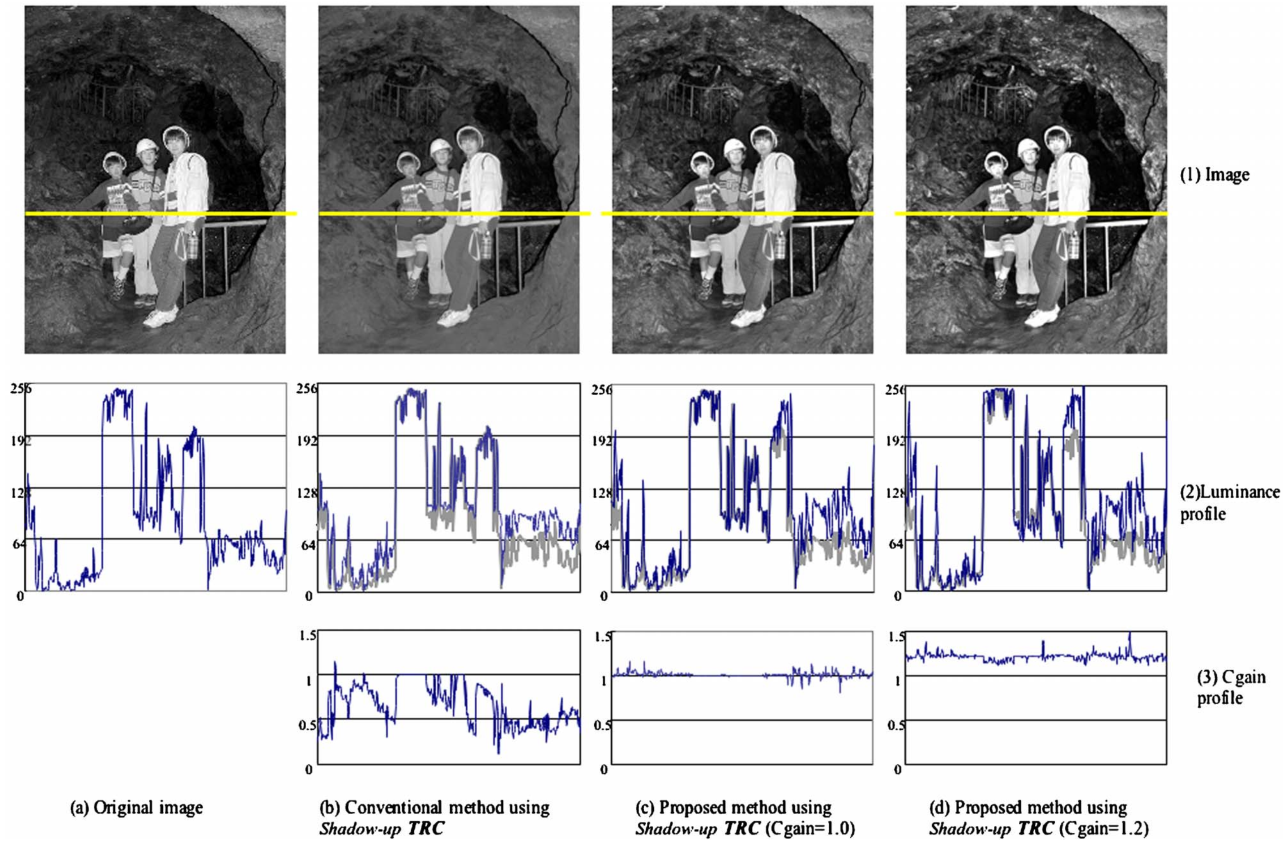

Figure 13. Luminance and *Cgain* profiles of each evaluation images. (a) Original image, (b) conventional method using shadow-up TRC, (c) proposed method using Shadow-up TRC (*Cgain*=1.0), (d) proposed method using shadow-up TRC (*Cgain*=1.2), (1) image, (2) luminance profile, and (3) *Cgain* profile.

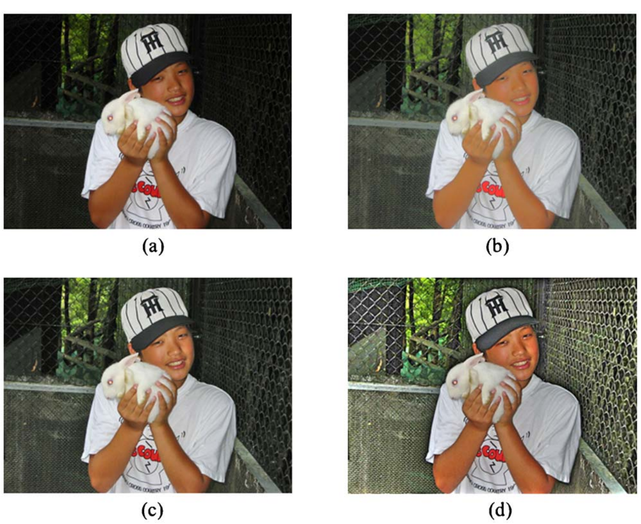

Figure 14. (a) The original image, (b) conventional method, (c) proposed method, and (d) retinex by Kotera

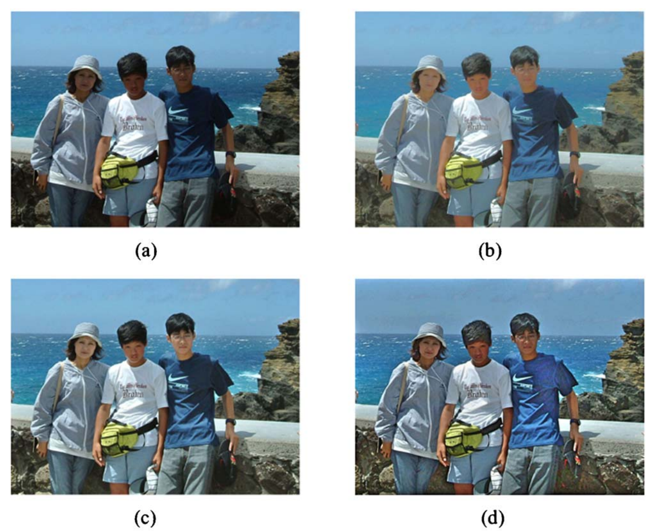

Figure 15. (a) The original image, (b) conventional method, (c) proposed method, and (d) retinex by Kotera.

ing a shadow-up TRC, (c) an image processed using the proposed method, and (d) an image processed using the retinex method described by Kotera. Images designated (b) appear unnatural due to a decrease in contrast at the medium ranges. The effect of eliminating unevenness in illumination is evident in (d); however, the lightness correction in Figs. 14 and 15 is too strong and in Fig. 16 it is weak, and the contrast creates varying impressions depending on the picture. In all the images, only (c) creates a good effect that is closest to natural illumination.

These results illustrate the effectiveness of the *Cgain*-based visual tone mapping method using *stone*, which en-

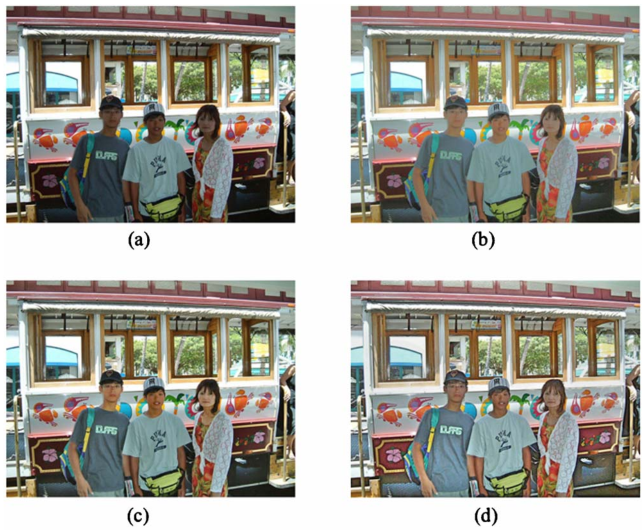

Figure 16. (a) The original image, (b) conventional method, (c) proposed method, and (d) retinex by Kotera.

ables the lightening of only the dark areas (it is a curve that considers *Cgain* as a measure of visual contrast and maintains it at a specified value).

CONCLUSION

This paper defined *Cgain* as an evaluation function for quantitatively evaluating changes in visual contrast due to tone mapping and showed that it is an effective quality measure of visual contrast. Based on this function, we proposed a spatially variant mapping algorithm that can simultaneously achieve tonal rendition corresponding to the desired global TRC and visual contrast.

We also formalized a shadow-up TRC that provides an effect similar to that when auxiliary light is provided with a reflection board in professional photography. It was shown that the *Cgain*-based spatially variant shadow-up mapping algorithm could achieve a natural image quality similar to that obtained by focusing light on shadow areas; this cannot be obtained by a conventional spatially invariant TRC.

In comparison with the spatially invariant TRC and retinex approaches, the proposed technique enables an amateur photograph to be converted into a professional quality one with regard to visual contrast and naturalness; further, it is applicable to sufficiently high quality images shot with a digital camera. This novel technology can be widely applied not only to photo printers but also to provide backlighting compensation for digital cameras, video movies, displays, etc.

Nonetheless, in Figs. 3 and 5, the gain is high and the light areas are saturated for a curve when $f_{ave}(x,y)$ is small, i.e., when the surroundings are dark. Therefore, there is a possibility that unnatural image artifacts may have appeared. With actual photographs in settings involving a large number of pixels and dark surrounds—for example, stars in the night sky—the tone of the bright object (stars) would pose a slight problem. This is undesirable in the proposed tone conversion method. Therefore, in the future we intend to examine the possibility of improvements that will provide an unsaturated characteristic to the algorithm of this technique.

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