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Real-time digital processing of color bronchoscopic images

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Abstract

In this paper we present possibilities of improving conventional and fluorescence bronchoscopic diagnosis by means of digital image processing methods. After a description of the particularities of the bronchoscopic imaging system on one hand and the state-of-the-art in real-time digital image processing on the other hand, we present a series of methods which improve bronchoscopic diagnosis. These methods are based on real-time processing of the bronchoscopic images in video form. Among them, spatial and temporal filtering have been implemented with good results. For further improvements of the bronchoscopy in general and the fluorescence bronchoscopy in particular, we propose two other methods which are histogram equalization and the generation of an intrinsic fluorescence image.

Introduction

Until very recently, digital image processing was limited to individual, still images. Hence research in digital image processing has brought a large number of processing methods which were applicable in only a limited number of cases. The processing of images with high rates had still to be performed by analog techniques which suffer mainly from a lack of flexibility.

Recent advances in microelectronics were decisive for changing this situation by making fast and complex components available for fast digital image processing systems. Such systems are now commercially available and with them, digital image processing techniques are now practically applicable to animated images. The purpose of the work presented here is to evaluate the practical use of this new technology as applied to conventional and fluorescence bronchoscopy.

Bronchoscopy is the visual inspection of the bronchus walls by means of a bronchoscope which is introduced into the bronchus through the patient's mouth and trachea. The bronchoscope itself consists of a flexible tube in which the central element is a bundle of optical fibers which images the bronchus onto the observer's retina. Recent investigations[1,2] have shown the new potential of bronchoscopy for the detection and the treatment of lung cancer. In substance, detection and localization of tumors can be greatly improved by a new technique called fluorescence bronchoscopy, which is based on the selective retention by malignant cells of a fluorescent compound, namely hematoporphyrin-derivative (Hpd). In order to make the fluorescence apparent to the eye, a special bronchoscope is used which illuminates the bronchus with a high-intensity violet light and images the red spectral band where the fluorescence occurs.

Further research is presently carried on in several directions, with the purpose of exploiting this potentials. This paper describes our efforts to improve the bronchoscopic diagnosis by improving its images with the help offered by the newest techniques of digital image processing.

Here we present the characteristics of bronchoscopic images and analyse the possibilities for improvement by means of real-time digital processing methods. We will show several methods providing aid and improvements to the bronchoscopist.

Although this analysis an these results are presented in the context of bronchoscopy, the methods are general enough and common to other imaging applications, particularly by virtue of the fact that we use a standard video signal.

Bronchoscopy and digital image processing system (DIPS)

Figure 1 describes the conceptual arrangement of the image processing system. A tv camera is attached to the bronchoscope making the images seen by the bronchoscopist available in video form. During clinical procedures, the video signal is monitored for the examination by co-workers and also recorded on tape for subsequent examination and control, as well as educational purposes. This video signal is the source for the proposed processing. The digital image processing system accepts this signal and transforms it into an output signal which is in the same video format. Both the unprocessed and the processed signal can thus be displayed side by side and the bronchoscopist will automatically

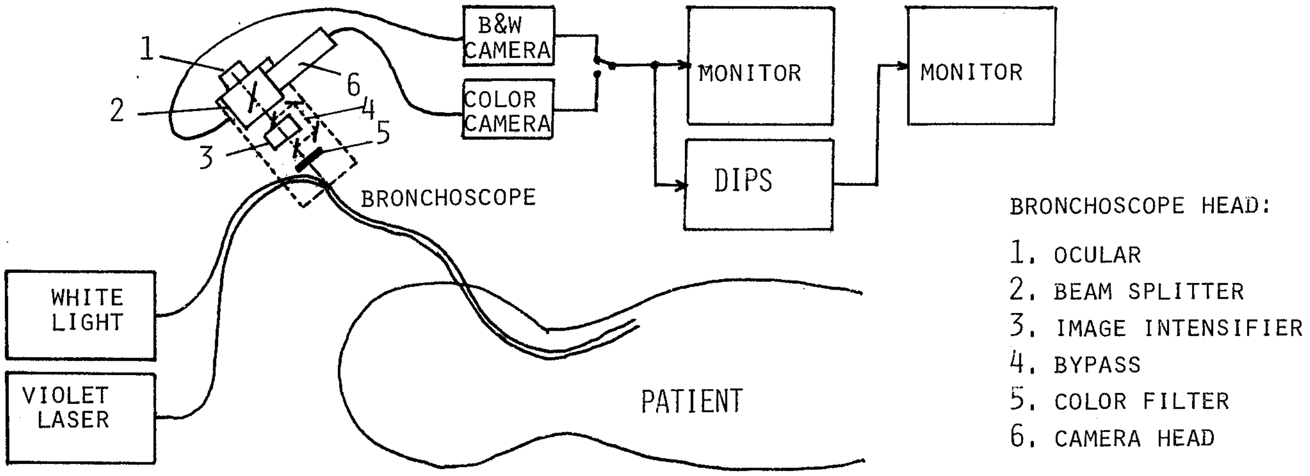


Figure 1. Arrangement for white light and fluorescence bronchoscopy

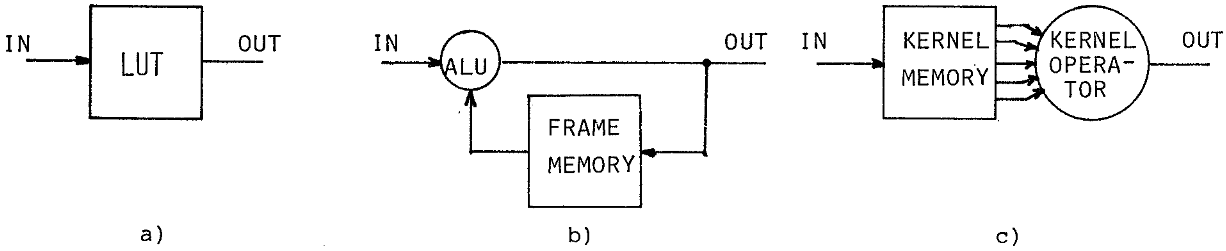
concentrate on the best image. The important system constraint dictated by the procedure requires instantaneous results, i.e. no noticeable delay is permissible.

It is important for the detection of tumors that the bronchoscopy takes advantage of the spectral characteristics of the lung tissues. Both the white light inspection and the inspection of induced fluorescence are routinely used. The fluorescence of concern here is a red fluorescence produced by an illumination with a short-wavelength violet light. According to that, we expect three different images to be processed: a color image resulting from the illumination with white light and two monochrome images available during fluorescence bronchoscopy. The two later are the image of the unfiltered violet radiances on one hand and the image of the filtered red fluorescence on the other hand. A particularity of the fluorescence image is its very low light level which requires intensification and results in a very poor signal to noise ratio.

Real-time processing

The processing of video images in real-time requires a rate of 30 frames per second with typically 512 by 512 pixels each. With line and frame retrace, this entails processing 10 million pixels per second. Real-time transforms are thus limited to operations which can be implemented with fast, and therefore relatively simple hardware structures. The three structures of figure 2 are typical and basic architectures which are found in the newest commercial digital video processing systems.

The first structure (figure 2a) has a single element: a programmable look-up-table (LUT). It transforms the input values according to a transfer function loaded into the LUT.



a) b) c)

Figure 2. Basic structures for the processing in real-time

When compared with similar functions performed analogically, the digital transfer function has the advantage of total flexibility.

The second structure (figure 2b) combines a frame memory and an arithmetic and logical unit (ALU). It performs interframe operations on a pixel to pixel basis and can therefore be refered to as a temporal filter. The transformed value is an arithmetic combination of the corresponding pixel values in the input and stored images. Weighted addition and subtraction are common arithmetic operations. Image multiplication and divison are performed indirectly by adding or subtracting the signal in the logarithmic domain. Moreover, this structure can perform iterative operations by taking advantage of the feedback path. The frame averaging method described below can for example be implemented by iterative summing.

The third structure (figure 2c) combines a kernel memory and a kernel operator, whereby the kernel consists of all pixels which lie in the neighborhood of the current pixel. As opposed to the second structure, this architecture performs spatial filtering which is an intraframe operation and is implemented here in the form of a two-dimensional convolution of the image with a filter function. Because a general filter function requires complexe hardware, available systems implement such filter functions with either a limited kernel size - 3 by 3 kernel for example - or a limited number of possible shapes - highpass and lowpass filters with variable cutoff frequencies for example.

After describing the bronchoscopic images on one hand and the potentials of real-time digital processing sytems on the other hand, we will now present the different methods capable of improving the bronchoscopic diagnosis.

Still image

At any time during the procedure, the current image can be grabbed into the frame memory of the DIPS and from then, it is displayed as a still image for an arbitrary amount of time. This feature offers a convenient way to capture and examine the images from lung locations which can be reached with difficulty only, or when the examination is perturbated by the respiratory movements.

Automatic ranging

Because of important changes in the distance from the light source attached to the bronchoscope tip to the bronchus wall, the object illumination is varying in a wide range causing similar variations of the object brightness. A control is required which accomodates this important variation to the limited dynamic range of the video system. This control can be performed in the optical path by a variable aperture, in the analogical electric path by mean of an automatic gain control circuit and finally, in the digital path by a LUT. For the purpose of automatic ranging, the digital method has no real advantage over the analogical methods.

Histogram equalization

This method transforms the image grey scale to obtain statistically equally distributed levels[3,4] and it is used with the purpose of better fitting the image to the eye. Its implementation is done very simply by sending the input image through a LUT loaded with the adequate transfer function. Computation of this transfer function is simple enough that it can be implemented in hardware. Moreover, one can take advantage of the high similarity of subsequent images within an animated sequence to update the transfer function at lower rate than the video frame-rate without significatly affecting the result.

The expected effect of image equalization must be analysed in the context of its principle. Equalization optimizes the amplitudewise representation of an image under the assumption of a spatially equally distributed information content. This method is thus successful to improve a bronchoscopic image with a small unsignificant image area, like for instance an image where the dynamic range has been over-extended as a consequence of the presence of a small and very bright specular spot. This method fails however when the image contains a large unsignificant area, because its algorithm tends to enhance precisely this area. In this form, this method should therefore be used with circonspection. However, full advantage of this method is taken when the equalization is performed based on a region of interest which can be adjusted interactively. For bronchoscopy, where the area of interest covers only a fraction of the full screen, the equalization must be performed based on this area only.

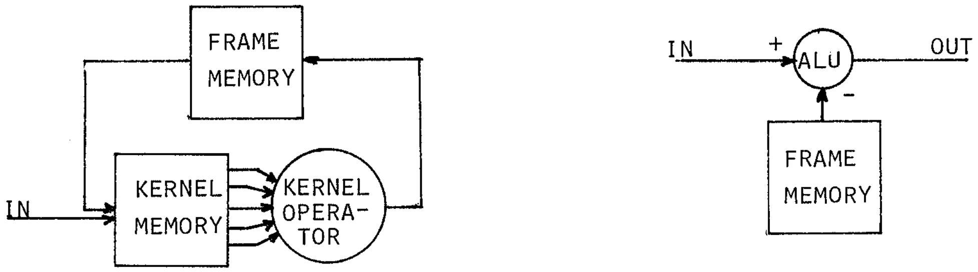
Spatial filtering

The large variations of the light source to object distance cause important brightness variations. Bronchoscopic images are characterized not only by important temporal or interframe brightness variations as mentionned above, but also by important interframe brightness variations. Due to the tunnel-like shape of the bronchus, the single bronchoscopic views have usually brightnesses which extend on a very wide range. At its best, the imaging system maps this range into the full video range which typically has a rather small maximum contrast of 1:50. The faint differences in the image are thus reduced in contrast and tend to disappear.

Spatial filtering is a remedy to this degradation[5]. Indeed, the important brightness variations have rather low spatial frequencies whereas the subtle differences which are found for instance in the wall details have higher spatial frequency components. Attenuating the low frequency components by highpass filtering is thus a mean to improve the detail visibility. This can be done practically by two means. The first method consists of using the spatial filter of figure 2c as a direct highpass filter. This method is very simple and fast.

Iterative spatial filtering

The second method overcomes one limitation of this first method which comes from the finite size of the kernel available in contemporary equipement and consists of the limited range of the filter cutoff frequency. Lowering this cutoff frequency is sometimes desirable and can be performed by a method based on iterative filtering. Figure 3 shows its principle.



a) updating b) processing

Figure 3. Structure implementing the two steps of iterative filtering

Two elements of figure 2, namely the temporal and the spatial filter are now assembled in a loop. The highpass filtering is performed in two steps, namely an updating and a processing step. During the updating step, a lowpass version of the image is generated in the frame memory by looping it several times through the spatial filter selected now as a lowpass filter. The higher the number of iterations, the larger the effective filter kernel and the lower the cutoff frequency. During the processing or second step, the lowpass version of the image now stored in the frame memory is subtracted from the input images in order to perform their highpass filtering.

The two steps have distinct timings. The processing is performed at video rate and can thus be applied continuously to the live input video. The updating is performed at a lower rate however. Here again, the similarity of consecutive images is used in order to justify the use of this lower rate. With this method, a mean is available to filter the live video with a filter whose cutoff frequency can be as low as a few cycles per image width. Only the brightness variations with very low spatial frequency are thus attenuated. However, periodic updating of the lowpass image momontarily perturbs the filtering. The fact that the required updating rate increases as the camera movements increase limits the use of this method to the rather still image sequences.

Noise reduction

The detection of the red fluorescence in bronchoscopy is made possible by use of an image intensifier and results in images which have the strong noise characterizing low light level images. As long as the noise is uncorrelated, the signal-to-noise ratio of such images can be improved by a factor of $\sqrt{N}$ by averaging N frames. Practically, the structure of the temporal filter of figure 2b is used. In the basic version of the method, N frames are added iteratively into the frame memory and on completion, the normalized content is displayed as a still image. For real-time viewing, moving averaging[6] is preferable . Here, the averaging is performed continously with the advantage that the resulting image can be observed all the time.

Fluorescence

The conventional fluorescence bronchoscopy is based on the observation of the bronchus image in the spectral band where fluorescence occurs. Because this image reproduces the variations of both the illumination and the fluorescence, it is often misleading and difficult to interprete. We propose therefore to substitute it by another image which represents the fluorescence efficiency which is an illumination independent value. A good approximation of the fluorescence efficiency is given by the quotient of the fluorescence to the non-fluorescence radiances, i.e. the quotient of the red and violet images. With this, the background for the generation of an intrinsic fluorescence image is given.

The ressources of the DIPS permit to implement this method by a technique which generates the new image from a single video signal which carries the sequence of the periodically switched red and violet images. This switching is performed optically with color filters. It has the nice particularity to keep both images geometrically registered which is the required condition for dividing them. The division itself is performed in the DIPS by subtracting, in the logarithmic domain, the violet image previously loaded in the frame memory from the red image presently available at the DIPS input (figure 4). The new image of the fluorescence efficiency is then loaded into the frame memory and displayed.

Processing color images

The previous methods were described as processing methods for monochrome signals. Some of them, however, like still image, image equalization and spatial filtering apply, in the context of bronchoscopy, to color images. This arises the question of the color implementation of these methods. The principle is simple. The transform methods valid for monochrome images can be extended to color images by applying the same transform to their luminance and by keeping their chrominance unchanged. Its implementation requires a color decoder which isolates the chrominance, a color memory which stores and delays it, as well as a color encoder as shown in figure 5.

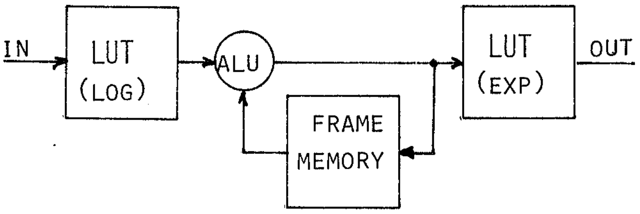


Figure 4. Structure generating the image of the fluorescence efficiency

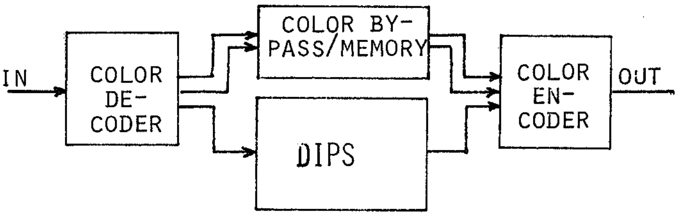
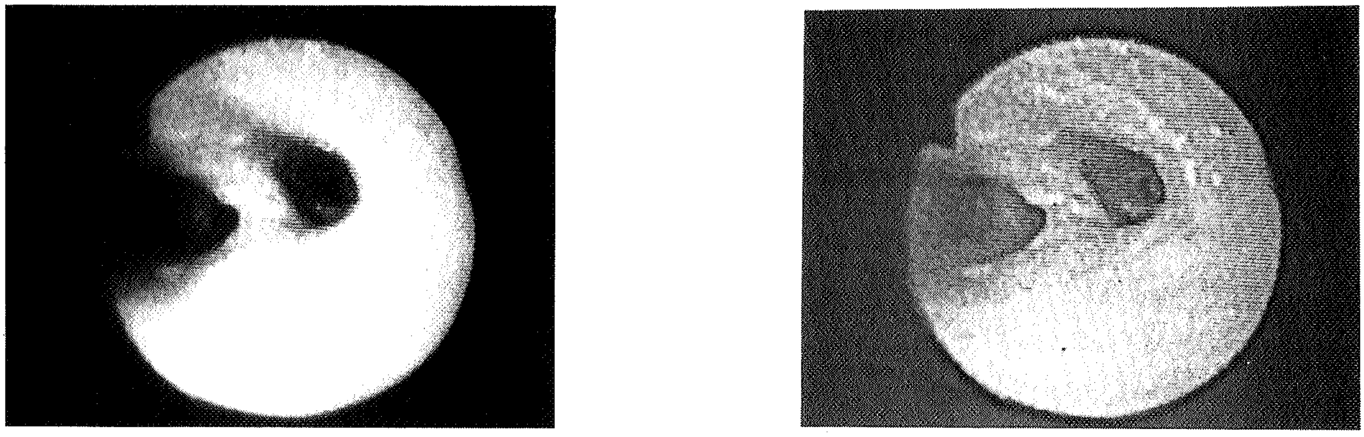


Figure 5. Structure for processing color images

Results

Practical experiments have been carried out with a state-of-the-art real-time DIPS which combines the temporal filter system DS-20 and the spatial filter system DF-80 from Quantex. The complete system is set up in a unique configuration which adds the capability of iterative processing to the various capabilites offered by the normal versions of the two filters.

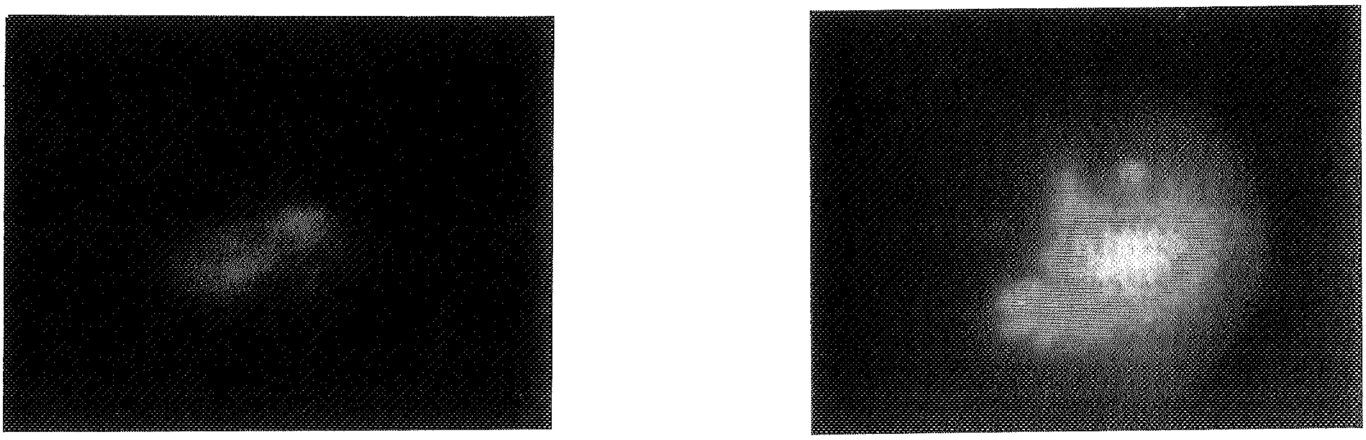
The highpass filtering of bronchoscopic images results in a general improvement of the subjective quality of the images as well as an improvement of the image intelligibility in the areas with very low contrast. The direct filtering method is implemented strictly real-time with a kernel size of 15*15 elements. An example is given in figure 6. The iterative filtering method takes advantage of the special iterative mode of the system. The



a) before

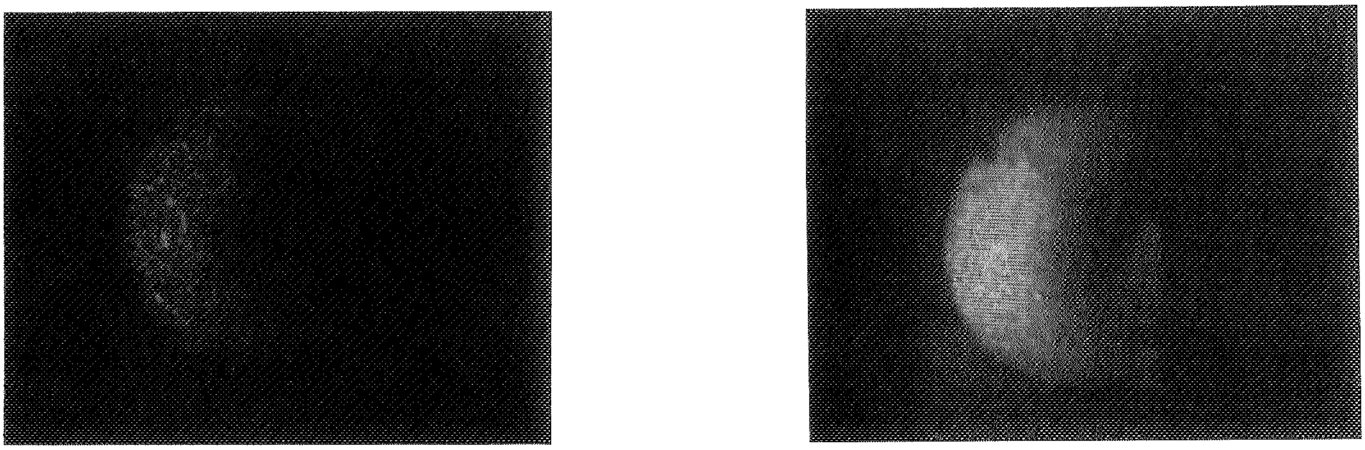
b) after

Figure 6. Detail enhancement by real-time spatial filtering. The kernel size of the highpass filter is 15*15 elements



a) before b) after

Figure 7. Illumination compensation by iterative spatial filtering. The fluorescent tumor in the background becomes visible



a) before b) after

Figure 8. Signal-to-noise improvement by frame averaging

results show its usefulness for the compensation of illumination effects (figure 7). Because of the image interruptions related to the updating sequence, its practical use is juged limited to steady or quasi-steady images.

The noise reduction in fluorescence images by the method of moving frame averaging shows both subjective and objective image improvements. Figure 8 is an example. In practical cases, the number N of frames to be averaged is adjusted for maximum improvement. It is a trade-off between reduction of noise and motion blurr. Our results show a decisive subjective improvement, even with small N.

The other methods remain to be tested. To our knowledge, no equipment is presently available commercially which performs image equalization in real-time. However, the fact that a prototype is under construction is our good hope to implement this method for bronchoscopy soon.

Finally, the proposed technique for generating the image of the fluorescence efficiency is probably the application where a DIPS can contribute the most to the advance of bronchoscopy.

Conclusion

Different methods to improve the bronchoscopy by the means of a real-time digital image processing system have been shown. The present results amply justify the use of such a processing system in bronchoscopy. Further improvements are expected with the implementation of two additional methods which are histogram equalization and particularly the generation of the image of the fluorescence efficiency.

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