A Pseudo-HDR Method Implementation for Medical Images Enhancement

New post-processing method for X-ray chest image quality enhancement

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***Abstract*— Medical images are an important part of the diagnostic process. In many cases the accuracy of diagnosis depends on the quality of the image. The investigation and development of new medical image processing methods and systems has received great attention over the last two decades. This is due to its wide range of applications in computer-assisted methods and computer-aided methods. The proposed paper presents a new image enhancement method for X-ray images. The method uses an HDR-image creation as a technique to increase the image dynamic range. This allows after mapping an HDR-image to an LDR-image (low dynamic range image) to get a better distribution of the intensity over all pixels in the image. The result is enhancing brightness, contrast and/or sharpness of images without the appearance of visible medical artefacts.**

Keywords - X-ray medical imaging; HDR-images; image quality enhancement.

I. INTRODUCTION

Medical imaging is the process of creating images (visual representations) of the human body organs and tissues for medical purposes to diagnose and treat disease - it is intended to reveal internal human body structures hidden by the skin and bones. The process is defined as non-invasive as it does not disturb the physical integrity of the skin and tissues.

The main method of medical images interpretation is the visual one, makes the process depend on the observer [1]. It has been found that some doctors have systematic underestimation or overestimation of the information in the image - they reject some information as insignificant or overestimate the importance of structures in the image. Additional influence on the final image is exerted by overall readability of the image because the conclusions "no changes" or "no noticeable changes" are not the same thing. Some other factors for the proper medical image interpretation are time for investigation, environment, image lighting, type of media of the image, and the physiological/functional status of the physician [2][3]. All this leads to the need to improve the readability of images and to reduce the factors influencing the perception of information in images.

The techniques for obtaining medical images are not harmless to patients: different amounts of radiation are absorbed by the various body tissues (bones, muscles, soft tissues, etc.), leading to resulting physical and chemical reactions, as well as to a variety of physiological changes in the human body. Clinical practice mainly uses two types of X-ray images: the standard radiological images obtained by projection, and fluoroscopic images representing X-ray images in real time, used as an aid in medical procedures. Notwithstanding the advantages of CT and PET imaging, these two radiographic techniques are widespread due to their low price, relatively high quality and relatively low doses of patient radiation.

To obtain better quality X-ray images with greater contrast and clearer details it is necessary to increase the amount of radiation that a patient is subject to. To avoid this harmful effect on humans, a variety of technologies have been developed by using additional grids to the X-ray detectors for absorbing the scattered radiation and reduction of the size of the X-ray beam. Another approach, which is widely used, is the use of methods for computer-assisted diagnosis, to improve the quality of medical images without increasing the radiation load on the patient.

Radiographic studies are one of the most commonly used techniques of the diagnostic process in pulmology (the X-rays and CT scans are the most frequently used image acquisition techniques). For the proper interpretation of X-ray images the quality of the image has the greatest importance. While the image quality of modern digital X-ray apparatus is good, with conventional X-ray apparatus in many cases the quality is unsatisfactory. This is one of the main sources for the wrong interpretation of the image, resulting in hypo- or hyper- diagnosis. An example of a disease that may be "masked" is the peripheral lung carcinoma. In the initial stages of this carcinoma the X-ray density is usually not big and when the X-ray image is overexposed it may not be visible. Detection of this carcinoma in this early stage is very important because it rarely manifests any symptoms at this stage, but in an advanced stage radical treatment is impossible. So the X-ray image reading is the only way for early diagnosis.

Other examples of lung diseases that require high quality images are secondary tuberculosis (especially in the case of circular fireplace), viral pneumonia and pulmonary embolism.

This paper presents a new image enhancement method for X-ray images. The method uses HDR-image creation as a technique to increase the image dynamic range. This allows after mapping HDR-image to LDR-image (low dynamic range image) to get a better distribution of the intensity over all pixels in the image. The result is enhancing brightness, contrast and/or sharpness of images without the appearance of visible medical artefacts.

This present paper is structured as follows: Section II looks into the set of methods for HRD imaging; Section III presents the proposed new enhancement method; Section IV presents the implementation and analyses of the presented method; Section IV presents the conclusion.

II. WHY MEDICAL IMAGE ENHANCEMENT METHODS ?

The investigation and development of new medical image processing methods and systems has received great attention over the last two decades. This is due to its wide range of applications in computer-assisted methods and computer-aided methods.

Regardless of the quality of X-rays, there are many reasons that necessitate the creation of new methods and techniques for improving quality and readability of digital images used for medical diagnosis. Our research showed that the most frequent by encountered reasons for using methods and techniques for medical images post-processing can be grouped in the following way:

- The image isn't captured with the optimal X-ray apparatus settings. The most important for the X-ray picture quality is the choice of exposure, because it can get overexposed or underexposed images (for digital the X-ray apparatus the selected type of linearization of X-ray sensor affects also the choice of exposure values). Often the resulting image is acceptable, but the contrast is not the best for a correct interpretation of the image (Fig. 1a). This has a significant impact on reading images containing small size structures or in need of early diagnosis of diseases, where the change in X-ray density of the abnormality is less pronounced, i.e. the change in gray tones for an examined area is still small and hardly noticeable.
- The characteristics of the display or output media do not allow you to see all the special features of the examined image. This most often occurs when the image has a greater depth than the possibilities for visualisation. Since, in this case, the computer system performs compression of the image depth; the result is loss of contrast and dynamic range. A very common manifestation of this problem is recording the medical image in a format different from the DICOM one (Fig. 1c). Most often this is used to reduce the volume of archieved images (the digital patient archive), or if necessary to make a copy for the patient.
- It is physicians who diagnose using X-ray picrutres. It has been established that the physician's functional, physiological and mental status has direct impact on the ability to correctly read the X-rays [2][3][4]. In this case, the image post-processing allows altering the digital image characteristics so that they become readable for the physician.

a. b. c. d.

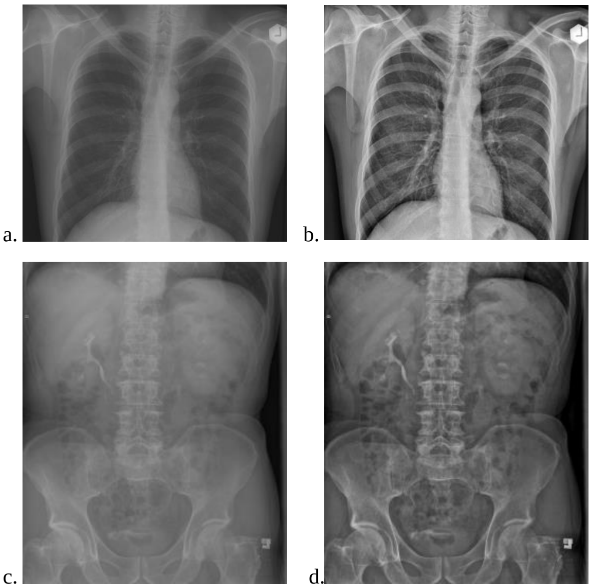

Figure 1. Examples of the necessity to use a post-processing of the images before they are used for diagnostic: a) image after capturing by incorrect apparatus settings; b) improvement of quality of image (1.a) with our method; c) image from digital X-ray apparatus, recorded in a file with 8 bits depth (JPG without compression); d) improvement of quality of image (1.c) with our method.

Among the many types of image processing tools, image enhancement is one of the vital processes in medical imaging systems – it is one of the preparatory steps and it is applied before starting the image analyses. Image enhancement refers to any technique that improves or modifies digital images, so the resulting image is better suited than the original for a particular application. Essential image enhancement includes but is not limited to intensity and contrast manipulation, noise reduction, background removal, sharpening and filtering edges. In this context, 'image enhancement' means any method or technique which change digital images, so the resulting image is better suited than the original to a particular application. Due to this the basic types of image enhancement include manipulation of intensity, changing the local or global contrast, noise reduction, filtering and sharpening edges. During the image enhancement process one or more attributes of the image are modified. The choice of attributes and the way they are modified is specific to a given task. Moreover observer-specific factors such as the human visual system and the observer's experience will introduce a great deal of subjectivity into the choice of image enhancement methods [1].

X-ray images are grayscale images with 12-14 bits depth and their visual perception depends on the three most common image characteristics: brightness, contrast (local and global) and sharpness. Apart from these saturation and image dynamic range have a significant influence on the human perception of the images but they are not directly relevant to X-ray images, because images are grayscale (no saturation), and the dynamic range of the visualization systems (computer displays) is less than human vision dynamic range. Therefore, all quality enhancement methods change the intensity of pixels so as to provide optimal brightness, contrast and sharpness values. While brightness, contrast and sharpness may appear to be the simplest of image controls on the surface and may appear to be mutually exclusive controls, they are related and intertwined in such a way that changing any one of them can create quite complex effects in post-processed images. This specifies a wide variety of methods that have been proposed and are being created now – each of these methods seeks to solve the task of determining the image characteristics optimal values.

A sample classification of medical image enhancement methods is shown in the Fig. 2. [8][9][10][11]

In the image processing literature there is a wide variety of image processing operators, but only a part of them are used for the processing of medical images. The main reason is the need for preservation of the medical authenticity of the image after applying the selected operator. Our analyses show that medical systems most often use the following functional groups of operators.

- Arithmetic and Logic operators: these are different forms of unification/fusion of the pixels of the two images to obtain the resultant pixel.
- LUT operators (Look-up-table operators): these operators change pixels' grayscale levels by functional transformation on a single pixel.

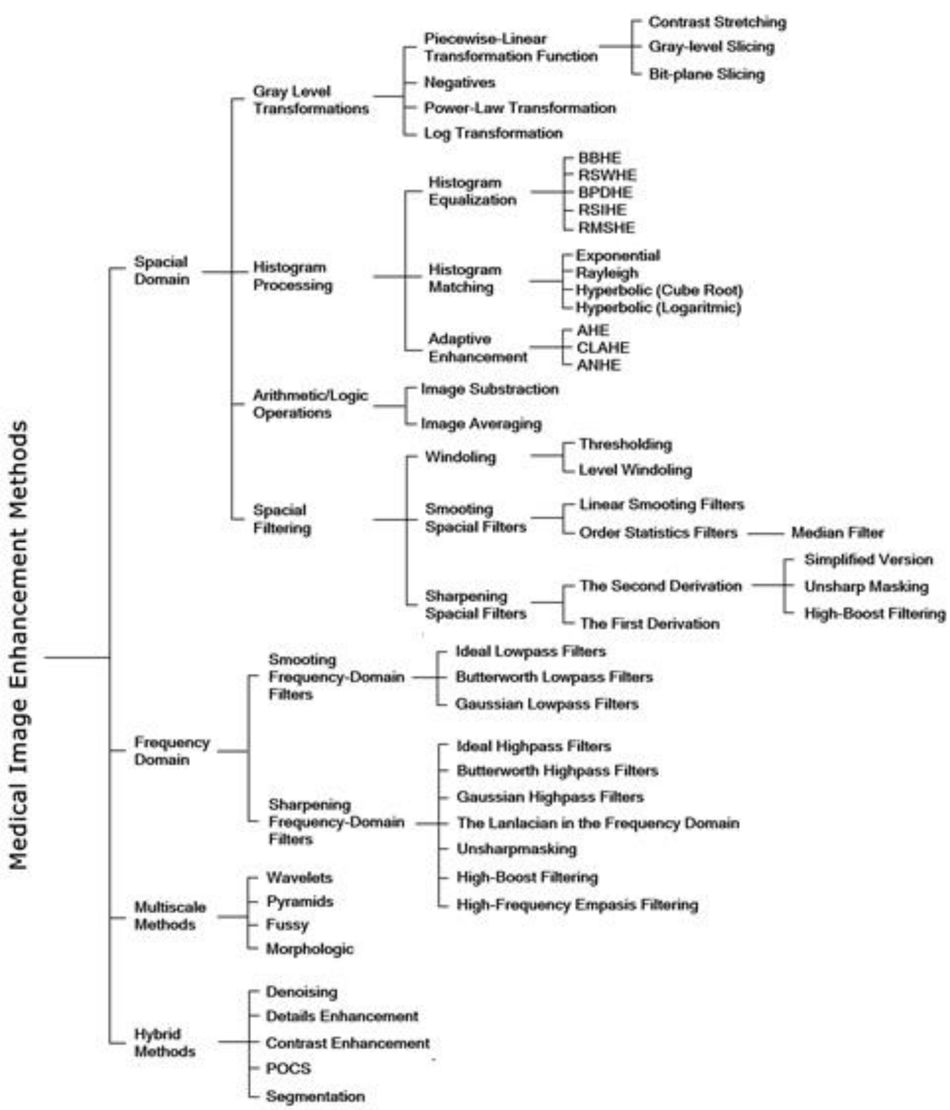

Figure 2. Medical image enhancement methods classification.

Geometric operators: the most common purpose of these operators is to remove the geometric distortions and shifting of the image, due to the image acquisition. Operators for image translation, rotation, and scaling are among those most often used.

- Image analysis operators.
- Morphologic operators: these are operators for analyzing pixels groups using mathematical morphology.
- Digital filters
- Attribute operators: these are operators for detection of basic properties or characteristics; this group includes operators, which are used to detect edges, lines or other specific structures.
- Image transformation operators: they are used to transform the image into another presentation in order to more easily process it for certain needs.
- Synthesis operators: most often these are noise generation methods.

Fig. 3 shows a more extended classification of the most commonly used operators for image processing in medical imaging systems.

III. X-RAYS IMAGE ACQUISITION AND QUALITY CHARACTERISTICS

During the X-ray image creation process the number of X-rays which interact with the human body tissues and organs depends on the thickness and distribution of the anatomical structures in the body. The ‘diagnostic’ X-rays are primarily those that occur in photoelectric and Compton processes:

- Photoelectric interactions are the most important ones in the formation of images, because of the strong dependence of the photoelectric process on the location of the absorbent tissue atoms and the absence of secondary radiation.
- Compton-type interactions occur in soft tissues, depending mainly on their density. During these interactions multiple scattered photons occur, which leave the patient's body and reach the detector. Their direction is not associated with the focal point of the X-ray tube, which primarily causea a decrease of the image contrast.

There are three main options for the interaction of photons with the human body organs and tissues:

- All the X-ray photons pass through the patient and reach the detector (the X-ray plate or the digital X-ray sensor). Such is the case when the X-ray photons pass through areas with air in the lungs. In this case the result is an image with dark (almost black) areas in the lungs.
- The X-ray photons are absorbed completely, for example in interaction with metal elements. In this case the metal objects are displayed in white on the X-ray.
- The most common case of interaction of radiation with human tissues is when the X-ray photons reach tissues and there is photons scattering and attenuation. So only part of the photons reach the detector and this creates areas with different levels of gray in the final X-ray image.

If the X-ray photons will be absorbed or not by the patient’s tissues depends on several factors, the most important of which are the energy of the X-ray beam and the density of the human tissue. Therefore, one of the main tasks of the radiologist is the correct selection of the energy of the X-ray beam according to the patient tissues, which will be explored. This directly affects the X-ray image quality.

In medical X-rays five basic grey levels (from black to white) can be defined. This classification is based on the main basic X-ray densities of tissues and organs, as the tissues with low density are plotted with darker tones, compared to those with greater density:

- black – air in the lungs;
- dark gray – subcutaneous tissue (fat);
- light gray – the heart and blood vessels (soft tissues, water, blood, etc.)
- near to white – clavicles, ribs and bones;
- white - metal items (jewelry, orthopedic items, hospital equipment, marker left side).

The principle of reading the X-rays is based on the fact that the structures or organs can be recognized in the image only based on the differences in X-ray density of adjancent structures, such as light gray areas of the heart to black areas of air in lungs. In this way the interpretation of X-ray images requirs the areas with normal and pathological coloring in gray tones to be defined [12][13][14][15].

According to modern concepts the medical image quality can be described by three basic physical characteristics: contrast, sharpness and noise [16][21][22]. Between these characteristics there is a mutual interdependence, the improvement of one can lead to the deterioration of another [17][19]. Three levels, characterizing the quality of the image [1], are used in practice:

- Visualization – the object is detected without its details being reproduced;
- Display - details of anatomical structures are outlined, but out necessarily distinct;
- Imaging - details of the anatomical structures are clearly outlined.

Contrast is one of the main characteristics of the X-ray image, directly affecting the general readability of the image. Ray contrast is defined as the relationship between the difference of power transmission at two different points, and its average (background) value [20]. It depends on the tissues attenuation coefficients and the tissues thickness. Radiographic contrast is determined by the resulting visible image: it represents the difference between the optical densities (or between brightness) in two adjacent areas [21]. At the same time, the effect of the scattering of X-rays is expressed in almost constant intensity of the background I_S, imposed on the real image. This results in the decreasing of the image contrast which can be expressed by the formula:

$$C = \log_{10}\left(\frac{I_1 + I_S}{I_2 + I_S}\right) \quad (1)$$

where I_1 is the intensity of X-rays passed through the soft tissue and I_2 is the intensity of the X-rays passed through the bones.

The type of transition in optical density (or brightness of the image) characterizes the sharpness of the X-ray image.

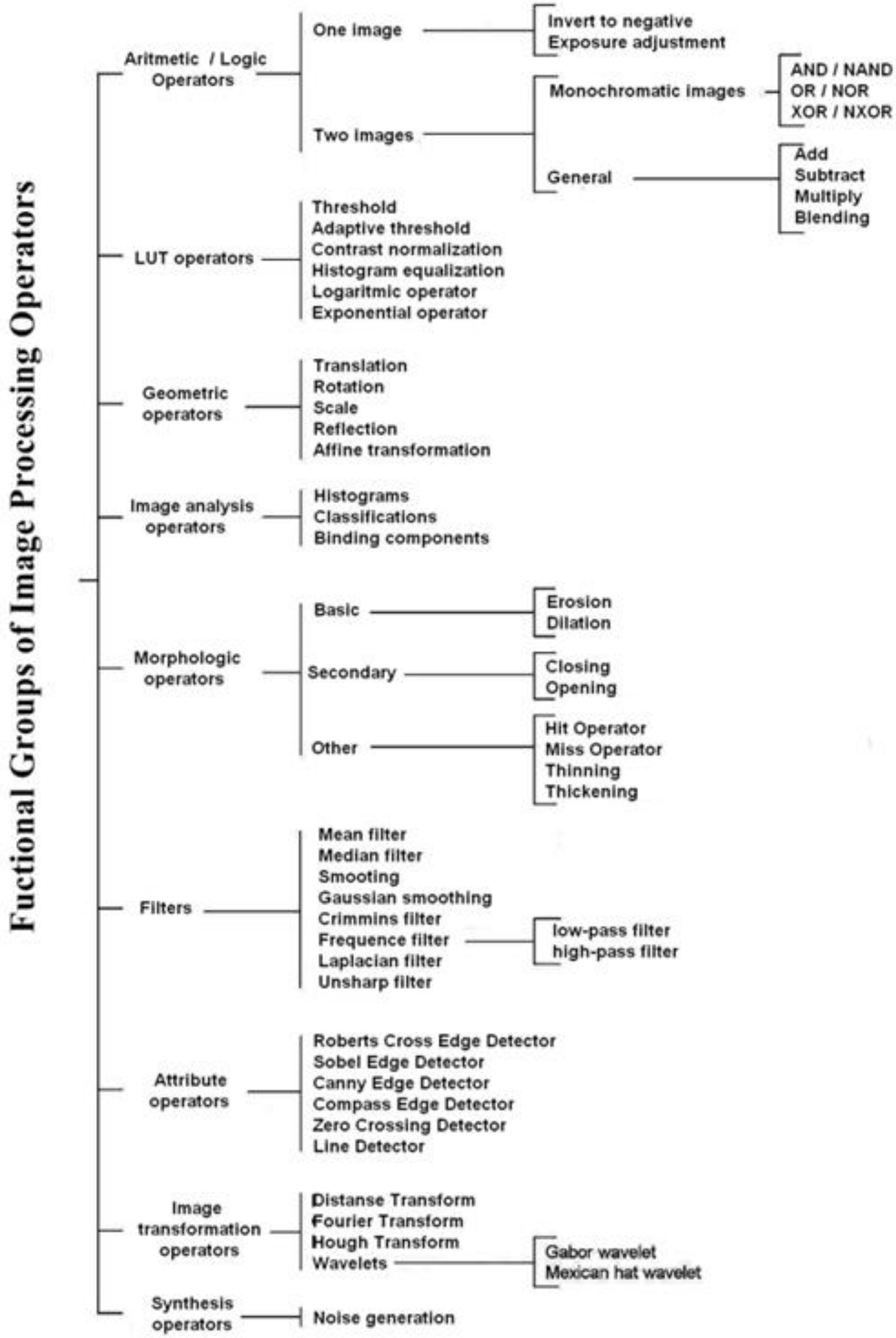

Figure 3. The most commonly used operators for the image processing in the medical imaging systems.

In medical imaging the main reasons for the decrease in sharpness are the following:

- Loss of geometric sharpness is a consequence of the size of the optical focus of the X-ray tube. Apart from reduction of its size, it can be limited through the use of as little as possible zoom for less distance between the object and the detector.
- Loss of dynamic sharpness is due to patient movement during the X-ray image capturing and can be reduced by shorter exposure times.
- Loss of contour sharpness is caused by rounded shapes of the organs and structures in the patient body.

Total loss of sharpness of the image U_{TOT} depends on several factors and the influence of each of them can be expressed by the expression:

$$U_{TOT} \approx \sqrt{\left(U_G^2 + U_M^2 + U_D^2 + U_I^2\right)} \qquad (2)$$

where:

- U_G characterizes the position of the patient relative to the X-ray tube and the detector and can be determined by the formula (FP_{size} is the size of the focal point; $D_{obj\text{-}sensor}$ is the distance between the object and the detector; and $D_{focus\text{-}obj}$ is the distance between the focus point and the object)

$$U_G = \frac{FP_{size} * D_{obj-sensor}}{D_{focus-obj}} \qquad (3)$$

- U_M expresses the effect of the patient shift during image capturing.
- U_D is called a detector blur and characterizes the effect of the detector type;
- U_I is the so-called ‘inherent blur’, which is determined by the shape of the captured object.

In this way, the total loss of sharpness characterizes the change in the size of the smallest visible detail in the image.

The X-ray image noise appears as random variations in the signal of the converter in a homogeneous structure of objects in digital radiographic systems. There are several noise sources and the main source of noise is quantum noise – it is the result of statistical fluctuations in the number of X-rays reaching the detector [19].

For grayscale images, as most medical images are, the image histogram can be used as an initial characteristic of image quality – it may show the areas that need digital enhancement. It is particularly important to take into account the fact that grayscale levels and pixels values are not the same thing, because the change of the image can be done by changing the grayscale levels, without changing the pixels values [18]. This is realized through the change of the Look up Table (LUT).

Another important characteristic and criterion for the image quality evaluation is the dynamic range – it describes the difference between the maximum (a_{max}) and minimum (a_{min}) value for a pixel in the image:

$$D = 20 * \log_{10} (a_{max} - a_{min}) \qquad (4)$$

The correlation between the dynamic range and the contrast of the image has been a long-known fact. For the grayscale medical images this relationship is even more pronounced, but that does not mean that contrast and dynamic range are synonymous – contrast depends not only on the dynamic range, but also on the average distribution of the values of the pixels in the image, as well as on the number of peaks in the image histogram.

Theoretically, for medical X-ray image capturing the dynamic range of the detector should be similar to the range of the emitter. In cases in which the emitter has a greater dynamic range than the detector, a cut of received values outside the dynamic range of the detector is obtained – it can easily be seen in the histogram of the image (the histogram has peaks in the black part and/or in the white part). In practice the reverse also occurs: the dynamic range of the detector is sagnificantly larger than the dynamic range of the transmitter – in this case, the values are grouped in a limited part of the histogram, and in the black and/or in the white part of the histogram there are no values.

IV. The most common problems with the X-ray image quality

Digital X-ray images can be obtained in two ways – after digitization of X-ray plates/films, or from digital X-ray apparatus. These are two completely different sources of images, so there are different reasons for change in the quality:

- With digital X-rays the main problem is related to the image format in a long-term registers – the DICOM format is very unconvinient for those purposes due to the large volume of images. Our studies showed that a hospital with 50 000 patients needs 5-8 GBytes per year new external space only for storage of digital X-rays. So increasingly, hospitals after a certain period transfer images from external memory on new generation X-ray plates or films.
- The main problems of quality of X-rays captured by the classical X-ray apparatus are related to the calibration of the X-ray apparatus and with changes in X-ray plate during a prolonged storage. The digitalization process can also lead to changes in the quality of the final digital X-rays, but these kinds of problems of are not part of the discussion in this article.

The two most common problems resulting from the of X-ray apparatus calibration (other than the noise) are obtaining overexposed or underexposed X-rays. This leads to a change in the image dynamic range and/or the image contrast, as well as to the possibility to improve X-image quality by post-processing techniques:

- Underexposed X-rays - these are very bright images and the main problem is related to the lack of sufficient visual information in the image. Such images have small dynamic range and a unimodal histogram with a clearly expressed peak in the white end of the histogram (Fig. 4). Additionally, the histogram may have several distinct local peaks (usually one or two). In this case, the classical methods for histogram manipulation do not create medical trustworthy images, because a post-processed image has characteristics of pronounced pathologies.

- Overexposed X-rays – these images are too dark areas, due to the large amount of radiation passed through the patient. They have a bimodal histogram with peaks near the white and black ends, i.e. they have a good dynamic range (Fig. 5). This is the result of overexposure in the soft tissues (the tones close to the black) and the regions with higher radiographic density (e.g., thicker bone) that have colors near to white. This pronounced bimodal histogram with large and very distant peaks greatly decreases the applicability of classical methods for image contrast improvement.

Problems, which are the result of improper storage of X-ray plates, are due to the change of the physical and/or photo-optical characteristics of the plates. These changes have led to a change in the quality of the recorded image:

- The whitening of the X-ray image – this leads to loss of the image dynamic range (Fig. 6).

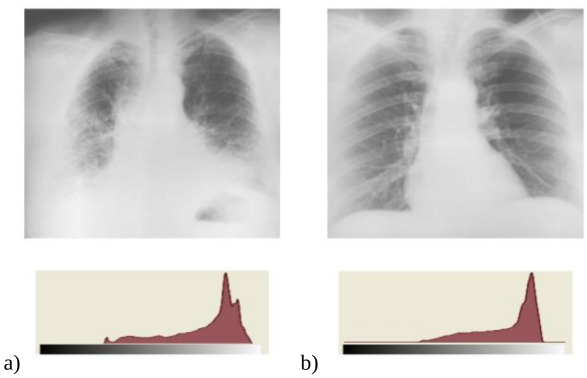
a) b)

Figure 4. Examples of underexposed X-rays and their histograms.

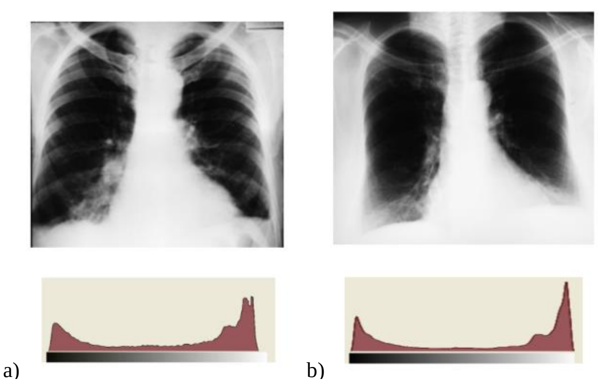
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Figure 5. Examples of overexposed X-rays and their histograms.

- The X-rays cease to be grayscale images and turn into colored images (Fig. 7).
- The appearance of characteristic and clearly distinct linear or point changes in the X-ray plate surface.

In terms of quality enhancement methods the X-rays whitening is the most interesting problem. The reason for its occurrence is exposing plates to constant external light (e.g., sunlight). This leads to change of photo-optical characteristics of the plate, i.e. light levels in adjacent dark and light areas converge. The result is a reduction of the image dynamic range and/or decreasing of the image contrast. In this case the histogram change resembles the change, which is the result of gamma-correction.

The coloring of the X-ray plates is also a significant problem, because quality enhancement methods of digital X-ray images are developed for grayscale images. The problem is very interesting, but its discussion is out of the scope of this article.

V. HDR Imaging

High Dynamic Range Imaging is a set of methods in photography/imaging, supposed to capture/create a greater dynamic range between the darkest and lightest image areas than current standard digital imaging methods [5][6]. The information in the HDR-image file isn‘t based on based on the chosen color model – the stored values are logarithmically encoded or floating-point linear values, or gamma compressed values of luminance [5].

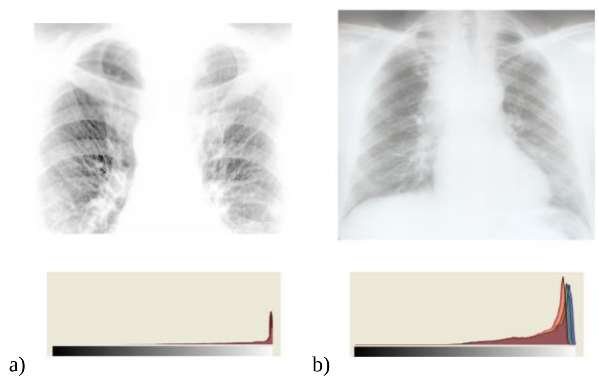

a) b)

Figure 6. The result of whitening of X-rays: a) clean whitening; b) whitening+coloring.

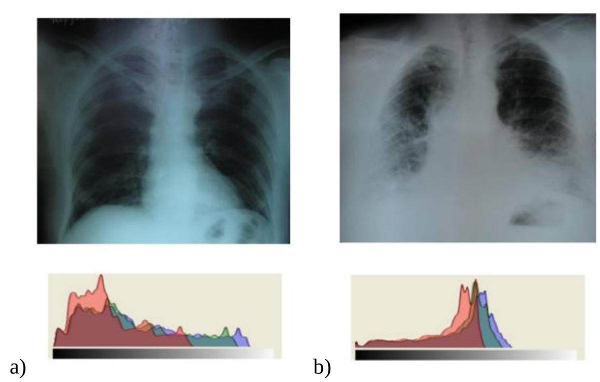

a) b)

Figure 7. Examples of X-ray plates coloring resulting of aging of the plate material.

At the same time the HDR-images don’t use fixed presentation of individual color channels – to represent the increased amount of colors they use floatin-point values (the LDR-images use integer values to represent the color channels of selected color model). That is why HDR-images provide much more correctly the luminance levels in the captured scene compared to classic images with low dynamic range (LDR-images).

The human eye covers the dynamic range of about 10^5:1 at one time and this is bigger than the top dynamic range of most real-world scenes. For comparison, computer displays have dynamic range of 10^3:1 and digital cameras have dynamic range of 10^4:1. In the last two years HDR cameras with dynamic range just over normal human vision dynamic range and displays with near to human vision dynamic range began to appear on the market.

The human vision can be accommodated to a dynamic range of 10^{14}:1 but the iris is simply not as flexible and the human perception of intensity changes is logarithmic (the Weber law). This is much more than the capabilities of modern devices for image creation and visualization. Therefore, a non-HDR image device takes pictures at one exposure level with a limited contrast range. This leads to the loss of details in dark or bright image areas, depending on the camera exposure setting. HDR methods compensate detail loss by taking multiple pictures at different exposure levels and stitching them together to create an image which presents the greatest number of details in both dark and bright areas. Data stored in HDR-images typically corresponds to the physical values of luminance/radiance that can be observed in the real world and this presents a great difference from classical digital images: classical digital images represent intensities and colours that should appear on an output device (display, printer, plotter, etc.). Therefore, HDR image formats are called scene-referred while classical digital images are called device-referred.

In photography dynamic range is measured in EV (Exposure Values) differences between the darkest and brightest parts of the image that show detail: an increase of 1 EV is a doubling of the amount of light. Using EVs not very strict categories of images are [7]:

- High Dynamic Range (HDR) images: These have a dynamic range of about 14EV and these images (they use 32-bit float values without limitation for channels bits depth) are usually produced by merging multiple 12-14 bits images of different exposures (most often these are raw data files).
- Medium Dynamic Range (MDR) images: These have a dynamic range of [9 EV, 12 EV] and can originate from a file with 16-bit depth, or by merging 3 or more 8-bits images with different exposures.
- Low Dynamic Range (LDR) images: These have a dynamic range of lover than 8 EV. This means one 8-bits image.

Historically, the first versions of obtaining images with greater dynamic range began in the 19th century when films having several layers with different sensitivities were developed. By analogy, the computer-based generation of HDR-images require several images captured at different exposure, and then these LDR-images are merged. So each separate exposure captures various illuminations in the natural scene, i.e. each LDR-image stores information for a different part of the real dynamic range of the scene. Therefore, the information about the luminance from the individual parts of the scene dynamic range can be merged to generate the final HDR image [23]. The main problem in this case is the correct selection of the number of LDR-images and the choice of exposure values suitable to the characteristics of the scene.

VI. OUR METHOD FOR CHEST X-RAY IMAGE QUALITY ENHANCEMENT

X-ray images are 12-14 bit grayscale images and their visual perception depends on the three most common image characteristics: brightness, contrast (local and global) and sharpness. Thus, when the image has no sufficient quality, this is the result of some incorrect values. As stored information in the grayscale images is the values for intensity of the image pixels, then all methods for quality enhancement are aimed at changing the pixel intensity as a way to change the basics characteristics of the image. This limits the opportunities for selection of optimal values, because a limited amount of information about the luminosity/radiance power stored as pixel intensity is used.

The most common feature of the existing medical image quality enhancement methods is the fact that they cannot substantially increase the dynamic range of the image, which is why the improvement of the characteristics of the image (contrast, sharpness, brightness) is achieved through redistribution of the values of the intensity of the pixels in the image. Therefore, these methods improve the basic image characteristics (contrast, sharpness, brightness) by redistribution of intensity values to the pixels in the image. The main problem of this approach is the possibility of occurrence of medical artifacts – the classical criteria for evaluation of contrast enhancement (eg, increasing the dynamic range and maximizing the contrast) are inapplicable, since the resulting grayscale levels of pixels can be an indicator of pathological changes in tissues and organs (Fig. 8). Since there is no established computer metrics for medical authenticity, it cannot rely on automated techniques for evaluation of image quality of post-processed medical images. It is necessary to seek new approaches to solve this task which enable a qualified physicion to control the image quality enhancement process manually.

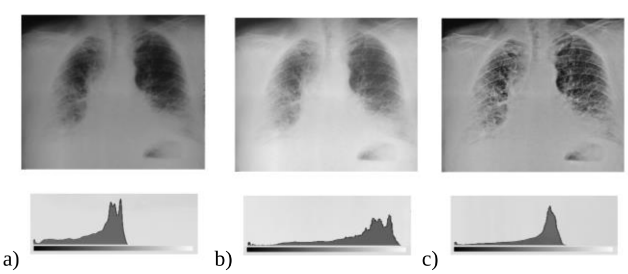


Figure 8. The most important factor of the medical image post-processing is the preservation of the authenticity of the image: a) the generic image; b) the image after classical enhancement of the dynamic range and the contrast; c) the most improved image without the occurrence of medical artifacts.

Our method uses a different approach to solve the issue of the optimal intensity distribution over image pixels. Following this approach a model of the luminosity distribution is created instead, which has led to the current image. This is achieved by creating a HDR-image because it represents the description of the luminosity/radiance in the nature scene. After a HDR-image is created the method allows determining the optimal mapping from a HDR-image to a LDR-image.

The use of the HDR-image to describe the scene luminosity model is justified, because the photosensitive material of the X-ray films and the X-ray-plates doesn't represent a monolayer structure – it is a multilayer structure. Thus, the energy of the photons passing through the material determines the level of the change in depth. Therefore, the photo-sensor catches different illumination information from different levels of photosensitive material under different exposure levels. This approach can be used directly for digitalization of X-ray plates [24] but if you want to use it as an image quality enhancement method you needed to create a technique for generating LDR-images with pixels intensity values corresponding to the relevant exposure values of the scene. This is one of the main tasks of the proposed method.

The proposed new quality enhancement method of for digital X-rays has the following three consecutive stages:

- Creating the LDR-images simulating capturing at different exposure;
- Creating an HDR-image as a luminosity model.
- Obtaining the final image by controlling the process of transformation from the HDR-image to the LDR-image.

A. *Stage 1: Simulation capturing at different exposure*

To achieve the correct results, it is necessary to establish a correct luminosity model of the simulated scene. For the HDR-image this is achieved by correctly selected additional images with different exposure. In photography this is achieved through capturing a new image with a selected exposure. Here this is not applicable and the main problem is to obtain an image that is accurate enough to simulate changes in the original image after changing the exposure.

From the image processing point of view increasing or decreasing the exposure changes the values of brightness, contrast and sharpness. Therefore, if the change of image pixels intensity resulting from the exposure change can be imitated, it can be used to simulate the image exposure change when a HDR-image is created. Our tests and analyses of results showed that for simulation a change in intensity a few different techniques can be used: using the brightness and the contrast control; using the gamma-correction; using the brightness and the contrast control followed by a gamma-correction; using the gamma-correction followed by a brightness and contrast correction

1) *Using the brightness and the contrast control*

One approach to solve the problem is based on the understanding that exposure change by 1 EV means doubling the amount of light. As the visual result is increasing of the pixels intensity for the entire image, the imitation of intensity shift requires calculation of brightness shift. Unfairness of this approach is that doubling the amount of light does not lead to doubling pixels intensity, because graphic devices and the characteristics of the created images reflect the human vision characteristics (logarithmic law for change of the intensity sensibility). Therefore, besides brightness there is also a considerable change in contrast.

Tests to determine brightness and contrast values were conducted: X-rays are captured with different exposures (from -3 EV to +3 EV by a 0.5 EV step) and the difference between the real image and the simulated image is evaluated to select values for brightness and contrast – Table I shows the results obtained for brightness and contrast (values of brightness and contrast are between -100 and +100). An example of -1.5 EV exposure simulations is shown in Fig. 9.

TABLE I. EXPOSURE SIMULATION: GAMMA-CORRECTION VALUES

	Exposure (EV steps)					
		-2.5	***-2***	***-0.5***	***-1***	***-0.5***
Brightness		-81	-70	-55	-38	-21
Contrast		-35	-27	-20	-11	-5
	Exposure (EV steps)					
	0.5	***1***	***1.5***	***2***	***2.5***	
Brightness	22	40	56	71	83	
Contrast	6	16	26	34	46	

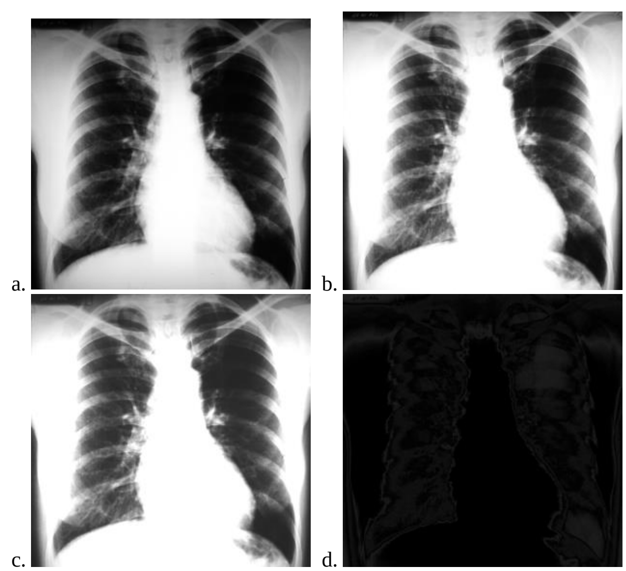


Figure 9. Using brightness and contrast control: a) the original image; b) the image with +1.5 EV; c) the simulated image with -1.5 EV; d) the difference between images (b) and (c) - the histogram is stretched twice in order to see the difference.

Our experiments show that simulation of exposures above 2.5 EV and below -2.5 EV is unrealistic and cannot be used for HDR-like image generation – when mapping to a LDR-image the result always contains medical artefacts.

However, for bone X-rays, this approach gives very good simulations.

2) Using the gamma-correction control

Another way to simulate changing the intensity of pixels is by changing the gamma-correction.

The difference between brightness and gamma-correction control is that increasing the value of gamma-correction can make the image to look brighter, but it is a non-linear change and it only increases brightness of the shadows and mid-tones in the image without affecting the highlights. Our experiments showed that this is particularly useful for simulating the overexposed images or the lung X-rays.

Another significant difference is the ability to simulate exposure values in the range [-5 EV, +5 EV]. Fig. 3 shows an example from Fig. 10, and Table II shows calculated values for gamma-correction.

TABLE II. EXPOSURE SIMULATION: GAMMA-CORRECTION VALUES

	Exposure (EV steps)					
	-3	***-2.5***	***-2***	***-0.5***	***-1***	***-0.5***
gamma-correction	6.0	4.9	3.7	2.8	1.9	1.3
	Exposure (EV steps)					
	0.5	***1***	***1.5***	***2***	***2.5***	***3***
gamma-correction	0.81	0.71	0.6	0.52	0.45	0.4

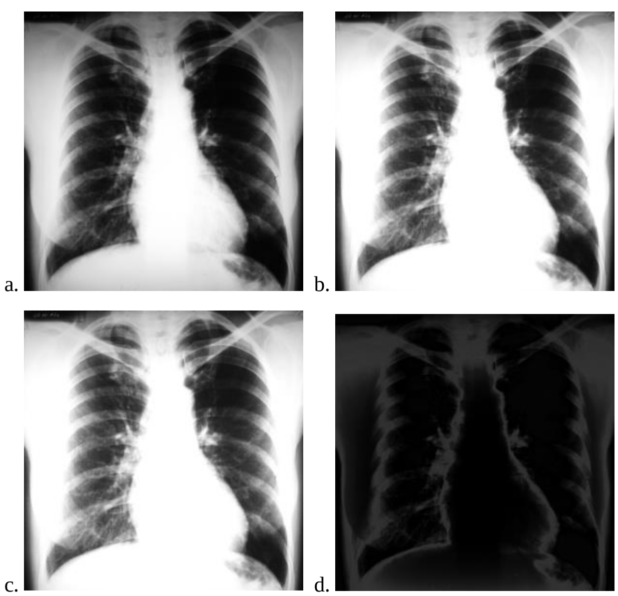


Figure 10. Using gamma-correction control: a) the original image; b) the image with +1.5 EV; c) the simulated image with -1.5 EV; d) the difference between images (b) and (c) - the histogram is stretched twice.

3) Using the brightness and the contrast control followed by gamma-correction

The main disadvantage of using brightness and contrast control is the incorrect change of local contrast between lung structures and ribs. That is why we tested additional image correction – the gamma correction. The result is a significant improvement of the simulation - Fig. 11 shows the example from Fig. 9, but now with the new way of correction. Table III shows calculated values for simulation of an exposure change.

4) Using the gamma-correction control followed by brightness and the contrast correction

The last approach to create an exposure simulation is gamma-correction control followed by brightness and contrast correction. This approach differs from the previous one, because the operations are not commutative. When comparing the result with the second approach, it appears that in this case the lighter areas are correctly changed.

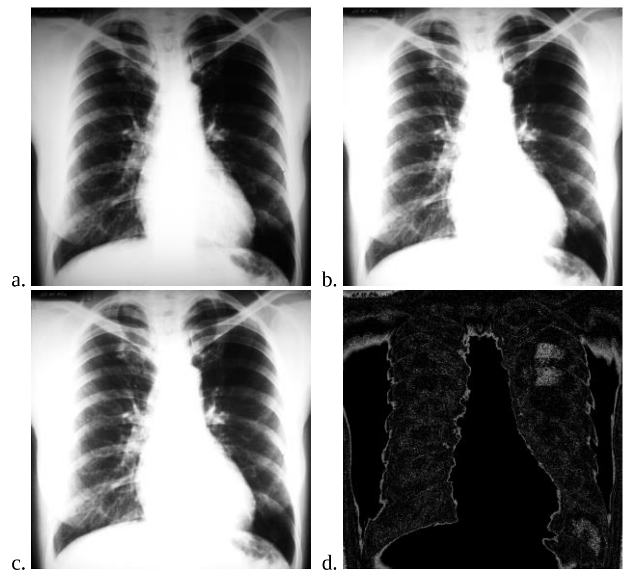


Figure 11. Using brightness and contrast control: a) the original image; b) the image with +1.5 EV; c) the simulated image with -1.5 EV; d) the difference between images (b) and (c) - the histogram is stretched 32 times.

TABLE III. EXPOSURE SIMULATION: BRIGHTNESS AND CONTRAST FOLLOWED BY GAMMA-CORRECTION

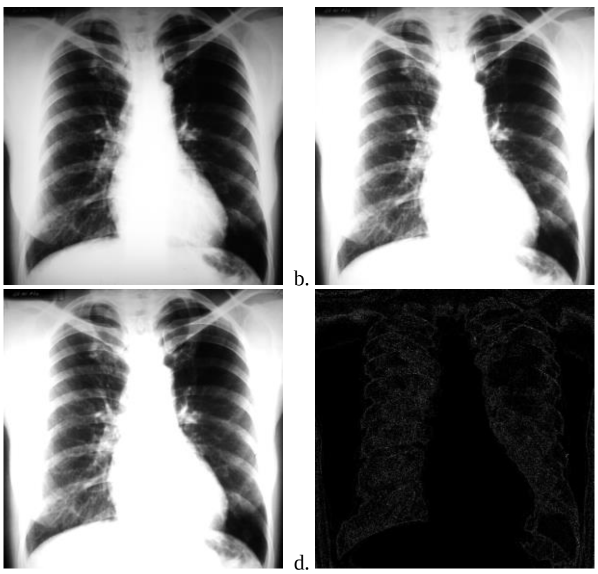
	Exposure (EV steps)					
		-2.5	***-2***	***-0.5***	***-1***	***-0.5***
brightness		-81	-70	-55	-38	-21
contrast		-35	-27	-20	-11	-5
gamma-correction		1.55	1.34	1.21	1.12	1.05
	Exposure (EV steps)					
	0.5	***1***	***1.5***	***2***	***2.5***	
brightness	22	40	56	71	83	
contrast	6	16	26	34	46	
gamma-correction	0.95	0.87	0.78	0.66	0.53	

The result is the best simulation of exposure change of an image - Fig. 12 shows the example from Fig. 10. Table IV shows calculated values for simulation of an exposure change.

Another advantage of the third approach is the possibility to simulate a much larger range of exposure values.

B. *Stage 2: The HDR-image generation*

To implement this step of the method, it is necessary to use a product for HDR-image generation based on a set of LDR-images with known exposure values. Analysis of the reqirements for digital X-ray images was conducted. The possibilities for creating an image with different exposures have been determined.



a. b. c. d.

Figure 12. Using brightness and contrast control: a) an original image; b) an image with +1.5 EV; c) a simulated image with -1.5 EV; d) the difference between images (b) and (c) - the histogram is stretched 32 times.

TABLE IV. EXPOSURE SIMULATION: GAMMA-CORRECTION CONTROL FOLLOWED BY BRIGHTNESS AND CONTRAST CORRECTION

	Exposure (EV steps)					
	-3	***-2.5***	***-2***	***-0.5***	***-1***	***-0.5***
brightness	-52	-41	-26	-13	-4	-2
contrast	-55	-48	-34	-23	-17	-9
gamma-correction	6.0	4.9	3.7	2.8	1.9	1.3
	Exposure (EV steps)					
	0.5	***1***	***1.5***	***2***	***2.5***	***3***
brightness	6	14	18	22	25	27
contrast	7	17	24	32	38	42
gamma-correction	0.81	0.71	0.6	0.52	0.45	0.4

Using the above analysis and the deretmined possibilities the following criteria for usability of the existing sowtwate sysytems for HDR-generation have been defined:

- Criterion 1: The level of realism of the resulting images after mapping an HDR-image to an LDR-image – this is the main criterion for the product selection because it is characterized by the appearance of artifacts in the final image, which is unacceptable for medical diagnosis. The evaluation of products by this criterion was done by a pulmonary diseases specialist.
- Criterion 2: The available set of input file formats – mainlywe evaluate the ability to work with 16-bits or 32- bits formats for input LDR images (8-bits images strongly restrict the possibility of achieving a large dynamic range)
- Criterion 3: Feasibility of alignment control by geometrical criteria or by image objects features - in the theory of HDR-images for calculation of the scene dynamic range, it is necessary to specify the matching objects in images with different exposures, because changes in their illumination is used for determination of illumination of the real scene, i.e. to calculate the real dynamic range of the scene. As for the proposed method the scene is static, the change of exposure greatly changes the forms and structures of the objects, but not their location relative to the boundary of the image. That is why the use of geometric criteria (available to pivot) gives much better quality results and there are much less artifacts in the final image. In real scenes (shooting nature) this is very rare and therefore most products use object alignment only.
- Criterion 4: the ability to edit the HDR-image – This is very significant, because the generation of an HDR-image can lead to the occurrence of noise or chromatic aberration in the ldr-image. At the same time, the ability to edit the scene luminance model allows generation of an LDR-image with much higher quality.
- Criterion 5: Ability to manually control the process of mapping an HDR-image to an LDR-image – the process of selecting the optimum dynamic range of an LDR-image directly affects the quality of the final image, because changing the contrast, the brightness, and the dynamic range affect the distribution of intensities levels over tissues with different radiographic densities.
- Criterion 6: Ability to generate a 16 bits output ldr-image - this is a mandatory requirement for X-ray images (digital X-rays are 12- or 14-bits images).

The results of the survey on the individual criteria are shown in Table V – the marks are between 1 star (the lowest) and 5 stars (the highest).

Based on these analyses, the Photomatix Pro system was selected, since it best meets the needs of the proposed method – a medically inauthentic image was not generated in any of the tests.

C. *Stage 3: The mapping of HDR-image to LDR-image*

When setting the tasks for this method stage, analogy with methods for image pre-processing in digital X-ray apparatus has been used – medical X-rays apparatus have a group of methods for the digital sensor calibration and linearization (the goal is the best possible distribution of intensities levels over captured image). Since in the developed method the HDR-image acts as a digital sensor, the task at this stage is to use a mapping procedure between the HDR-image and the LDR-image to select optimal LDR-image characteristics (dynamic range, contrast, ryaskost, noise, brightness, etc.) without generating medical artifacts.

TABLE V. EVALUATION OF PRODUCTS FOR HDR IMAGE GENERATION.

	1	2	3	4	5	6
Artizen HDR	****	*****	***	**	*****	****
Dynamic Photo HDR	***	***	***	****	****	****
easyHDR	***	*****	**	***	****	****
Essential HDR	**	***	**	***	***	***
HDR Darkroom	****	****	***	**	***	***
HDR Photo Studio	****	*****	***	***	****	*****
Luminance HDR	***	***	***	****	****	**
Photomatix Pro	*****	****	*****	****	*****	*****
Photoshop CS5 HDR Pro	*****	*****	****	****	*****	*****
Picturenaut	****	****	***	**	***	****
HDR Efex Pro	****	****	***	****	****	****
HDR Expose	****	***	**	***	***	***
Oleono HDREngine	*****	****	***	*****	****	*****
SNS-HDR	***	***	***	***	*****	**
Fhotoroom HDR	***	*****	**	***	****	*****

The tests and the analysis of the results showed that the chosen approach allows physicians to make the following kinds of image quality improvements:

- Control of the global characteristics of the final LDR-image as a dynamic range, global contrast, global sharpness, and global brightness.
- Control of the level of details for the LDR-image - for medical images the size of the structures that will be visible in the final image is of gtear importance.
- Local contrast of small structures and details – in medical imaging, it is important to increase the image readability.
- Adjustment of the simulated light conditions - in digital X-ray machines the final image has illumination that simulates the standard for background lighting on X-ray plates. This type of control in our method provides the same opportunity because the medical information perception in the X-rays is reduced without the background lighting.
- Halo-effect adjustment – this effect occurs around concentrated structures with low permeability when strong lighting is applied (the central part becomes darker, and the periphery becomes lighter). Very strong halo-effect may cause medical artifacts, but full suppression can lead to unrealistic contrast between structures.
- Extreme areas managing - these are image areas that should not be involved in determining the mapping between an HDR-image and an LDR-image (these areas aren't parts of the human body). This affects the quality of the contrast adjustment between organs and tissues with different radiographic density.
- Noise adjustment –all X-ray images have low-frequency noise, because the sensor elements are not fully homogeneous. Since this noise is part of the feel of background lighting, the complete removal of its alleged influence does not always give reliable results (the low-pass filter removes not only the results of the noise, but also the effects of different radiographic density of human organs and tissues). At the same time the low-pass filter creates a sense of non-uniformity in the backlight, which further reduces the readability of the image.

Fig. 13 shows the changes in the standard image when some discussed techniques are used. According to medical consultants results obtained by using the Oleono HDREngine and the Photomatix Pro have the highest medical reliability.

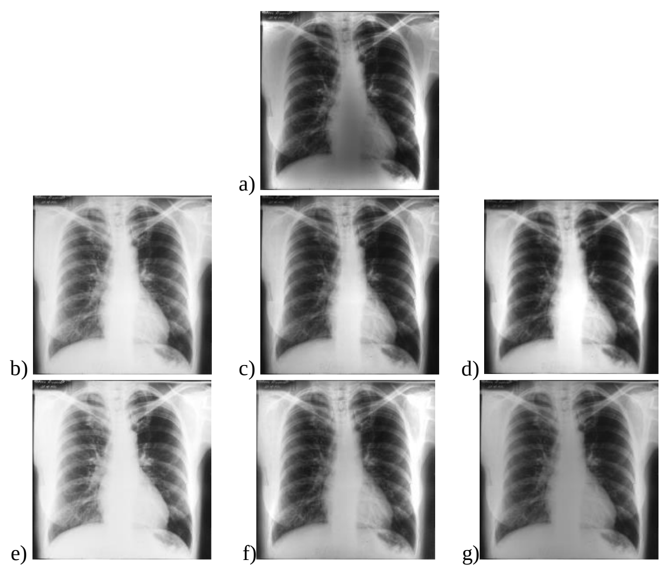


Figure 13. Changes in image, resulting from the use of stage 3techniques: a)image without corrections; b) the detail-level contrast reduction; c) the detail-level contrast increase; d) extermely high global smoothing; e)level of detail adjustment; f) global brightness manipulation; g) extreme areas manipulation.

VII. METHOD IMPLEMENTATION AND ANALYSIS OF RESULTS

Using this method for enhancing X-ray quality gives a significant change even in the exposure values [0 EV, -0.5 EV, +0.5 EV] but in general this is not the best combination of values. The correct implementation of the proposed method and the maximum use of its capabilities needs answers to three main questions:

- How many LDR-images with different exposure values should be used?
- Symmetrical or asymmetrical exposure values should be used?
- What should be the maximum and the minimum value of the simulated exposure, so that there is a significant image quality improvement, but without medical artifacts?

The experiments and the analysis of chest X-rays have led to the following conclusions:

- The difference in the final image when 3 or 5 LDR-images have been used is irrelevant for the diagnosis of lung diseases, since the changes are primarily in the field of the trachea and the heart, ie the space outside the lung (Fig. 14).
- The use of asimetric exposure values for LDR-images with positive and negative exposure most often does not lead to noticeably better results in the area of the lung (Fig. 15).

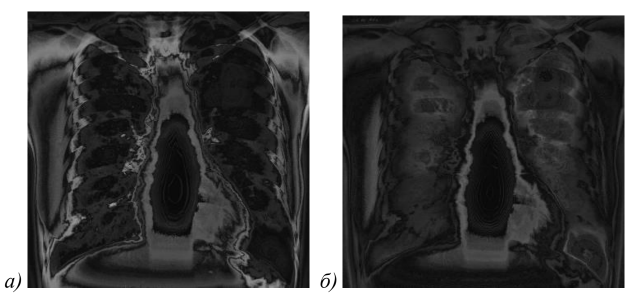


Figure 14. Comparing the results using 3 or 5 LDR-images - images show the subtraction of both final images and the image histograms are stretched 10 times to show the differences: a) the different exposures are simulated by gamma-correction; b) the different exposures are simulated by brightness and contrast adjustment.

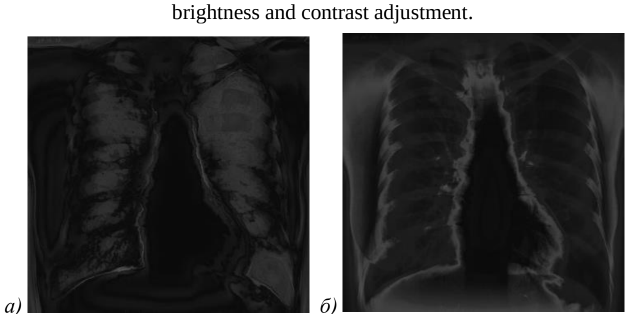


Figure 15. Comparing the results using asymmetrical exposure values - the image shows the difference of the final images of two exposure values sets (the image histograms are stretched 10 times to be able to show the differences): a) the differens between [0 EV,-1.5 EV,+1.5 EV] and [0 EV, -1.5 EV,+1 EV]; b) the differens between [0 EV,-1.5 EV,+1.5 EV] and [0 EV,-1 EV,+1.5 EV].

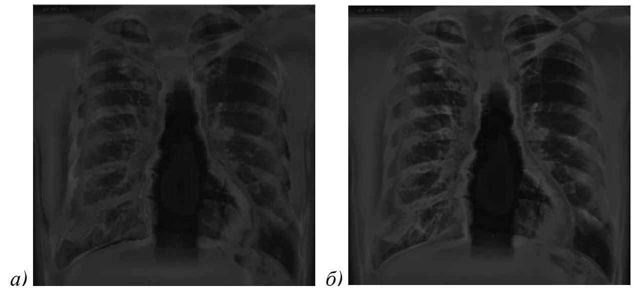


Figure 16. Comparing the results using asymmetrical exposure values - the image shows the difference of final images of two exposure values sets (the image histograms are stretched 10 times to be able to show the differences): a) the differens between [0 EV,-1.5 EV,+1.5 EV] and [0 EV, -2 EV,+2 EV]; b) the differens between [0 EV,-1.5 EV,+1.5 EV] and [0 EV, 2.5 EV,+2.5 EV].

- The use of exposure values distant more than 1.5 EV from the base image doesn't lead to noticeable contrast change, but increases the probability of medical artifacts occurrence (Fig. 16).

So, as a standard set of exposure values, we used [0 EV, -1.5 EV, +1.5 EV]. This set of exposure values can be used in most cases, but for some specific purposes there are other parameters:

- In case of overexposed images, the best results are achieved with a set of 5 images with exposure values [0 EV, -1.5 EV, +1.5 EV, -2 EV, +2 EV].
- In case of underexposed images, the best results are obtained when using the set of exposure values [0 EV, -1 EV, - 2.5 EV].
- In case of X-rays of bones, good results are obtained with asymmetric values for the minimum and maximum exposure – for example [0 EV, -2 EV, +1 EV]. This set increases details in lighter areas (like bone structures).
- In case of lung or soft tissues X-rays, good results are obtained with opposite asymmetric values for the minimum and maximum exposure – for example [0 EV, -1 EV, +2 EV]. This set increases details in darker areas.
- In case of an image with a small dynamic range, a set of 5 images has to be used. This increases the details for all structures with different radiographic densities.

Another major advantage of the proposed method is the ability to manage the transformation from a HDR-image to the final LDR-image. This allows an optimal image quality to be obtained without the occurrence of medical artefacts.

The comparison of the results of the proposed method with other techniques showed that this method can help to obtain a major improvement in quality without the occurrence of medical artefacts. Especially important is the opportunity to use the same characteristics in all cases and always to get good quality – for example 5 images with exposure values [0 EV, -1.5 EV, +1.5 EV, -2 EV, +2 EV].

A few examples of the method implementation and comparison with Laplacian pyramids filter and CLAHE are shown in Fig. 17.

VIII. Conclusion

Image quality enhancement is very important because it increases readability and understandability of the analysed images, their details and structure. When the exploited for image generation model is known this increases possibilities to correct the image without generation of medical artefacts. The presented method for pseudo HRD enhancements of medical images enables increasing quality of understanding and information gathering.

The next steps of this research are oriented to X-ray images of other body parts like bones, abdominal cavity, and other soft tissues as well analyses of images from CT and other medical image sources.

Acknowledgment

This work is funded partially by the Bulgarian NSF under DO02/113 and DRNF02/3 projects.

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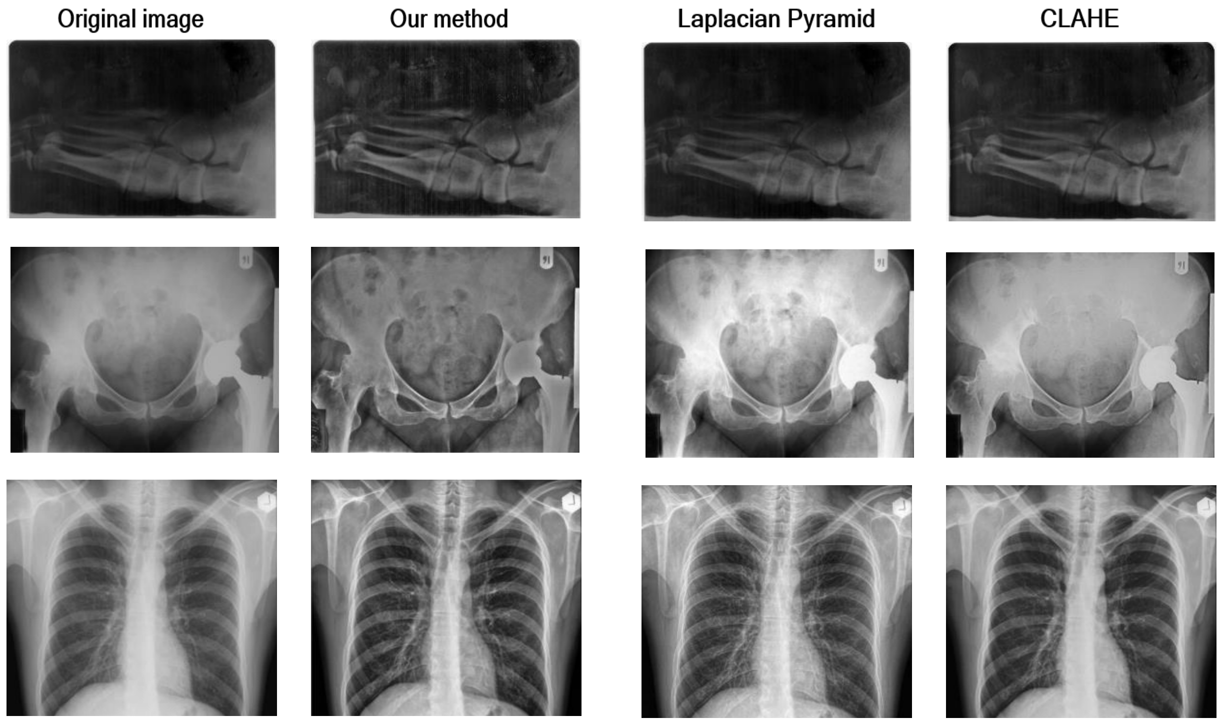

Figure 17. Comparison between our method, Laplacian pyramids and CLAHE: the proposed method improves contrast and details.