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An Efficient Linear Programming Approach for Optimal Contrast-Tone Mapping

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ABSTRACT*:* This paper proposes a novel algorithmic approach of image enhancement via optimal contrast-tone mapping. In a fundamental departure from the current practice of histogram equalization for contrast enhancement, the proposed approach maximizes expected contrast gain subject to an upper limit on tone distortion and optionally to other constraints that suppress artifacts. The underlying contrast-tone optimization problem can be solved efficiently by linear programming. This new constrained optimization approach for image enhancement is general, and the user can add and fine tune the constraints to achieve desired visual effects. Experimental results demonstrate clearly superior performance of the new approach over histogram equalization and its variants.

KEYWORDS: Contrast enhancement, dynamic range, his-to gram equalization, linear programming, tone reproduction.

I. INTRODUCTION

In most image and video applications it is human viewers that makes the ultimate judgment of visual quality. They typically associate high image contrast with good image quality .Indeed, a noticeable progress in image display and generation (both acquisition and synthetic rendering) technologies are the increase of dynamic range and associated image enhancement techniques [1].

The contrast of a raw image can be far less than ideal, due to various causes such as poor illumination conditions, low quality inexpensive imaging sensors, user operation errors, media deterioration (e.g., old faded prints and films), etc. For improved human interpretation of image semantics and higher perceptual quality, contrast enhancement is often performed and it has been an active research topic since early days of digital image processing, consumer electronics and computer vision. Contrast enhancement techniques can be classified into two approaches: context-sensitive (point-wise operators) and context-free (point operators). In context-sensitive approach the contrast is defined in terms of the rate of change in intensity between neighboring pixels. The contrast is increased by directly altering the local waveform on a pixel by pixel basis. For instance, edge enhancement and high-boost filtering belong the context-sensitive approach. Although intuitively appealing the context-sensitive techniques are prone to artifacts such as ringing and magnified noises, and they cannot preserve the rank consistency of the altered intensity levels. The context-free contrast enhancement approach, on the other hand, does not adjust the local waveform on a pixel by pixel basis. Instead, the class of context-free contrast enhancement techniques adopts a statistical approach. They manipulate the histogram of the input image to separate the gray levels of higher probability further apart from the neighboring gray levels. In other words, the context-free techniques aim to increase the average difference between any two altered input gray levels. Compared with its context-sensitive counterpart, the context-free approach does not suffer from the ringing artifacts and it can preserve the relative ordering of altered gray levels. Despite more than half a century of research on contrast enhancement, most published techniques are largely ad hoc. Due to the lack of a rigorous analytical approach to contrast enhancement, histogram equalization seems to be a folklore synonym for contrast enhancement in the literature and in textbooks of image processing and computer vision. The justification of histogram equalization as a contrast enhancement technique is heuristic, catering to an intuition. Low contrast corresponds to a biased histogram and, thus, can be rectified by reallocating underused dynamic range of the output device to more probable pixel values. Although this intuition is backed up by empirical observations in many cases, the relationship between histogram and contrast has not been precisely quantified. No mathematical basis exists for the uniformity or near uniformity of the processed histogram to be an objective of contrast enhancement in general sense. On the contrary, histogram equalization can be detrimental to image interpretation if carried out mechanically without care. In lack of proper constraints histogram equalization can over shoot the gradient amplitude in some narrow intensity range(s) and flatten subtle smooth shades

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in other ranges. It can bring unacceptable distortions to image statistics such as average intensity, energy, and covariances, generating unnatural and incoherent 2-D wave- forms. To alleviate these shortcomings, a number of different techniques were proposed to modify the histogram equalization algorithm [2]–[7]. This line of investigations was initiated by Pisano *et al.* in their work of contrast-limited adaptive histogram equalization (CLAHE) [8]. Somewhat ironically, these authors had to limit contrast while pursuing contrast enhancement. Recently, Arici *et al.* proposed to generate an intermediate histogram in between the original input histogram and the uniform histogram and then performs histogram equalization of. The in-between histogram is computed by minimizing a weighted distance.

The authors showed that undesirable side effects of histogram equalization can be suppressed via choosing the Lagrangian multiplier. This latest paper also gave good synopses of existing contrast enhancement techniques. We refer the reader to [9] for a survey of previous works, instead of reparaphrasing them here.

Compared with the aforementioned works on histogram-

Based contrast enhancement techniques, this paper present a more rigorous study of the problem. We reexamine contrast enhancement in a new perspective of optimal allocation of output dynamic range constrained by tune continuity. This brings about a more principled approach of image enhancement. Our critique of the current practice is that directly manipulating histograms for contrast enhancement was ill conceived. The histogram is an unwieldy, obscure proxy for contrast. The wide use of histogram equalization as a means of context-free contrast enhancement is apparently due to the lack of a proper mathematical formulation of the problem. To fill this void we define an expected (con- text-free) contrast gain of a transfer function. This relative mea- sure of contrast takes on its base value of one if the input image is left unchanged (i.e., identity transfer function), and increases if a skewed histogram is made more uniform. However, perceptual image quality is more than the single aspect of high contrast. If the output dynamic range is less than that of the human visual system, which is the case for most display and printing technologies, context-free contrast enhancement will inevitably distort subtle tones. To balance between tone subtlety and contrast enhancement we introduce a counter measure of tone distortion. Based upon the said measures of contrast gain and tone distortion, we formulate the problem of optimal contrast-tone map-ping (OCTM) that aims to achieve high contrast and subtle tone reproduction at the same time, and propose a linear programming strategy to solve the underlying constrained optimization problem. In the OCTM formulation, the optimal transfer function for images of uniform histogram is the identify function.

Although an image of uniform histogram cannot be further enhanced, histogram equalization does not produce OCTM solutions in general for arbitrary input histograms. Instead, the proposed linear programming-based OCTM algorithm can optimize the transfer function such that sharp contrast and subtle tone are best balanced according to application requirements and user preferences. The OCTM technique offers a greater and more precise control of visual effects than existing techniques of contrast enhancement. Common side effects of contrast enhancement, such as contours, shift of average intensity, over exaggerated gradient, etc., can be effectively suppressed by imposing appropriate constraints in the linear programming frame work. In addition, in the OCTM framework, put gray levels can be mapped to an arbitrary number L of output gray levels, allowing L to be equal, less or greater than. The OCTM technique is, therefore, suited to output conventional images on high dynamic range displays or high dynamic range images on conventional displays, with perceptual quality optimized for device characteristics and image contents. As such, OCTM can be useful tool in high dynamic range imaging. Moreover, OCTM can be united with Gamma correction. Analogously to global and local histogram equalization, OCTM can be performed based upon either global or local statistics. However, in order to make our technical development in what follows concrete and focused, we will only discuss the problem of contrast enhancement over an entire image instead of adapting to local statistics of different sub images. All the results and observations can be readily extended to locally adaptive contrast enhancement. The remainder of the paper is organized as follows. In the next section, we introduce some new definitions related to the intuitive notions of contrast and tone, and propose the OCTM approach of image enhancement. In Section III, we develop a linear programming algorithm to solve the OCTM problem. In Section IV, we discuss how to fine tune output images according to application requirements or users' preferences within the proposed linear programming framework. Experimental results are reported in Section V, and they demonstrate the versatility and superior visual quality of the new contrast enhancement technique.

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II. CONTRAST AND TONE

Consider a gray scale image of bits with a histogram of nonzero entries, Let be the probability of gray level we define the expected context-free contrast of by (1) By the definition, the maximum contras is achieved by a binary black-and-white image and it the minimum contrast when the image is a constant. As long as the histogram of is full without holes, i.e., the intensity distribution regardless Likewise, if then Contrast enhancement is to increase the difference between two adjacent gray levels and it is achieved by a remapping of input gray levels to output gray levels. Such a remapping is also necessary when reproducing a digital image of gray levels by a device of L gray levels, integer transfer function L. This process is an integer-to- integer transfer function L (2) In order not to violate physical and psycho visual common sense, the transfer function should be monotonically no decreasing such that does not reverse the order of intensities.1 In other words, we must have if and, hence, any transfer function has the form L (3) This restriction may be relaxed in locally adaptive contrast enhancement. But in each locality the monotonicity should still be imposed.

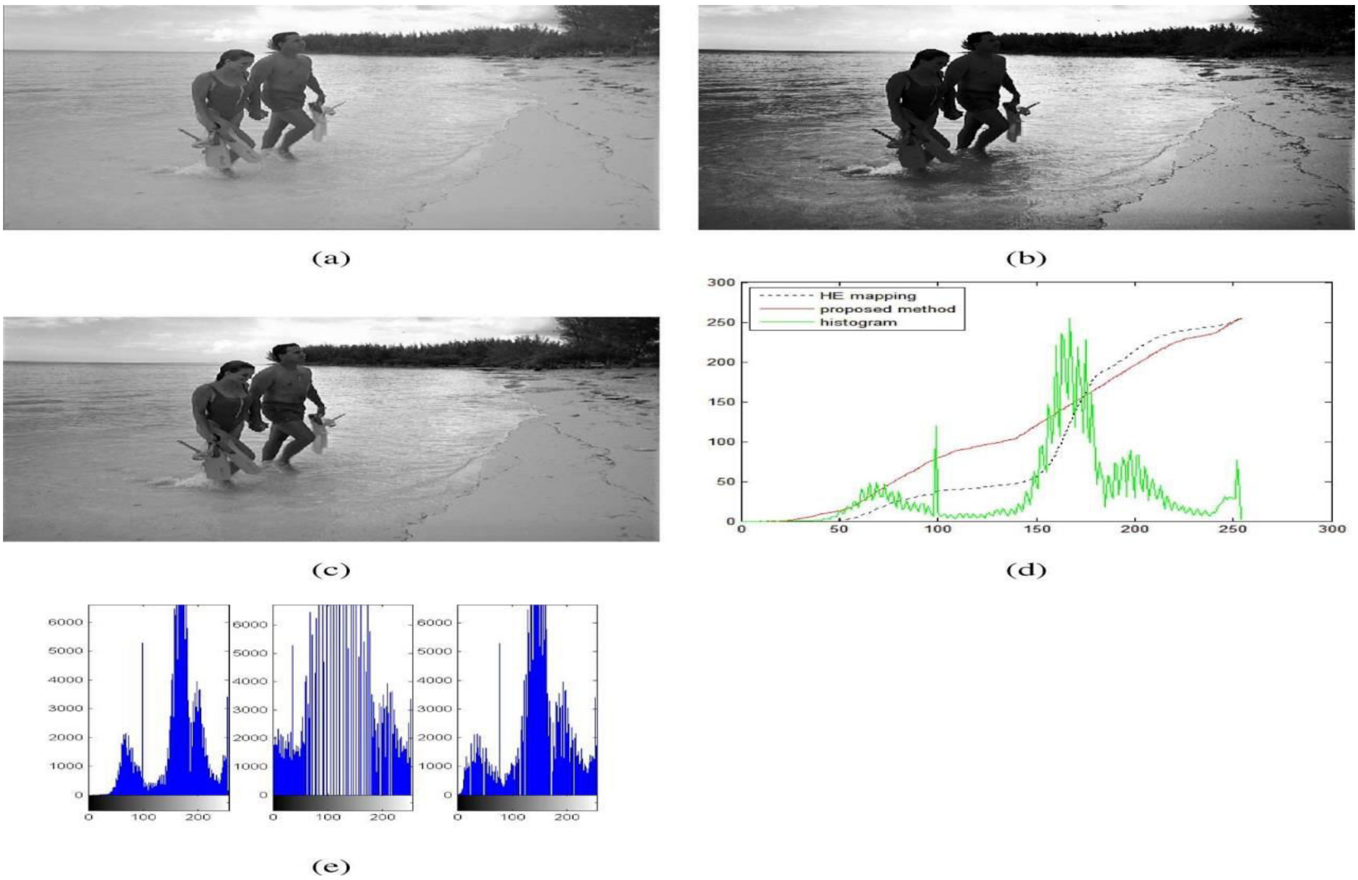

Fig.1. (a) Original. (b) Output of histogram equalization. (c) Output of the proposed OCTM method. (d) Transfer functions and the original histogram. (e) Histograms of the original image (left), the output image of histogram equalization (middle), and the output image of OCTM.

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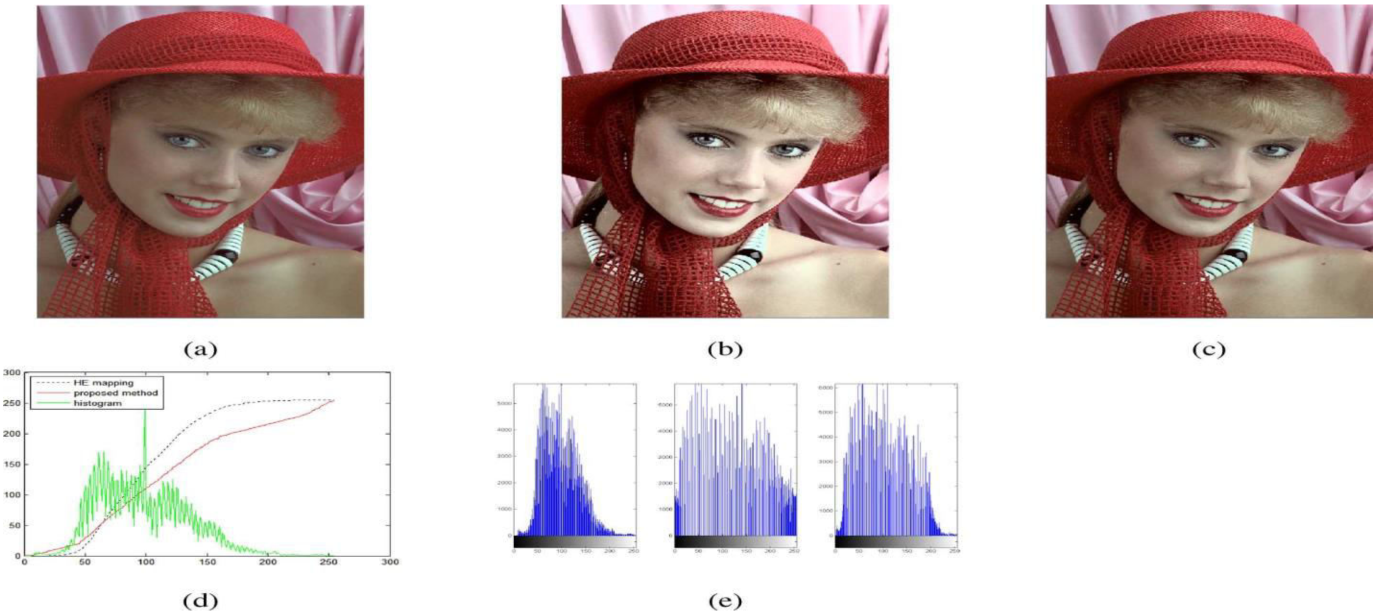

Fig. 2. (a) Original. (b) Output of histogram equalization. (c) Output of the proposed OCTM method. (d) Transfer functions and the original histogram. (e) Histograms of the original image (left) the output image of histogram equalization (middle), and the output image of OCTM

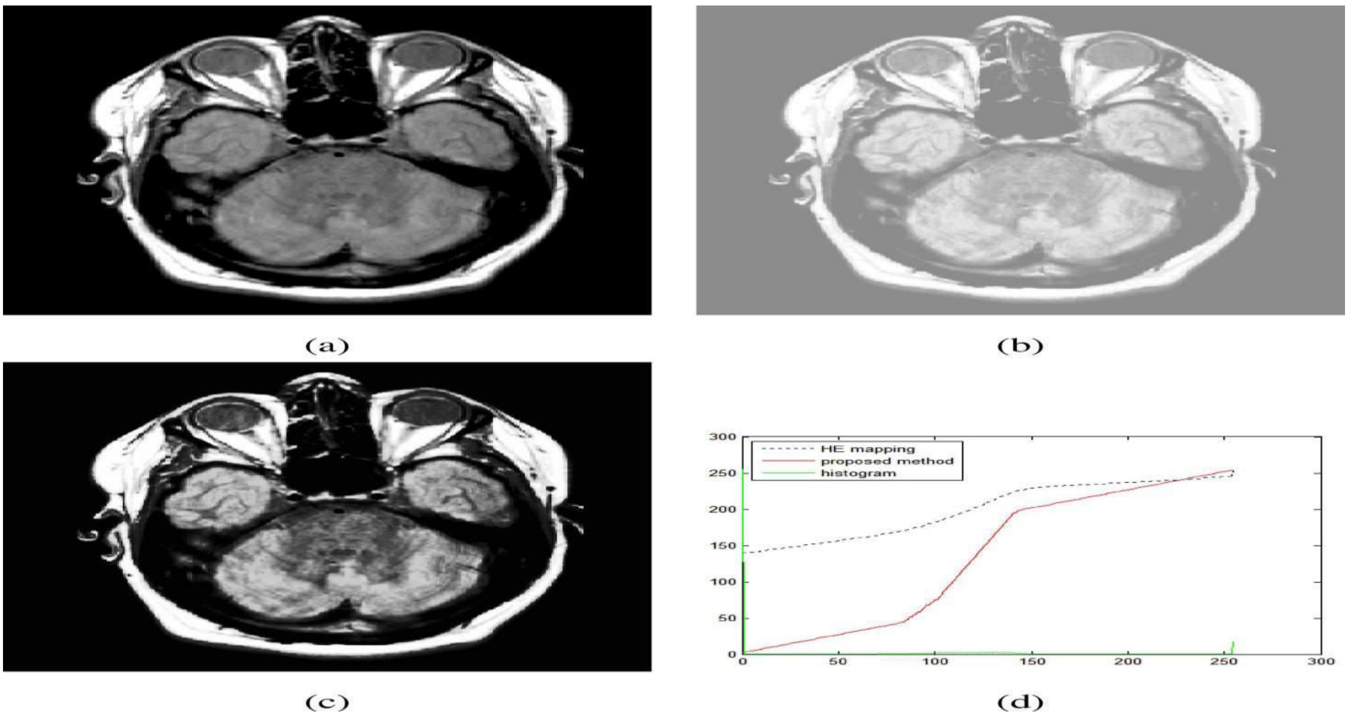

Fig.3. (a) Original. (b) Output of histogram equalization. (c) Output of the proposed OCTM method. (d) Transfer functions and the original histogram.

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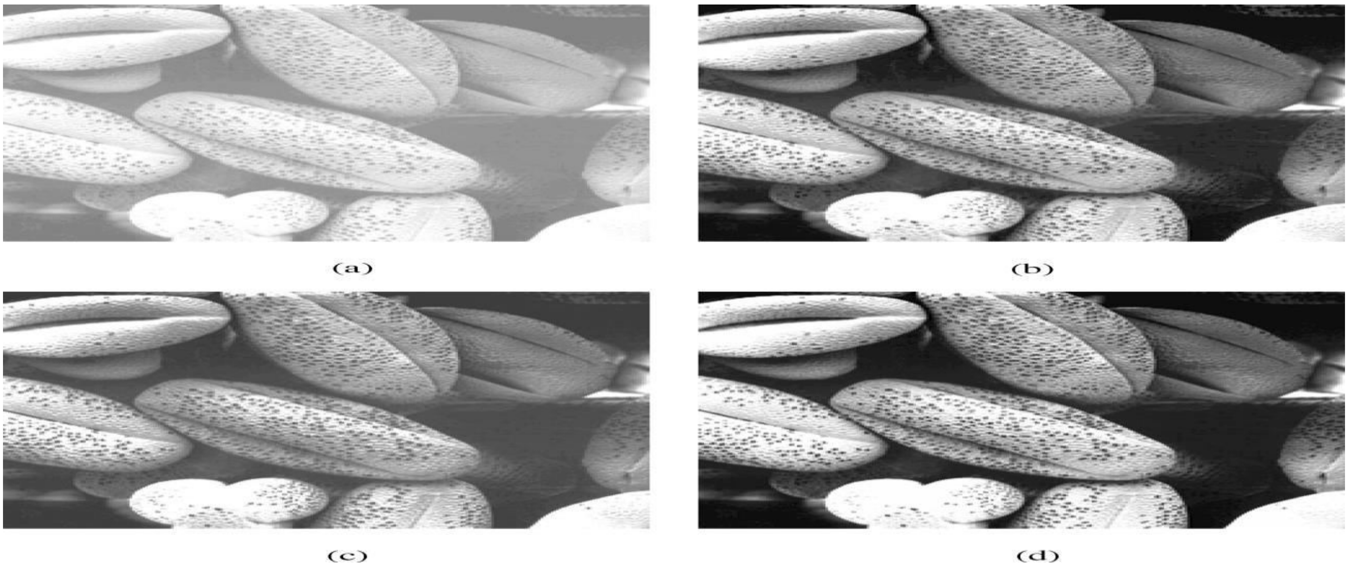

Fig. 4. (a) Original image before Gamma correction. (b) After Gamma correction. (c) Gamma correction followed by histogram equalization. (d) Joint Gamma correction and contrast-tone optimization by the proposed OCTM method.

Fig. 5. Comparison of different methods on image Pollen. (a) Original image. (b) HE. (c) CLAHE. (d) OCTM.

III. CONTRAST-TONE OPTIMIZATION BY LINEAR PROGRAMMING

To motivate the development of an algorithm, it is useful to view contrast enhancement as an optimal resource allocation problem with constraint. The resource is the output dynamic range and the constraint is tone distortion. The achievable contrast gain and tone distortion are physically conned by the output dynamic range L of the output device.

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In the optimization variables represent an allocation of L available output intensity levels, each competing for a larger piece of dynamic range. While contrast enhancement necessarily invokes a competition for dynamic range (an insufficient resource), a highly skewed allocation of L output levels to input levels can deprive some input gray levels of necessary representations, incurring tone distortion. This causes unwanted side effects, such as fattened subtle shades, unnatural contour bands, shifted average intensity, and etc. Such artifacts were noticed by other researchers as drawbacks of the original histogram equalization algorithm, and they proposed a number of ad hoc. Techniques to alleviate these artifacts by reshaping the original histogram prior to the equalization process. In OCTM, however, the control of undesired side effects of contrast enhancement is realized by the use of constraints when maximizing contrast gain.

IV. FINE TUNING OF VISUAL EFFECTS

The proposed OCTM technique is general and it can achieve desired visual effects by including additional constraints. We demonstrate the generality and flexibility of the proposed linear programming framework for OCTM by some of many possible applications. The first example is the integration of Gamma correction into contrast-tone optimization. The optimized transfer function can be made close to the Gamma transfer function in applications when the enhancement process cannot change the average intensity of the input image by certain amount, the user can impose this restriction easily in (10) by adding another linear constraint. Besides the use of constraints in the linear programming framework, we can incorporate context-based or semantics-based fidelity criteria directly into the OCTM objective function. The contrast gain depends only upon the intensity distribution of the input image. We can augment by weighing in the semantic or perceptual importance of increasing the contrast at different gray levels by. In general, can be set up to reflect specific requirements of different applications. We can augment by weighing in the semantic or perceptual importance of increasing the contrast at different gray levels by. In general, can be set up to reflect specific requirements of different applications. In medical imaging, for example, the physician can read an image of gray levels on an L-level monitor, L, with a certain range of gray levels enhanced. Such a weighting function presents itself naturally if there is a preknowledge that the interested anatomy or lesion falls into the intensity range for given imaging modality. In combining image statistics and domain knowledge or/and user preference, in this paper, we focus on global contrast-tone optimization. The OCTM technique can be applied separately to different image regions and, hence, made adaptive to local image statistics. The idea is similar to that of local histogram equalization. However, in locally adaptive histogram equalization, each region is processed independently of others. A linear weighting scheme is typically used to fuse the results of neighboring blocks to prevent block effects. In contrast, the proposed linear programming approach can optimize the contrasts and tones of adjacent regions jointly while limiting the divergence of the transfer functions of these regions. The only drawback is the increase in complexity. Further investigations in locally adaptive OCTM are underway

VI. CONCLUSION

Figs. 1–4 present some sample images that are enhanced by the OCTM technique in comparison with those produced by conventional histogram equalization (HE). The transfer functions of both enhancement techniques are also plotted in accompany with the corresponding input histograms to show different behaviors of the two techniques in different image statistics. In image Beach (Fig. 1), the output of histogram equalization is too dark in overall appearance because the original histogram is skewed toward the bright range. But the OCTM method enhances the original image without introducing unacceptable distortion in average intensity. This is partially because of the constraint in linear programming that bounds the relative difference (<20 % in this instance) between the average intensities of the input and output images.

Fig. 2 compares the results of histogram equalization and the OCTM method when they are applied to a common portrait image. In this example histogram equalization overexposes the input image, causing an opposite side effect as in image Beach, whereas the OCTM method obtains high contrast, tone continuity and small distortion in average intensity at the same time.

Fig. 3 shows an example when the user assigns higher weights in (14) to gray levels , where is an intensity range of interest (brain matters in the head image). The improvement of OCTM over histogram equalization in this typical scenario of medical imaging is very significant.

In Fig. 4, the result of joint Gamma correction and contrast tone optimization by the OCTM technique is shown, and compared with those in difference stages of the separate Gamma correction and histogram equalization process. The

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image quality of OCTM is clearly superior to that of the separation method. The new OCTM approach is also compared with the well-known contrast-limited adaptive histogram equalization (CLAHE) in visual quality. CLAHE is considered to be one of the best contrast enhancement techniques, and it alleviates many of the problems of histogram equalization, such as over- or under-exposures, tone discontinuities, and etc.

Figs. 5- are side-by-side comparisons of OCTM, CLAHE, and HE. CLAHE is clearly superior to HE in perceptual quality, as well recognized in the existing literature and among practitioners, but it is somewhat inferior to OCTM in overall image quality, particularly in the balance of sharp details and subtle tones. In fact, the OCTM technique was assigned and implemented as a course project in one of the author's classes. There was a consensus on the superior subjective quality of OCTM over HE and its variants among more than one hundred students.

A new, general image enhancement technique of optimal contrast-tone mapping is proposed. The resulting OCTM problem can be solved efficiently by linear programming. The OCTM solution can increase image contrast while preserving tone continuity, two conflicting quality criteria that were not handled and balanced as well in the past.

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