TECHNICAL REPORT

A contrast correction method for dental images based on histogram registration

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Contrast correction is often required in digital subtraction radiography when comparing medical data acquired over different time periods owing to dissimilarities in the acquisition process. This paper focuses on dental radiographs and introduces a novel approach for correcting the contrast in dental image pairs.

The proposed method modifies the subject images by applying typical registration techniques on their histograms. The proposed histogram registration method reshapes the histograms of the two subject images in such a way that these images are matched in terms of their contrast deviation. The method was extensively tested over 4 sets of dental images, consisting of 72 registered dental image pairs with unknown contrast differences as well as 20 dental pairs with known contrast differences. The proposed method was directly compared against the well-known histogram-based contrast correction method.

The two methods were qualitatively and quantitatively evaluated for all 92 available dental image pairs. The two methods were compared in terms of the contrast root mean square difference between the reference image and the corrected image in each case. The obtained results were also verified statistically using appropriate *t*-tests in each set.

The proposed method exhibited superior performance compared with the well-established method, in terms of the contrast root mean square difference between the reference and the corrected images. After suitable statistical analysis, it was deduced that the performance advantage of the proposed approach was statistically significant.

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Introduction

In digital medical imaging there is often the need to directly compare two or more images from different modalities or simply to compare images from the same modality, including dental radiographic images acquired at different times.

In the case of dental radiographs, experts commonly identify structural changes in the bone supporting the teeth by comparing radiographs acquired over a short or long period of time. This allows them to identify image

features that are solely related to the progression or regression of a particular disease and thus evaluate the effectiveness of a certain therapy. The comparison process can be performed automatically by subtracting aligned digital versions of the compared radiographs.^{1–4} Ideally, these images should have the same luminosity and contrast properties, however, this is rarely the case. Even in the case of images acquired through the same system, several factors may affect the acquisition process itself, especially when the images are acquired at different times. These factors include the acquisition angle, the presence of noise during acquisition and equipment-related factors (settings of the acquisition system).

Digital subtraction radiography (DSR) is extremely sensitive to contrast and luminosity differences between

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the subtracted images. When subtracting two images with high contrast deviation, the result of the subtraction may be distorted by unwanted information in areas with high contrast differences. In such cases, evaluation of the subtracted images is rather problematic as the reviewer will have to mentally distinguish between desired (useful) and spurious information. Therefore, in such cases, contrast correction is a strong requirement.

Numerous contrast correction methods have been devised over the years. In general, those methods can be classified into two broad categories:⁵ (1) methods that operate directly on the images by considering pixel intensities^{6,7} and (2) methods that operate solely on the histogram of the images.^{8–15} The methods falling into the first category are conceptually simple techniques such as contrast stretching⁶ (normalization) and filtering⁷ (boxcar filter). These methods usually lack the accuracy of more advanced approaches but are much faster and thus more suitable for time-critical applications such as computer vision. The second category includes rather complex techniques^{8–13} that are mostly based on the cumulative probability function^{9,16} or the cumulative density function,¹⁵ both of which are extracted from the histograms of the subject images. Such methods include the robust film contrast correction approach proposed by Ruttimann *et al*,⁹ histogram equalization,⁸ histogram shaping¹⁰ and histogram flattening.¹⁶ Histogram-based methods usually provide superior accuracy at the cost of increased execution time and are more suitable for medical use, such as DSR.

This paper presents a novel contrast correction approach, focusing on the processing of dental radiographs. The proposed histogram registration method operates directly on the histogram of the corrected image by using registration techniques similar to those used in standard image registration.¹⁷ The proposed method was qualitatively and quantitatively evaluated using 4 sets of 92 dental image pairs. The sets consisted of aligned pairs of images with both known and unknown contrast differences. The histogram registration method was also compared against the well-established and widely used film contrast correction method proposed by Ruttimann *et al*.⁹ The 2 methods were assessed over all 92 available image pairs and the histogram registration method showed advantageous performance compared with Ruttimann's approach, as it was capable of producing corrected images with relatively small contrast deviations from the reference image in each set.

The rest of the paper is organized as follows: the Materials and methods section describes the proposed method in some detail. It also presents the data used in the study, refers to the techniques used to evaluate the performance of the proposed method and briefly describes Ruttimann's method. The Results section presents qualitative and quantitative results obtained by the application of the two contrast correction methods on the available dental image data. The

Discussion refers to some crucial issues related to the application of the proposed contrast correction method along with a presentation of the basic parameters that affect the performance of the proposed method.

Materials and methods

Histogram registration

As mentioned, the proposed histogram registration contrast correction method extends the principles of typical image registration to operate on the histograms of the images rather than the images themselves.^{1,18,19} In that way, the spatial information of the corrected image remains intact, but its luminosity and contrast are adjusted. Hence, given two images, a reference image and a floating image that needs to be corrected, the proposed method first extracts the histograms of the two images and then tries to reshape the histogram of the floating image in order to match that of the reference image as well as possible. The steps of the algorithm are listed below:

1. Extraction of the histograms in both images.
2. Use of simplex optimization to estimate the parameters of a linear transformation.
3. Application of a linear transformation on the histogram of the floating image.
4. Calculation of a measure of match (penalty function) by comparing the transformed histogram of the floating image with the histogram of the reference image.
 - 4.1. If the measure of match has not reached a local minimum or if the maximum number of iterations has not been reached, go back to step 2 to calculate a new pair of parameters.
 - 4.2. Else, the last two produced parameters are considered to be the optimal ones.
5. Transformation of the histogram of the floating image in order to produce its contrast corrected version.

The transform used to reshape the target histogram is a simple linear function with two parameters as shown in Equation (1):²⁰

$$i_{H_C} = i_{H_F}\alpha + D \quad (1)$$

where i_{H_C} is the new level (histogram position) of the corrected histogram, i_{H_F} is the old level of the floating image histogram and α and D are the parameters of the linear transformation. Therefore, each histogram level from the floating histogram is shifted to its new position, according to the two parameters of the linear transformation. The best possible parameters are estimated through the simplex optimization method, which is an extremely popular algorithm for finding the numerical solution of a linear programming problem.^{21,22} The algorithm itself is repetitive and

estimates the best possible solution (in our case the transformation parameters) by minimizing a given measure of match function. The range of values used for the limits of the two parameters is shown in Equation (2). The optimum values depend on the characteristics of each image pair, so specific values from within the particular range have been selected after a series of trials for assessing the proposed method in each pair separately. A detailed evaluation of the two parameters is provided in the discussion.

$$1 \leq \alpha_{\max} \leq 2 \quad (2)$$

$$25 \leq D_{\max} \leq 175, \alpha_{\max}, D_{\max} \in R \text{ (real numbers set)}$$

The proposed histogram registration method employs the cross-correlation coefficient as its measure of match function for examining the correlation between the reference and the transformed histogram.²³ The cross-correlation coefficient can be calculated using Equation (3):

$$CC = \frac{G \sum_{i=1}^G H_R(i) H_C(i) - \sum_{i=1}^G H_R(i) \sum_{i=1}^G H_C(i)}{\sqrt{G \sum_{i=1}^G H_R^2(i) - \left(\sum_{i=1}^G H_R(i) \right)^2} \sqrt{G \sum_{i=1}^G H_C^2(i) - \left(\sum_{i=1}^G H_C(i) \right)^2}} \quad (3)$$

where $H_R(i)$ and $H_C(i)$ are the histogram values of the reference and the corrected image, respectively, for grey-level i and G is the number of grey levels used to sample the images (256 for all greyscale images of the study).

As already mentioned, the linear transform shown in Equation (1) is employed in order to transform the histogram levels of the floating image. However, as both parameters of the linear model are real numbers ($\alpha, D \in R$), the resultant levels i_{H_C} are not integer values and hence have to be converted in order to represent a valid histogram level. For this purpose, a simple linear interpolation scheme was used between the two closest integer values of the resultant i_{H_C} level.²⁴ The employed interpolation scheme is shown in Equation (4):

$$H_C(i) = (1-h)H_F(j) + hH_F(j+1) \quad (4)$$

where the new level of the corrected histogram $H_C(i)$ is calculated for $j = \lfloor i_{H_C} \rfloor$ and $h = i_{H_C} - j$. In other words, j is the “floor” of i_{H_C} , that is the largest integer number not greater than i_{H_C} .

An example of applying the proposed method is shown in Figure 1, where a pair from set 2 of the registered images is used. As can be seen, the histogram registration method is capable of increasing the overall contrast of the floating image (Figure 1b), which is much dimmer than the reference image (Figure 1a). As a result, the contrast of the produced corrected image

(Figure 1c) matches that of the reference image. An additional example is provided in Figure 2, which demonstrates the need for contrast correction in DSR. An image pair from set 4 is used, with the floating image (Figure 2b) having a 30% contrast gain compared with the reference image (Figure 2a). In the particular example, the floating image is a contrast-adjusted copy of the reference image, so no registration error is introduced. As can be seen in Figure 2, if no contrast correction is used, the subtracted image representing the absolute difference between the reference and the floating image (Figure 2c) contains unwanted information owing to the large contrast and luminosity divergence between the two images. This is reflected in the relatively high mean intensity of the subtracted image, in this case 18.312. On the other hand, applying the histogram registration contrast correction method prior to subtraction produces the image shown in Figure 2d. The particular image contains virtually no spurious information, which may also be verified by its low mean intensity value of 1.039.

Data acquisition

The proposed histogram registration contrast correction method was evaluated over 4 sets of 92 dental image pairs in total. The method was applied to the floating images in all sets and the produced corrected images were compared against the reference in each set, in order to assess the performance of the method.

All dental images used in this paper were acquired from an *in vitro* study. A dry mandible was mounted on a device which permitted the object and the film to be rotated vertically and horizontally relative to the central part of the X-ray beam. The focus-to-object and the object-to-film distance were kept constant at 40 cm and 0.5 cm, respectively. The radiographs were digitized with a flat scanner (Agfa Arcus II, Agfa Graphics, Kista, Sweden), producing 8-bit greyscale image files. The reference radiograph was taken with the central ray of the X-ray beam perpendicular to the long axes of the teeth as judged subjectively and with no resulting overlaps of adjacent tooth surfaces. Subsequent images were then obtained by rotating the object either vertically or horizontally relative to the X-ray beam at 0°, 3° and 6°. This corresponds to motion about the x - and y -axes in three-dimensional space.

Registered dental data with unknown contrast differences

Three sets (sets 1–3) were produced by aligning all floating images to the reference images in each set. The preferred registration process was independent of the intensity and contrast of the subject images. First, the edges of the reference and floating images were extracted using a Canny edge detector.²⁵ The parameters of an affine transformation were then estimated,¹⁷ based on the edges of the images. The particular affine transformation may be defined as shown in Equation (5):

Figure 1 Visual assessment of the histogram registration method on an image pair from set 2 of the registered images with unknown contrast differences. (a) The reference image. (b) The floating image. (c) The corrected image

$$\begin{pmatrix} x' \\ y' \\ 1 \end{pmatrix} = \begin{pmatrix} a_1 & a_2 & d_x \\ a_3 & a_4 & d_y \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ 1 \end{pmatrix} \quad (5)$$

where (x', y') are the transformed co-ordinates of a pixel from the floating image with initial co-ordinates (x, y) , according to the six parameters of the transformation. The optimal parameters of the transformation were estimated using the distance map method.²⁶ According to that method, the optimal parameters are obtained when the following measure of match (MOM) is minimized:

$$\text{MOM} = \frac{1}{M \times N} \sum_{i: I_R(x, y)_i \neq 0} DM_{I_{\text{GTR}}}(x', y')_i \quad (6)$$

where the distance map produced by the transformed image, with height M and width N pixels, is defined by $DM_{I_{\text{GTR}}}$. In effect, the particular measure of match is the average Euclidean distance between the pixels of the reference image I_R with co-ordinates (x, y) and their respective pixels from the transformed image I_{GTR} with transformed co-ordinates (x', y') . Finally, when the optimal parameters were obtained, the floating images

were transformed using those parameters to define the affine transformation shown in Equation (5). In some cases the image displacements caused by the registration process introduced dark areas on the registered images that could affect the evaluation of the contrast correction. Thus, the aligned images were further cropped, reducing the size of images in sets 1–3 to 380×242 pixels.

Dental data with known contrast differences

Finally, an additional set (set 4) was produced from image pairs with known contrast differences. The contrast of the non-cropped reference image (428×310 pixels) from set 1 was manually adjusted, using a third-party image-processing application (GIMP²⁷). Therefore, floating images were produced by progressively increasing and decreasing the contrast of the reference image from 5% to 50%, in 5% intervals. As a result, 10 images were acquired with a contrast loss of 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45% and 50% relative to the reference image. Likewise, another 10 images were produced with a contrast gain of 5%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45% and 50% relative to the reference image. Sets 1–3 contain image pairs that exhibit minor contrast deviations and

Figure 2 Visual assessment of the histogram registration method on an image pair from set 4 of the images with known contrast differences. (a) The reference image; (b) the floating image; the subtraction product representing the absolute difference between (c) the reference and the floating image (without contrast correction); and (d) the reference and contrast corrected image using the histogram registration contrast correction method

reflect more realistic medical scenarios. On the other hand, set 4 consists of images with higher deviations and was specifically included to test the capabilities of the algorithm under extreme conditions. A more detailed description of the four sets is presented in Table 1.

Evaluation methods

The proposed histogram registration method was evaluated both qualitatively and quantitatively.

Qualitative evaluation mostly concerned visual assessment of the contrast corrected image. However, this is a rather trivial process which mainly depends on the subjective judgment of the human observer. Especially in cases with small contrast differences (sets 1–3), the results of the correction may not be obvious. Therefore, additional quantitative assessment was performed, based on objective measurements on the corrected images.

Table 1 Details for the four dental datasets of the study

Set	Number of images	Image size	Description	Acquisition method for floating images
Set 1	24	380 × 242	Aligned pairs with unknown contrast differences	Edge-based registration according to the reference image
Set 2	24			
Set 3	24	428 × 310	Image pairs with known contrast differences	Manual contrast modification of a copy of the reference image
Set 4	20			

The preferred criterion used for this purpose is the contrast root mean square difference (CRMSD). This criterion is an adaptation of the classic root mean square deviation (RMSD) generally used to assess the difference between two vectors.²⁸ In our case, the assessed vectors consist of pixel contrast values from the two subject images. Consequently, the CRMSD between the reference and the contrast corrected image, with height M and width N , is defined in Equation (7):

$$\text{CRMSD} = \sqrt{\frac{\sum_{y=0}^M \sum_{x=0}^N (c_r[x,y] - c_c[x,y])^2}{M \times N}} \quad (7)$$

where the quantities $c_r(x,y)$ and $c_c(x,y)$ represent the contrast of a single pixel with co-ordinates (x,y) from the reference and the corrected image, respectively.²⁹ The particular quantities can be obtained using Equation (8):

$$c(x,y) = \frac{lv(x,y)}{lm(x,y)} \quad (8)$$

For each pixel (x,y) of the image $I(x,y)$, the quantities $lv(x,y)$ and $lm(x,y)$ are calculated as follows:

$$lm(x,y) = \frac{1}{(2m+1)^2} \sum_{k=-m}^m \sum_{l=-m}^m I(x+k, y+l) \quad (9)$$

$$lv(x,y) = \frac{1}{(2m+1)^2} \sum_{k=-m}^m \sum_{l=-m}^m [I(x+k, y+l) - lm(x,y)]^2$$

where $I(x+k, y+l)$ is the intensity of the pixel in co-ordinates $(x+k, y+l)$ and $(2m+1)^2$ is a constant and represents the size of a square block in pixels. In our case 5×5 blocks were used ($m = 2$).

Using Equation (7), CRMSD measurements may be obtained for all reference-corrected image pairs in each set. As the CRMSD metric is in effect a measurement of the contrast deviation between the two subject images, it follows that small CRMSD values suggest a close match between the contrast of the reference and the corrected image. As a result, small CRMSD values correspond to high-quality contrast correction.

Comparative method

In order to better assess the performance of the proposed histogram registration algorithm, the method was compared with the widely used robust film contrast correction technique introduced by Ruttimann *et al*.⁹ This particular approach operates directly on the histograms of the subject images and uses their cumulative density functions (sums) in order to down-sample the corrected image in an attempt to reshape its histogram according to the histogram of the reference image.¹⁶

Ruttimann's algorithm processes the target histogram (histogram to be corrected) in a sequential

manner:⁹ for each level m in the target histogram, the largest grey level k in the reference histogram is found such that the cumulative sum over the reference histogram up to k is equal to or less than the cumulative sum over the target histogram up to m . The particular value should strictly be larger than the value of the cumulative sum up to grey level $m - 1$. Thus, for each grey level m from the target histogram, a correspondence with a grey level k from the reference histogram is formed. This correspondence defines the required grey-level transformation in order to correct the contrast of the floating image.

This technique was applied to all available 92 dental image pairs and the CRMSD metric between the reference and the corrected image was calculated in each case, according to Equation (7). Finally, the obtained measurements were compared with the respective measurements obtained when applying the proposed histogram registration method on the same images.

Results

The proposed histogram registration method was compared with the robust film contrast correction method suggested by Ruttimann *et al*, over all 4 sets of 92 image pairs. The comparison was performed according to the methodology described in the previous section both qualitatively and quantitatively. The CRMSD between the reference and the corrected image was recorded for all image pairs in each set. From the resultant metrics it was deduced that the proposed method outperformed Ruttimann's approach by being able to better approximate the contrast of the reference images in all considered cases. This section describes in some detail the results obtained using both methods. The quantitative results are discussed separately according to the acquisition process of each set (known and unknown contrast differences).

Qualitative evaluation

Qualitative evaluation was performed by means of visual assessment. An example is shown in Figure 3, featuring an image pair from set 3 of the registered images. In this case, the floating image (Figure 3b) is dimmer but it exhibits slightly higher overall contrast than the reference image (Figure 3a). As can be seen in Figure 3c, Ruttimann's approach further increases the contrast of the corrected image. This makes the new contrast much higher than that of the reference image, which is undesirable. The histogram registration method (Figure 3d) produces a corrected image with an overall contrast close enough to that of the reference image.

Visual assessment, however, is not always possible. In many cases (sets 1–3) the reference and floating images exhibit small contrast deviations, thus making it difficult for the human observer to evaluate the quality

a **b** **c** **d**

Figure 3 Visual assessment of the two contrast correction methods on an image pair from set 3 of the registered images. (a) Reference image; (b) floating image; (c) image corrected using Ruttimann's method; (d) image corrected using histogram registration

of the correction. Moreover, when comparing the two methods, there are numerous cases in which the performance difference is not perceivable when examining the corrected images visually. Such an example is shown in Figure 4, which features an image pair from set 4. Although there is a clear contrast gain (30%) of the floating image (Figure 4b) over the reference image (Figure 4a), there are no distinguishable differences between the corrected image produced using Ruttimann's approach (Figure 4c) and the one produced using the histogram registration method (Figure 4d). Therefore, quantitative analysis is a strong requirement for evaluating the effectiveness of contrast correction.

Quantitative evaluation

The quantitative analysis in this study was based on the CRMSD as described in the previous section. The CRMSD was calculated by considering the difference between the contrast of the reference and the corrected image on a pixel-by-pixel basis. The idea of the proposed evaluative scheme is that the lower the CRMSD value obtained, the higher the quality of

the contrast correction method. It follows that, when comparing two or more methods, the method capable of achieving the minimum CRMSD value is considered superior as far as contrast correction is concerned. The particular technique was used to assess the proposed histogram registration scheme against the contrast correction method introduced by Ruttimann *et al.* CRMSD measurements were obtained for both methods over all 92 image pairs. The results, presented in this section, are grouped according to the acquisition process of the test images. Therefore, the two methods are compared separately over registered image pairs with unknown contrast differences (sets 1–3) and image pairs with known contrast differences (set 4).

Measurements concerning the entire set 3 of registered image pairs are shown in Table 2. Table 2 records the CRMSD values obtained by comparing the contrast of the reference image in set 3 with the contrast of all corrected images in the set. In addition, the CRMSD of the uncorrected images is provided in each case. As can be seen, the histogram registration method is superior to the other method in 18 out of 24 cases. Furthermore, it performs better on average for the particular set

Figure 4 Visual assessment of the two contrast correction methods on an image pair from set 4 of the images with known contrast differences. (a) Reference image; (b) floating image with 30% contrast gain compared with the reference; (c) image corrected using Ruttimann's method; (d) image corrected using histogram registration

(0.725 over 0.760) and is more consistent than the other method as it achieves lower standard deviation. Especially for images 14 upwards of the particular set, Ruttimann's method consistently underperforms by resulting in higher CRMSD values than the proposed approach.

The histogram registration method also outperforms Ruttimann's approach for the rest of the sets featuring registered image pairs with unknown contrast differences (sets 1–2). Table 3 records average values for all CRMSD measurements obtained from sets 1–3. The proposed method achieves superior contrast correction as demonstrated by the lower CRMSD measurements for each set and consequently a lower overall average for all three sets of registered images. Those results may also be verified by examining Figure 5, in which the recorded CRMSD measurements are plotted for set 1 (Figure 5a) and set 2 (Figure 5b). Again, the CRMSD measurements obtained after the application of the histogram registration method (solid line with black circles) are generally lower than the ones obtained after

the application of Ruttimann's approach (dotted line with grey squares).

Finally, the two methods were compared over a set of image pairs with known contrast differences (set 4). As mentioned above, these particular images were especially tailored to exhibit quite large contrast differences in order to assess the two methods under extreme, albeit unrealistic, conditions. The CRMSD values between the reference and the corrected images for set 4 are recorded in Table 4. As can be deduced from Table 4, the proposed approach outperforms the robust contrast correction method introduced by Ruttimann in 15 out of 20 cases. Although the two methods yield similar results when considering floating images with contrast loss relative to the reference image, the proposed method exhibits superior performance in cases of contrast gain, as it outperforms the other method in all 10 such cases for the particular set. The superiority of the proposed method over set 4 is confirmed by its lower mean and standard deviation values (0.038 ± 0.052) compared with Ruttimann's

Table 2 Comparison of the two contrast correction methods over the entire set 3 (registered image pairs). The comparison is performed in terms of the contrast root mean square difference (CRMSD), between the reference and the corrected images. The CRMSD between the reference and floating image prior to contrast correction is indicated next to each image name

Corrected image (CRMSD of uncorrected floating image)	CRMSD	
	Histogram registration	Ruttimann's method
Image 1 (0.997)	0.887	0.963
Image 2 (0.788)	0.688	0.706
Image 3 (0.940)	0.844	0.876
Image 4 (1.148)	1.033	1.139
Image 5 (0.820)	0.722	0.772
Image 6 (0.897)	0.838	0.887
Image 7 (0.717)	0.628	0.549
Image 8 (0.699)	0.609	0.532
Image 9 (0.823)	0.822	0.829
Image 10 (0.686)	0.587	0.557
Image 11 (0.443)	0.422	0.347
Image 12 (0.371)	0.365	0.315
Image 13 (0.725)	0.710	0.685
Image 14 (0.453)	0.431	0.504
Image 15 (0.882)	0.770	0.830
Image 16 (0.588)	0.426	0.466
Image 17 (0.603)	0.446	0.527
Image 18 (0.743)	0.626	0.679
Image 19 (1.182)	0.944	1.040
Image 20 (0.979)	0.874	0.921
Image 21 (1.130)	0.997	1.127
Image 22 (0.931)	0.855	0.911
Image 23 (1.076)	0.989	1.073
Image 24 (1.083)	0.879	1.013
Mean $\pm$ standard deviation	0.725 ± 0.202	0.760 ± 0.245

correction method (0.062 ± 0.082), as shown in Table 4.

The above remarks are further supported by Figure 6, in which the CRMSD values obtained using the proposed method (solid line with black circles) and Ruttimann's approach (dotted line with grey squares) are plotted. The two methods perform equally well when correcting images with less contrast than that of the reference images by yielding CRMSD values of less than 0.015 in all cases. However, increasing the contrast of the floating images causes the performance of both methods to deteriorate. More specifically, Ruttimann's approach fails to properly correct images with a contrast gain of more than 25% relative to the contrast of the reference image, as its performance degrades rapidly after that point (CRMSD measurements of more than 0.100). On the other hand, the proposed

Table 3 Comparison of the two contrast correction methods over sets 1–3 of registered image pairs (average measurements). The comparison is performed in terms of the contrast root mean square difference (CRMSD), between the reference and the corrected images

Corrected image	CRMSD	
	Histogram registration	Ruttimann's method
Set 1	0.710 ± 0.137	0.738 ± 0.126
Set 2	1.114 ± 0.472	1.157 ± 0.536
Set 3	0.725 ± 0.202	0.760 ± 0.245
Mean over sets 1–3	0.850	0.885

method is much more tolerant to such images as it is effective for contrast gain values as high as 35%.

In order to assess the significance of the results presented in this section, an additional statistical test was performed. The obtained CRMSD measurements between the contrast of the reference image and that of the corrected images were compared pair-wise for the two methods, using a Student's paired *t*-test.³⁰ The *t*-test is broadly used to assess the significance of the difference between two means. In our case, the proposed histogram registration method performed better on average than Ruttimann's robust method, by achieving lower mean CRMSD values over all sets, as shown in Tables 3 and 4. A *t*-test was used to determine whether the difference between the two methods is statistically significant. In our case, four *t*-tests were performed, one for each set. The two-tailed paired *t*-tests were performed at a 95% confidence level, with the null hypothesis that the two methods do not differ significantly in each set. The *P*-values obtained were $P_1 = 0.0033$, $P_2 = 0.04553$, $P_3 = 0.01069$ and $P_4 = 0.00283$ for sets 1, 2, 3 and 4, respectively. The null hypothesis can thus be rejected with a confidence of 95% in all four sets.

Discussion

From the qualitative and quantitative results presented in the previous section, it may be deduced that the histogram registration method provides superior contrast correction quality to the well-established contrast correction method introduced by Ruttimann. The proposed method performs better on average over all 4 available sets used in this study, featuring a total of 92 dental pairs. Histogram registration was especially advantageous for image pairs where the floating image exhibited large contrast gain over the reference image. The assessment of the two methods was based on the CRMSD between the reference image and the corrected images in each case.

In the vast majority of similar works, the average intensity and standard deviation of the subject images are compared before and after contrast correction in order to evaluate the performance of the algorithm. Although those two metrics are sufficient in most cases, they only approximate contrast measurements. On the other hand, the CRMSD scheme proposed in the "Evaluation methods" section considers purely the contrast of the subject images and thus directly evaluates the contrast difference between the reference and the corrected image. As the contrast of a non-distorted image exhibits a very limited range (practically from 0.2 to 2.0), the CRMSD metric is very sensitive to even minor variations in the contrast of the two examined images. As a result, the relatively small differences shown in Tables 2–4 in favour of the proposed method actually correspond to a quite distinct divergence. The statistical tests were included in this study to support this claim.

Figure 5 Comparison of the two contrast correction methods for sets 1–3 (registered image pairs), based on the contrast root mean square difference (CRMSD) between the reference and the corrected images. Plots of the CRMSD values obtained using the histogram registration method (solid line with black circles) and Ruttimann's method (dotted line with grey squares) for (a) set 1 and (b) set 2

As mentioned in the Methods and materials section, the proposed method depends on two parameters that control the operation of the simplex optimization algorithm. More specifically, $D_{\max}$ and $\alpha_{\max}$ define the maximum allowable values for parameters D and α of the linear transformation which is used in our model, as shown in Equation (1). As mentioned above, the particular linear equation is applied in order to transform the histogram of the corrected images. Therefore, the optimization algorithm tries to minimize the preferred measure of match function by transforming the subject's histogram using several combinations for parameters D and α . The tested values are selected from the range shown below.

$$\begin{aligned} & -\alpha_{\max} < \alpha < \alpha_{\max} \\ & -D_{\max} < D < D_{\max} \end{aligned} \quad (10)$$

As a result the selection of suitable limits for D and α is quite important for the histogram registration contrast correction method as it affects its performance.

Nevertheless, the proposed method is able to operate using any of the values shown in Equation (2) for $D_{\max}$ and $\alpha_{\max}$. However, only specific values for those parameters ensure optimal performance. The particular values vary according to the characteristics of each image. Consequently, several trials were performed per image pair using different combinations for $D_{\max}$ and $\alpha_{\max}$ in order to produce the best possible contrast corrected image in each case.

A typical example is illustrated in Figure 7, in which an image pair from set 2 is used to examine the effects of varying the maxima for parameters D and α of the linear histogram transformation. The histogram registration method was applied using several combinations of $D_{\max}$ and $\alpha_{\max}$, and CRMSD measurements were obtained and recorded in each case. Figure 7a shows the efficiency of the proposed contrast correction when varying $\alpha_{\max}$ while keeping $D_{\max}$ constant. Similarly, Figure 7b depicts the effects when varying $D_{\max}$ with a constant $\alpha_{\max}$. As can be seen in Figure 7, the best possible contrast correction quality is achieved when $D_{\max} = 50$ and $\alpha_{\max} = 1.5$ for the particular

Table 4 Comparison of the two contrast correction methods over the entire set 4 (image pairs with known contrast differences). The comparison is performed in terms of the contrast root mean square difference (CRMSD), between the reference and the corrected images

Corrected image	CRMSD	
	Histogram registration	Ruttimann's method
5% contrast loss	0.000	0.010
10% contrast loss	0.009	0.011
15% contrast loss	0.012	0.011
20% contrast loss	0.004	0.010
25% contrast loss	0.007	0.010
30% contrast loss	0.008	0.011
35% contrast loss	0.010	0.010
40% contrast loss	0.013	0.010
45% contrast loss	0.012	0.011
50% contrast loss	0.014	0.010
5% contrast gain	0.000	0.010
10% contrast gain	0.000	0.011
15% contrast gain	0.013	0.034
20% contrast gain	0.027	0.038
25% contrast gain	0.035	0.089
30% contrast gain	0.067	0.130
35% contrast gain	0.081	0.150
40% contrast gain	0.122	0.188
45% contrast gain	0.147	0.229
50% contrast gain	0.171	0.259
Mean $\pm$ standard deviation	0.038 $\pm$ 0.052	0.062 $\pm$ 0.082

image pair. The aforementioned combination produces the minimum CRMSD measurement between the reference and the corrected image, compared with any other combination shown in Figure 7a,b.

Once the optimal parameter combination was obtained for each of the 92 image pairs, the proposed histogram registration method, as well as Ruttimann's method, were applied to all available pairs. In general, the proposed approach was marginally faster than the other method. It took from 1 to 2 s to correct the

contrast of the floating images in each set. The execution time mainly depends on the characteristics of each pair, as the time required for the simplex algorithm to minimize the measure of match may be different in each case. Ruttimann's method, on the other hand, exhibits a uniformly distributed performance, as far as its execution time is concerned. The proposed method, however, did not greatly depend on the morphology of the subject images as it required about 2 s to converge in most cases. Thus, in terms of execution time, the proposed approach in most cases outperforms Ruttimann's method. All tests were performed on a common reference system (AMD Mobile Sempron 1.6 GHz, 2 GB of RAM, running Microsoft Windows XP).

As mentioned in the Introduction, the most common use of contrast correction in medical imaging is to support DSR. This is mostly achieved by enhancing the interpretability of the subtracted images. In general, DSR schemes contain the following steps:

- contrast correction of the floating image according to the reference image,
- registration of the floating image according to the reference image, and
- calculation of the (absolute) difference between the reference image and the registered image.

Steps (b) and (c) are required, whereas step (a) is used to enhance the results obtained in steps (b) and (c). Contrast correction is optional but is commonly used in realistic medical scenarios in order to obtain easily interpretable results.

However, it is not clear in general when the contrast correction algorithm should be applied, especially in the case of registration methods based on the grey-level information of the two images. There are two possibilities: before and after the registration process.

Figure 6 Comparison of the two contrast correction methods for set 4 (image pairs with known contrast differences), based on the contrast root mean square difference (CRMSD) between the reference and the corrected images. Plots of the CRMSD values obtained using the histogram registration method (solid line with black circles) and Ruttimann's method (dotted line with grey squares)

Figure 7 Evaluation of the two parameters involved in the histogram registration algorithm, in terms of the contrast root mean square difference (CRMSD) between the reference and the corrected images. The evaluation is performed on an image pair from set 2. Effects on CRMSD for varying (a) $\alpha_{\max}$ and (b) $D_{\max}$

A simple assessment was additionally conducted in this study in an attempt to clarify this matter. The proposed histogram registration method was applied to all image pairs from set 1 before and after registration. The registration scheme used in this case features the affine transformation shown in Equation (5), the cross-correlation coefficient²³ (similar to Equation (3)) as a measure of match and the simplex optimization method²² to obtain the optimal affine parameters. These methods are similar to those used in the proposed contrast correction algorithm. In this case, nevertheless, they operate on the pixel intensities of the subject images and transform pixel co-ordinates rather than histogram levels.

The results are shown in Table 5, in which the two scenarios are compared in terms of the average (mean) intensity of the subtracted image. It follows that low values of the mean intensity correspond to superior quality for the subtracted images. As identical registration and contrast correction methods were used in the same images in both cases, any deviation in these values may be attributed to undesired contrast differences between the resultant and the reference image. As can

be seen in Table 5, the two scenarios perform equally. Correcting the contrast of the floating images after registration does indeed allow for marginally lower mean intensity on average (5.183 compared with 5.249), but the significance of this result could not be verified statistically. A *t*-test on the data shown in Table 5 failed to prove any statistical difference between the means of the two scenarios. Therefore, based on the data extracted from the particular set, the order in which registration and contrast correction steps are performed does not affect the end product of the subtraction process.

As mentioned in the Materials and methods section, the proposed histogram registration method tries to match the contrast of two subject images by transforming the histogram of the floating image according to that of the reference image. The parameters of the linear transformation used in this study are optimized through the simplex optimization method. The modulus design of the proposed algorithm allows for a wide variety of future improvements and further assessment. For instance, the rather simplistic linear transformation function could be replaced by a non-linear model with additional

Table 5 Comparison of the image subtraction quality for performing contrast correction before and after the registration process. The comparison is performed in terms of the mean intensity of the subtracted images

Corrected image	Mean intensity of subtracted image	
	Contrast correction before registration	Contrast correction after registration
Image 1	5.593	5.529
Image 2	5.470	5.094
Image 3	5.057	5.538
Image 4	5.130	5.518
Image 5	6.070	5.298
Image 6	4.847	4.847
Image 7	4.592	4.408
Image 8	4.103	4.158
Image 9	4.742	4.240
Image 10	4.848	4.644
Image 11	4.564	4.995
Image 12	4.330	4.674
Image 13	4.091	3.979
Image 14	4.568	4.242
Image 15	5.134	5.381
Image 16	5.042	4.883
Image 17	5.303	5.087
Image 18	5.186	5.308
Image 19	5.321	5.036
Image 20	7.315	6.793
Image 21	6.111	6.056
Image 22	6.440	5.948
Image 23	5.931	6.238
Image 24	6.195	6.494
Mean $\pm$ standard deviation	5.249 $\pm$ 0.786	5.183 $\pm$ 0.749

parameters to allow for finer histogram transformations. Moreover, the simplex optimization method could be supplemented with additional optimization techniques,

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such as Powel's method, which is quite common in conventional image registration schemes. Finally, several alternative measures of match could be used in place of the cross-correlation coefficient preferred in this study. Future studies could also evaluate the proposed method on medical data from several modalities (CT, MRI and retinal) as well as assess the proposed approach against several other contrast correction algorithms.

In conclusion, a novel contrast correction method based on histogram registration was proposed in this study. The proposed method uses typical image registration principles and techniques in order to match the histograms of an image pair. The method was compared against a widely used contrast correction method and showed advantageous performance in terms of the obtained contrast of the corrected image. The two methods were compared using the CRMSD between the reference and the corrected image. After applying the 2 methods in all available 92 image pairs of this study, the histogram registration method achieved lower CRMSD measurements on average. Additional statistical *t*-tests in each set proved that the proposed method systematically outperformed the other method for the particular datasets used in this study.

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