A Histogram-Based Technique for Echocardiographic Image Enhancement

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Abstract

Echocardiography is a very powerful diagnostic tool. However, the acquired images are often noisy and difficult to interpret. One well-known technique for image-enhancement is to apply predefined gray-level intensity transformations, or Brightness Transfer Functions (BTFs). This paper presents an innovative algorithm, called ABTF (Adaptive Brightness Transfer Function), designed to optimally determine the gray-levels used for each specific Echocardiographic cine-loop. The algorithm applies automatic segmentation to the initial gray-level histogram, based on curve fitting to the sum of three Gaussian functions, each of which is correlated to a different tissue type. A different procedure is applied to each segment. The ABTF algorithm has been tested on 23 cine-loops from 10 different patients, with varying degrees of Echogenicity. The results are clearly superior to the original images, with a much better contrast and richer gray-levels within the cardiac muscle.

1. Introduction

Echocardiography is the most common cardiac imaging modality, providing a multitude of functional parameters on-line. However, the acquired images, especially in patients with low Echogenicity, are often noisy and difficult to interpret [1]. Improving the image quality may lead to better visual tissue-classification and richer textures within the cardiac muscle [2], and thus – to better clinical diagnosis.

A simple and commonly used technique for image enhancement is Histogram Equalization [3]. This technique applies a Brightness Transfer Function (BTF) to the gray-levels in the image, aimed at increasing the spread of the gray-level histogram. However, this method treats all tissue types within the image in the same manner. In order the improve the displayed images, a process called "Rejection" is sometimes applied prior to the Histogram Equalization, setting all the pixels whose gray-level lies beneath a user-defined threshold to 0. Better image quality can sometimes be achieved using predefined BTFs. Nevertheless, tailoring the BTF to each cine-loop can dramatically improve the results.

This paper presents a novel method, called ABTF (Adaptive Brightness Transfer Function) [4], designed to optimally determine the gray-levels used for each patient, and for each specific Echocardiographic cine-loop. The algorithm uses automatic segmentation of the gray-level histogram, based on applying a curve-fit to the sum of three Gaussian functions, each of which corresponding to a different region of the image: the Left Ventricular (LV) cavity (first Gaussian), low-intensity pixels within the cardiac muscle (second Gaussian), and high-intensity pixels within the cardiac muscle (third Gaussian). For each of the three histogram-segments, a different set of rules is used for processing, in order to obtain the best possible results.

2. Methods

As described above, the ABTF procedure is based on curve-fitting the cine-loop's gray-level histogram to the sum of three Gaussian functions: G_1, G_2 and G_3 (e.g. Figure 1).
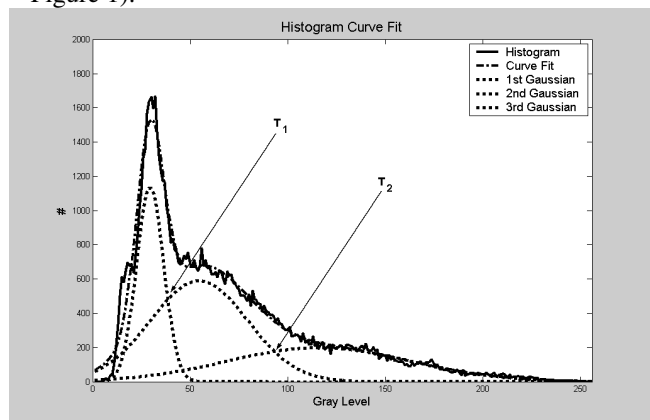

Figure 1. The cine-loop's gray-level histogram is shown using a solid line. The three Gaussian functions are displayed using dotted lines. The fitted curve is displayed using a dash-dotted line. Note that the curve-fit is quite good, and that the three Gaussian functions are acceptably separated.

The gray-level histogram is divided into three sections, each one dominated by a single Gaussian function. The division is performed at the intersection points between

the first and the second Gaussian (T_1), and between the second and third Gaussian (T_2). The degree of separation for each division point T_i can be described using two parameters, defined for the entire cine-loop:

- The "Detection probability" P_d^i, referring to the probability for a pixel whose intensity exceeds T_i to belong to the expected Gaussian function (G_2 or G_3 for $T_i = T_1$, G_3 for $T_i = T_2$).
- The "False-alarm probability" P_{fa}^i, referring to the probability for a pixel whose intensity exceeds T_i to belong to the incorrect Gaussian function (G_1 for $T_i = T_1$, G_1 or G_2 for $T_i = T_2$).

$$P_d^1 = \frac{\int_{T_1}^{\infty}[G_2(u)+G_3(u)]du}{\int_{-\infty}^{\infty}[G_2(u)+G_3(u)]du} \tag{1}$$

$$P_d^2 = \frac{\int_{T_2}^{\infty}G_3(u)du}{\int_{-\infty}^{\infty}G_3(u)du} \tag{2}$$

$$P_{fa}^1 = \frac{\int_{T_1}^{\infty}G_1(u)du}{\int_{-\infty}^{\infty}G_1(u)du} \tag{3}$$

$$P_{fa}^2 = \frac{\int_{T_2}^{\infty}[G_1(u)+G_2(u)]du}{\int_{-\infty}^{\infty}[G_1(u)+G_2(u)]du} \tag{4}$$

Ideal separation is achieved when $P_d^1 = P_d^2 = 1.0$ and $P_{fa}^1 = P_{fa}^2 = 0.0$.

Generally speaking, the gray-level information within the LV cavity has little clinical use. On the other hand, the low-intensity pixels within the cardiac muscle contain most of the texture information, which is of vital importance for visual tissue tracking and contractility estimation. These pixels usually utilize only a small portion of the gray-level scale.

Hence, the ABTF algorithm basically compresses the first section of the histogram ($1^{st} < T_1$), and stretches the second section ($T_1 \leq 2^{nd} < T_2$). In addition, Histogram Equalization is applied to the first and the second sections separately, in order to improve image quality. For the third section, Histogram Specification is used, so as to reduce the use of high-intensity pixels, whose presence causes the image to seem saturated.

The algorithm has been tested on 23 Echocardiographic cine-loops from 10 different patients with different degrees of Echogenicity. For each case, the detection probability and the false-alarm probability have been calculated. In addition, the ABTF results have been compared visually to the original cine-loops. As a reference, the images obtained by applying Rejection and Histogram Equalization to the cine-loops have also been examined.

For demonstration purposes, only the End-Diastolic (ED) and the End-Systolic (ES) frames for a single case are shown.

3.   Results (see figures 2 and 3)

The gray-level histograms of all the cine-loops in the test-set have been successfully curve-fitted to the sum of three Gaussian functions. The mean value of P_d^1 is 0.87 ± 0.03, and the value of P_d^2 is 0.74 ± 0.06. Furthermore, the value of P_{fa}^1 is 0.12 ± 0.08, and the value of P_{fa}^2 is 0.04 ± 0.02.

The results for the ED frame are shown in Figure 2, while the results for the ES frame are shown in Figure 3. For each frame, the original image, the Histogram-Equalized image and the result of applying ABTF are shown.

The ABTF calculated by the algorithm for the example cine-loop (from Figures 2 and 3) is shown in Figure 4. This BTF is applied to the image pixel-by-pixel. For each pixel, its new gray-level is defined by the value of the ordinate on the graph, whose abscissa is the initial gray-level.

4.   Discussion and conclusions

The success of the histogram curve-fit supports the assumption that the gray-level histogram can be fitted to the sum of three Gaussian functions, each of which corresponds to a different section of the image. The high detection probabilities and the relatively low false-alarm probabilities further support this model, showing that the separability between the three Gaussian functions is acceptable.

As to the image comparison – the authors are aware of the subjective nature of visual analysis. However, defining quantitative parameters would be artificial at best. Therefore, the optimized parameters have been defined with the help of renowned Cardiologists and Echocardiography experts (see Acknowledgements).

The ABTF results seem sharper and crisper than both the original images and the Histogram Equalized images, thus supporting visual tissue classification. They also have richer gray-levels within the cardiac muscle, therefore contributing to visual tissue tracking and to the evaluation of Myocardial contractility.
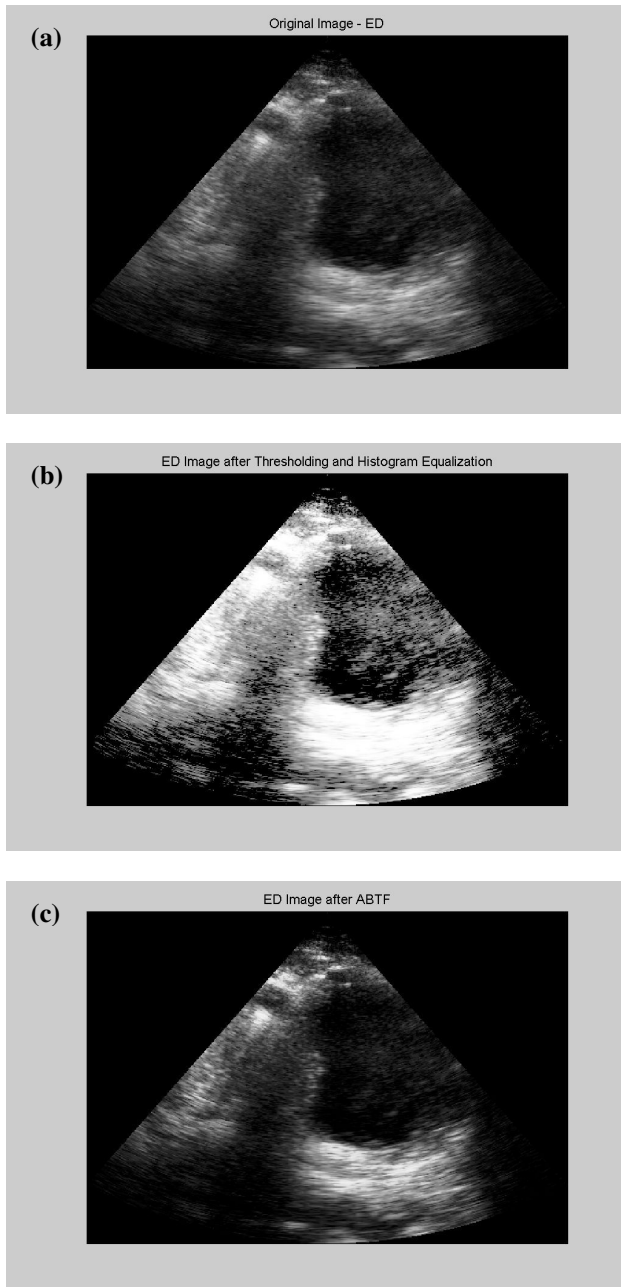
Figure 2. The End-Diastolic frame of the example cine-loop. (**a**) The original image. (**b**) The result of applying Rejection (using the threshold 38) and Histogram Equalization. (**c**) The result of applying ABTF. Note that the ABTF results are much sharper than both the original and the Histogram Equalized images.
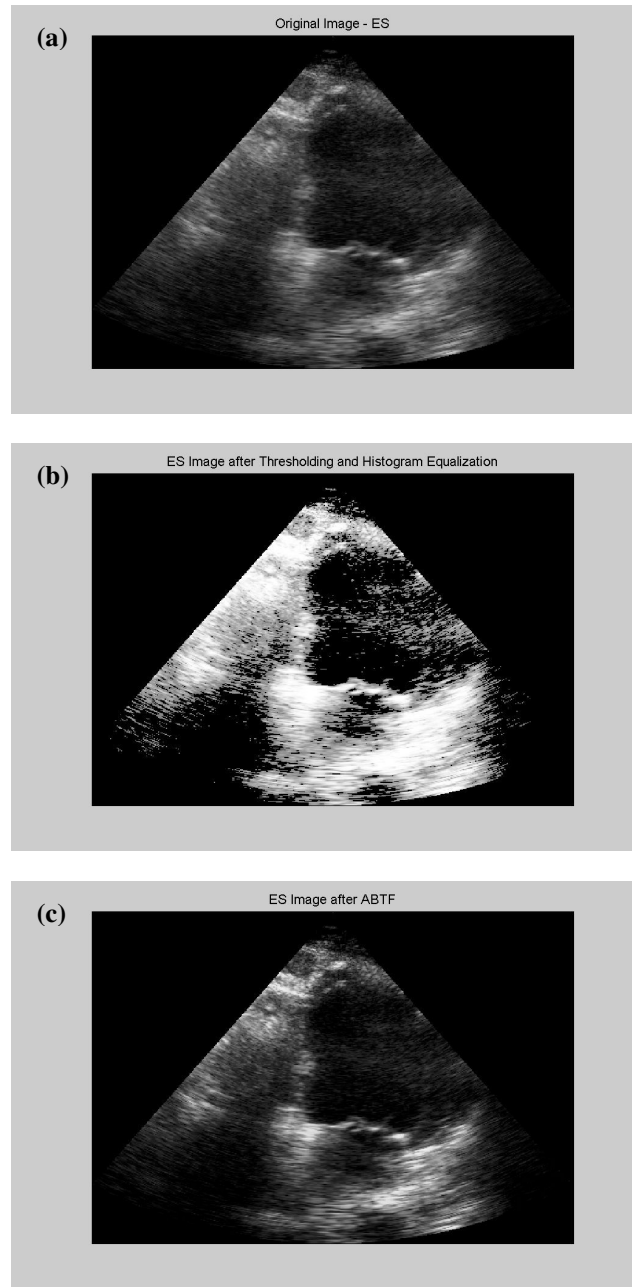
Figure 3. The End-Systolic frame of the example cine-loop. (**a**) The original image. (**b**) The result of applying Rejection (using the threshold 38) and Histogram Equalization. (**c**) The result of applying ABTF. As in Figure 2, the ABTF results are sharper than both the original and the Histogram Equalized images.
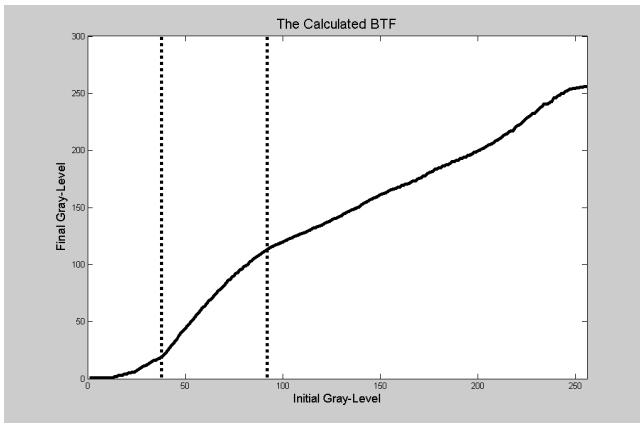
Figure 4. The calculated BTF is drawn using a solid line. The values of T_1 and T_2 are marked by dotted lines. Note the non-trivial form of the graph.

Conversely, the Histogram-Equalized images are characterized by strong contrast, but most of the texture information is lost.

In conclusion, this paper presents a novel method for Echocardiographic image enhancement, the ABTF algorithm, which automatically sets the gray-levels within the image to produce optimal results. The algorithm has been successfully tested on 23 cine-loops from 10 different patients. The improved images are expected to have a positive effect on clinical diagnosis, making it easier if not more precise.

Based on the aforementioned three-Gaussian model, we are currently developing a method for automatic delineation of both the inner (Endocardial) and outer (Epicardial) boundaries of the cardiac muscle. Preliminary results are very promising.

References

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