◊ VIII.5

Contrast Limited Adaptive Histogram Equalization

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This Gem describes a contrast enhancement technique called *adaptive histogram equalization*, AHE for short, and an improved version of AHE, named *contrast limited adaptive histogram equalization*, CLAHE, that both overcome the limitations of standard histogram equalization. CLAHE was originally developed for medical imaging and has proven to be successful for enhancement of low-contrast images such as portal films (Rosenman *et al.* 1993).

◊ Introduction ◊

Probably the most used image processing function is contrast enhancement with a lookup table, a 1-to-1 pixel transform as described in (Jain 1989). When an image has poor contrast, the use of an appropriate mapping function (usually a linear ramp) often results in an improved image.

The mapping function can also be non-linear; a well-known example is gamma correction. Another non-linear technique is *histogram equalization*; it is based on the assumption that a good gray-level assignment scheme should depend on the frequency distribution (histogram) of image gray levels. As the number of pixels in a certain class of gray levels increases, one likes to assign a larger part of the available output gray ranges to the corresponding pixels. This condition is met when cumulative histograms are used as a gray-level transform as is shown in Figure 1.

The histogram of the resulting image is approximately flat, which suggests an optimal distribution of the gray values. However, Figure 1 shows that histogram equalization in its basic form can give a result that is worse than the original image. Large peaks in the histogram can also be caused by uninteresting areas (especially background noise); in this case, histogram equalization mainly leads to an improved visibility of image noise. The technique does also not adapt to local contrast requirements; minor contrast differences can be entirely missed when the number of pixels falling in a particular gray range is small.

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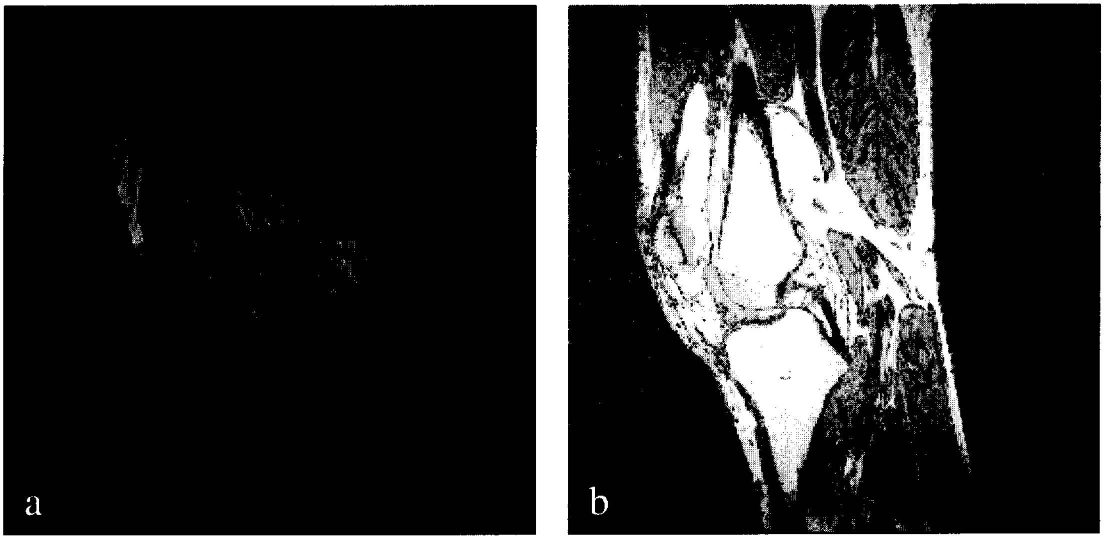

Figure 1. Example of contrast enhancement using histogram equalization. (a) The original image, an image of a human knee obtained with Magnetic Resonance Imaging. (b) Result of histogram equalization.

◇ Adaptive Histogram Equalization (AHE) ◇

Since our eyes adapt to the local context of images to evaluate their contents, it makes sense to optimize local image contrast (Pizer *et al.* 1987). To accomplish this, the image is divided in a grid of rectangular *contextual regions* in which the optimal contrast must be calculated. The optimal number of contextual regions depends on the type of input image, and its determination requires some experimentation. Division of the image into 8×8 contextual regions usually gives good results; this implies 64 contextual regions of size 64×64 when AHE is performed on a 512×512 image.

For each of these contextual regions, the histogram of the contained pixels is calculated. Calculation of the corresponding cumulative histograms results in a gray-level assignment table that optimizes contrast in each of the contextual regions, essentially a histogram equalization based on local image data.

To avoid visibility of region boundaries, a bilinear interpolation scheme is used (see Figure 2).

Applying adaptive histogram equalization on the image in Figure 1a results in the image that can be found in Figure 2b. Although the contrast of the relevant structures in the knee is largely improved, the most striking feature of the image is the background noise that has become visible. Although one can argue that AHE does what it is supposed to do — optimal presentation of information present in the image — noise present in AHE images turns out to be a major drawback of the method.

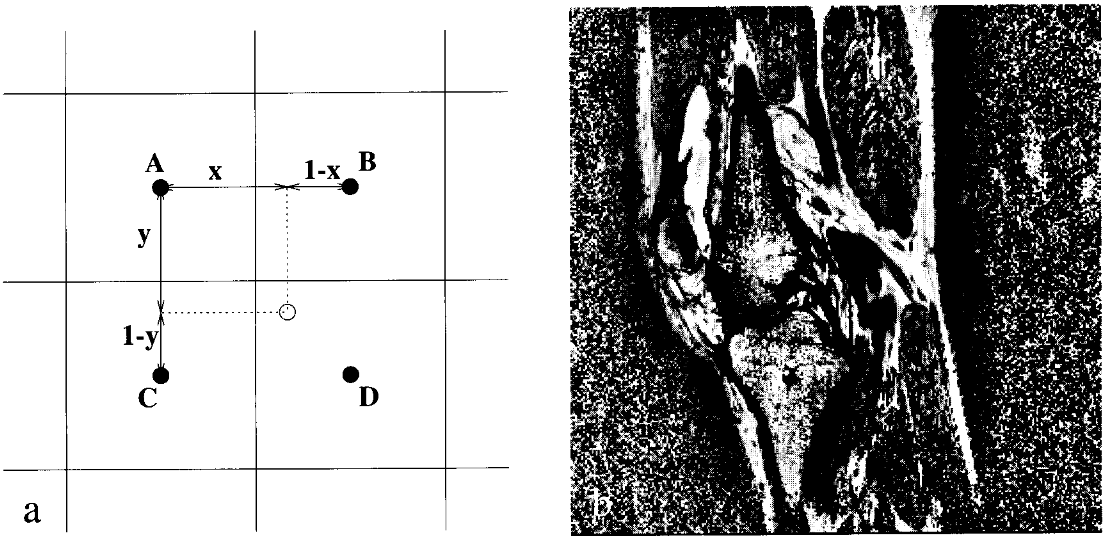

Figure 2. Subdivision and interpolation scheme used with adaptive histogram equalization and a typical result of AHE. (a) The gray-level assignment at the sample position, indicated by a white dot, is derived from the gray-value distributions in the surrounding contextual regions. The points A, B, C, and D form the center of the relevant contextual regions; region-specific gray-level mappings ($g_A(s)$, $g_B(s)$, $g_C(s)$ and $g_D(s)$) are based on the histogram of the pixels contained. Assuming that the original pixel intensity at the sample point is s, its new gray value is calculated by bilinear interpolation of the gray-level mappings that were calculated for each of the surrounding contextual regions: $s' = (1-y)((1-x)g_A(s) + xg_B(s)) + y((1-x)g_C(s) + xg_D(s))$ where x and y are normalized distances with respect to the point A. At edges and corners, a slightly different interpolation scheme is used. (b) Result of AHE using 8×8 contextual regions applied on the image in Figure 1a. Although structures in the knee can be better distinguished, the overall appearance of the image suffers due to noise enhancement.

◇ Contrast Limited Adaptive Histogram Equalization (CLAHE) ◇

The noise problem associated with AHE can be reduced by limiting contrast enhancement specifically in homogeneous areas. These areas can be characterized by a high peak in the histogram associated with the contextual regions since many pixels fall inside the same gray range. With CLAHE, the slope associated with the gray-level assignment scheme is limited; this can be accomplished by allowing only a maximum number of pixels in each of the bins associated with local histograms. After clipping the histogram, the pixels that were clipped are equally redistributed over the whole histogram to keep the total histogram count identical (see Figure 3).

The clip limit (or contrast factor) is defined as a multiple of the average histogram contents. With a low factor, the maximum slope of local histograms will be low and

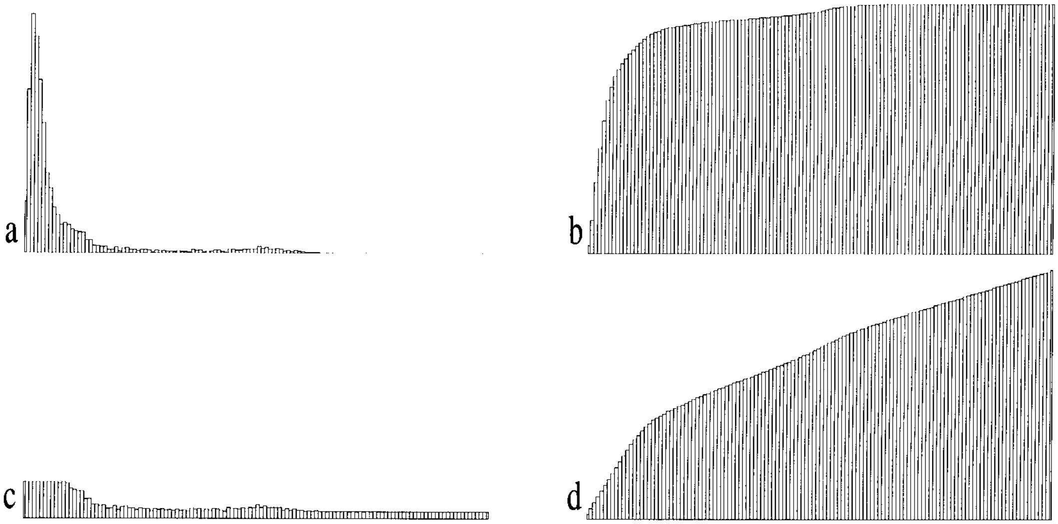

Figure 3. Principle of contrast limiting as used with CLAHE. (a) Histogram of a contextual region containing many background pixels. (b) Calculated cumulative histogram; when used as a gray-level mapping, many bins are wasted for visualization of background noise. (c) Clipped histogram obtained using a clip limit of three. Excess pixels are redistributed through the histogram. (d) Cumulative clipped histogram; its maximum slope (equal to the contrast enhancement obtained) is equal to the clip limit.

therefore result in limited contrast enhancement. A factor of one prohibits contrast enhancement (giving the original image); redistribution of histogram bin values can be avoided by using a very high clip limit (one thousand or higher), which is equivalent to the AHE technique.

Figure 4 shows two examples of contrast enhancement using CLAHE; although the image at the right was CLAHE processed using a high clip limit, image noise is still acceptable.

The main advantages of the CLAHE transform as presented in this Gem are the modest computational requirements, its ease of use (requiring only one parameter: the clip limit), and its excellent results on most images.

CLAHE does have disadvantages. Since the method is aimed at optimizing contrast, there is no 1 to 1 relationship between the gray values of the original image and the CLAHE processed result; consequently, CLAHE images are not suited for quantitative measurements that rely on a physical meaning of image intensity. A more serious problem are artifacts that sometimes occur when high-intensity gradients are present; see (Cromartie and Pizer 1991) for an explanation of these artifacts and a possible (but computationally expensive) solution. A detailed overview of AHE and other histogram equalization methods can be found in (Gauch 1992).

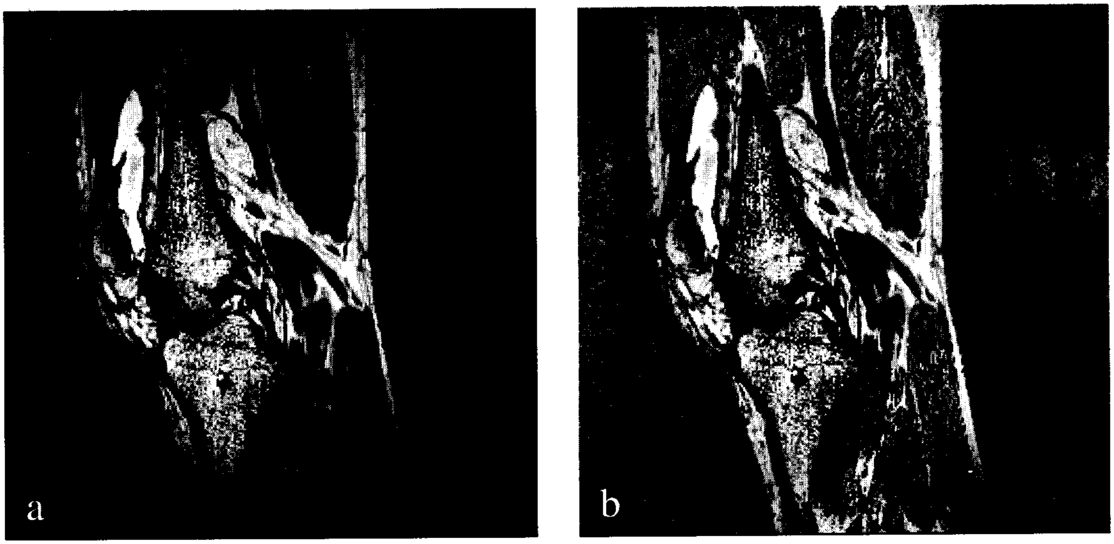

Figure 4. Result of CLAHE applied on the image in Figure 1a. (a) CLAHE with clip limit 3. (b) CLAHE with clip limit 10. Both images were obtained using 8 x 8 contextual regions.

◇ Implementation ◇

Since CLAHE has its roots in medical imaging, the earlier CLAHE implementations assumed 16-bit image pixels, since medical scanners often generate 12-bit images. This implementation is a rewrite of a K&R C version written more than five years ago; it is now Ansi-C as well as C++ compliant and can also process 8-bit images.

For a 512×512 image, this implementation of CLAHE requires less than a second on an HP 9000/720 workstation when 8×8 contextual regions are used.

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