Evaluation of Computer-assisted Image Enhancement in Minimal Invasive Endoscopic Surgery*

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Summary

Objectives: This paper focusses on the evaluation of the usage of computer-aided image processing methods for minimal invasive surgery. During video endoscopy of visceral cavities the images are displayed directly on the monitor without further processing. In the course of the operation the former good quality of the images decreases due to typical disturbances like bleeding, smoke or flying particles. These disturbances can be reduced by using image processing methods like color normalization, temporal filtering or equalization.

Methods: In this double-blinded analysis, 14 surgeons with different levels of experience evaluated 120 image pairs and 5 image sequences, directly comparing original and processed images or movies.

Results: Color normalization and equalization proved to significantly enhance video endoscopic images. With regard to temporal filtering, an improvement could be seen in the image sequences with filter size 5 being a greater enhancement than filter size 3. Comparing the state of experience and its influence on the results, it occurred that the experienced surgeons preferred the original color while altogether agreeing that the color-normalized images were better.

Conclusions: The results obtained in the present evaluation show that the image processing methods which were used can significantly improve the quality of video endoscopic images. As a result of this, necessary lavages of the operated area are reduced and a better overview and orientation for the surgeon can be reached.

Keywords

Minimal invasive surgery, computer-aided image processing, video endoscopy, evaluation, image enhancement

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1. Introduction and Objectives

In the past decades, an obvious change in surgery away from expanded interventions towards minimal invasive operations took place. During these so-called "endoscopic" operations, the camera images from the visceral cavities are displayed directly on the videomonitor without processing. Currently, standard endoscopic systems with only a few hardware-based image enhancement methods are used (e.g., white balancing at the beginning of the operation or refinement of contrast), but there is no possibility of software-assisted image processing. The consequence is that during the course of an operation, the surgeon inevitably has to face degradations of the endoscopic images.

The optical lenses, with small focal length, that are employed to enlarge the visible area and gain clarity lead to distortion (increasing towards the borders of the image). Inexact manufacturing of the lenses is another reason for image distortion. Wet surfaces in the visceral cavities, if illuminated directly (optical ray and light source of the endoscope run parallel), lead to the appearance of highlights which disturb the view. Cutting tissue with high frequency diathermy leads to the formation of smoke and small flying particles, which disturb the view. Due to bleeding, the visible organs and tissues get reddish (color error) and consecutively the ability to discriminate different structures in the operated area is reduced. The image degradations mentioned above often force the surgeon to repeatedly renew the insufflated gas or make lavages of the operated area. This is time consuming and often insufficient.

In principle, the endoscopic images can be processed by means of common image enhancement methods. The investigated image enhancement methods in this work are equalization [1] (reduction of the distortion of the image), color normalization [2] (reduction of color errors) and temporal median filtering [3] (reduction of small flying particles or smoke).

1.1 Equalization

The camera model of Tsai [4] serves as a general basis for calibrating the endoscope. By calibration, the intrinsic camera parameters that enable the equalization of the endoscopic image can be determined. For simplicity, a rectangular camera sensor coordinate system is assumed. The distorted sensor coordinates are calculated from the distorted image point, then undistorted and transformed into the undistorted corresponding image points. An example image pair is shown in Figure 1. Using the optimized image processing library OpenCV (based on the Intel Image Processing Library IPL), the endoscopic color images (PAL resolution, i.e. size 768 × 576) can be undistorted in real-time.

1.2 Color Normalization

During minimal invasive operations, bleeding with discoloring of the tissue because of the hemoglobin leads to an immoderate

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reddish color of the image. Color normalization provides the possibility to transform each color pixel so that different tissue types can be separated again. This is realized by an affine transformation of the color space [2]. At first the color covariance matrix C of the original image is calculated. Then the eigenvalues and eigenvectors of the 3 × 3 matrix C are determined. The direction of the main color axis is the eigenvector corresponding to the largest eigenvalue. A rotation of the color space, i.e. multiplication of each pixel by a 3 × 3 rotation matrix, is performed so that the main color axis is projected onto the main diagonal of the RGB color space. The rotation of the two other axes should be as small as possible. Currently, color normalization is not possible in real-time. For further details see [2, 5]. An example pair is shown in Figure 2.

1.3 Temporal Median Filtering

In the course of the operation the surgeon tries to keep the camera as still as possible to get a steady image. While cutting tissue, small flying particles are typically generated that quickly move through the visible field. Because the camera stands still and the particles fly very fast, the degradations are predominantly visible only at a certain pixel position for a short time and are therefore defined as temporal noise. Temporal color median filtering is a very good method to reduce this temporal noise in the image sequence.

Color median filtering can either be done by filtering each color channel separately by a grey value median filter, or by using the median value of the sorted color pixel values as the result, where the values are sorted according to an ordering criterion (e.g., the Euclidean norm). We decided to use the first method which also enables the usage of optimized image processing libraries.

Although currently available optimized image processing libraries (like the IPL) only provide spatial filters, these filters can be used to implement and accelerate temporal filtering. We described two possible implementation methods in [3], therefore we only sketch the method we used here. The technique merges single lines of temporal images into several spatial images. These images are filtered with the spatial color median filter of the IPL (color channels are filtered separately). The time filtered image is generated by extracting the corresponding lines from the spatial filtered images. Because only lines are copied and additionally the optimal filter of the IPL is used, the technique is very fast [3] and can be applied in real-time. An example pair is shown in Figure 3.

The main aim of this work is to describe an evaluation method for the application of these used image processing techniques in minimal invasive surgery and to analyze if these methods provide a significant improvement and better sight for the surgeon. We do not know of any other research group working on this kind of evaluation.

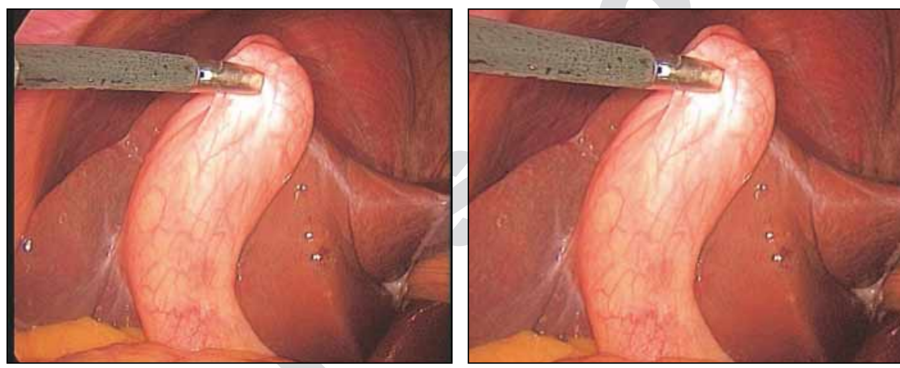

Fig. 1 Image pair equalization: original endoscopic image (left) and processed, undistorted image (right)

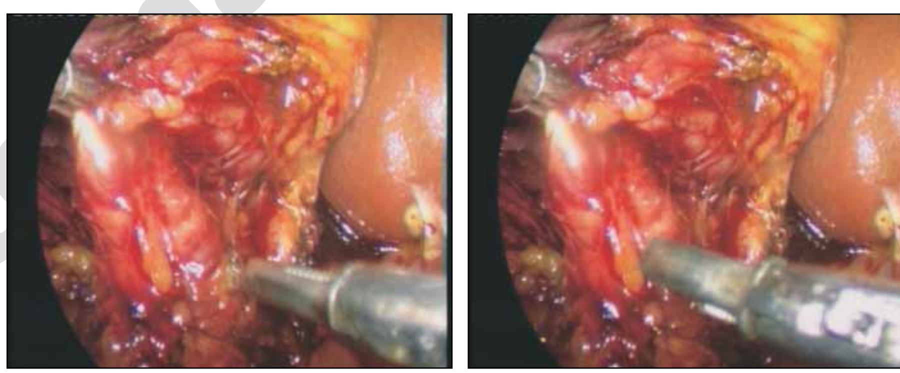

Fig. 2 Image pair color normalization: original endoscopic image (left) and processed, color-normalized image (right)

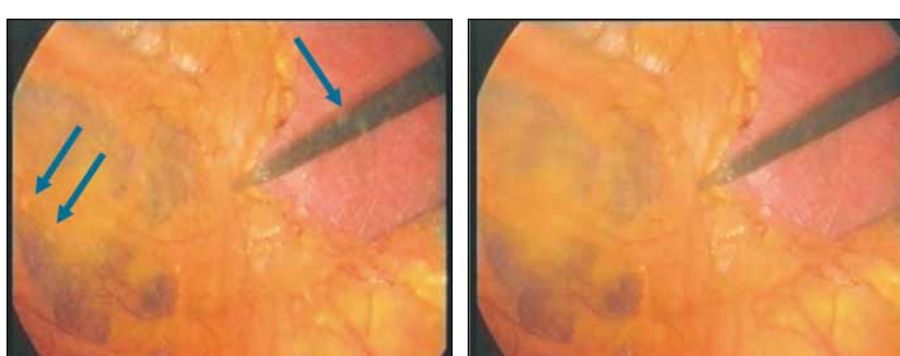

Fig. 3 Image pair temporal median filtering: original endoscopic image (left) and processed, temporal filtered (filter-size 3) image (right)

2. Methods

For the evaluation of the image processing methods, we implemented a program (in C++/Linux) called "EvaMedIm" (i.e. Evaluating Medical Images). An example of the user interface is shown in Figure 4. In this program the test person is submitted 120 image pairs (original endoscopic image and processed image) and 5 image sequences (original and processed movie) belonging to the four processed partitions: equalization, color normalization, temporal median filtering with size 3 and size 5. The images are taken from abdominoscopy, endoscopy of the thorax, calibration samples, colored objects, black and white objects. The image pairs and sequences are randomized and double-blinded (i.e. neither the physician nor the tutor knows which one is the original image). Concerning minimal invasive operations and endoscopy the evaluating physicians have either no experience (n = 7) or more than 5 years experience (n = 7). The assessment criteria include better/worse (with a range of –1, 0, +1) and sharpness, distortion, color impression (range –2, –1, 0, +1, +2 for each of them). Negative values mean the original image is the better one, positive values mean the processed image is better, and zero represents no observable difference. For each criterion, the mean value (MV) and standard deviation (SD) over all evaluated image pairs are calculated. To prove that the applied method leads to an enhancement of the image, the mean values should be larger than zero (the larger the better). To see if there are any significant differences, the t-test for independent samples was used. The results are itemized for each single test person, for the evaluating physicians altogether and differentiated into experienced/inexperienced.

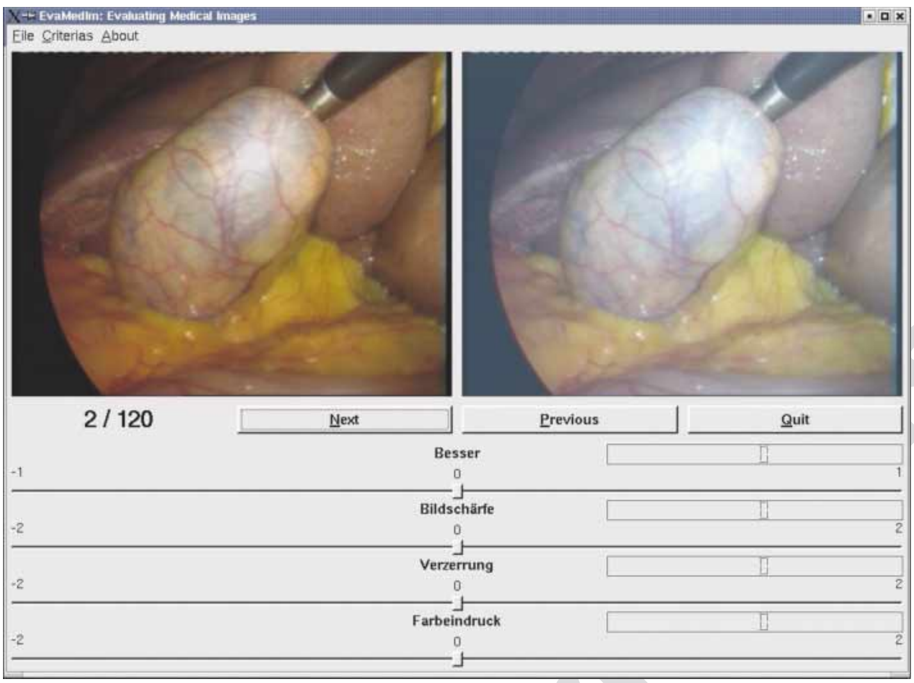

Fig. 4 User interface of the evaluation program (EvaMedIm). At each case a pair consisting of an original image (left side in this example) and processed image (right side, color-normalized in this example) is shown. The physician has to evaluate the criteria displayed below the image pair.

Table 1 Evaluation results (image pairs) of each individual physician (no. 1-14): Mean values (MV) and standard deviation (SD) for criterion better/worse applied for color normalization (CN), equalization (EZ) and temporal median filtering with sizes 3 (TF 3) and 5 (TF 5).

	CN		EZ		TF 3		TF 5	
	MV	SD	MV	SD	MV	SD	MV	SD
1.	0.13	0.97	0.80	0.48	0.00	0.67	-0.33	0.66
2.	0.53	0.86	0.63	0.72	0.00	0.83	-0.27	0.83
3.	0.90	0.31	0.73	0.45	-0.03	0.32	-0.07	0.37
4.	-0.87	0.43	0.40	0.68	-0.10	0.61	-0.33	0.55
5.	0.43	0.90	0.77	0.50	-0.23	0.63	-0.53	0.73
6.	-0.23	0.97	0.03	0.18	-0.07	0.37	-0.10	0.40
7.	0.23	0.94	0.60	0.56	0.07	0.79	-0.07	0.91
8.	-0.07	0.94	0.70	0.60	0.03	0.49	0.03	0.72
9.	1.00	0.00	0.77	0.63	0.00	0.74	0.30	0.65
10.	0.80	0.61	-0.37	0.89	-0.30	0.88	-0.27	0.86
11.	0.23	0.90	0.80	0.41	-0.10	0.55	-0.10	0.61
12.	0.00	0.26	-0.33	0.55	0.13	0.57	-0.10	0.61
13.	0.53	0.63	0.27	0.64	-0.27	0.74	-0.60	0.68
14.	0.27	0.83	0.23	0.73	-0.10	0.61	-0.23	0.77

3. Results

The results of the evaluation were considered under different aspects: the results for each physician, for the physicians altogether and for experienced vs. inexperienced physicians. Tables 1-3 show the mean values (MV) and standard deviations (SD) for the three different aspects. Positive values indicate that the processed image was the better one, negative values mean that the original endoscopic image is the better one and if there is no difference between original and processed image, the value is zero. Table 1 displays the evaluation results of the 120 image pairs for each physician (numbered 1-14). The values are displayed as mean value (MV) and standard deviation (SD) for the criterion better/worse in view of the applied methods color normalization (CN), equalization (EZ) and temporal median filtering with size 3 (TF 3) and filter size 5 (TF 5). With regard to color normalization and equalization, almost all physicians evaluated these methods to be an explicit enhancement of the images. In terms of temporal filtering 3, the mean values were close to zero, which means that the physicians predominantly did not see any difference between the original and the processed image. For temporal filtering with size 5, the original images were assessed as the better ones (mean values negative). The large standard deviations (compared to the difference of the mean values from zero) show that the evaluations of the physicians were not uniform.

Table 2 summarizes the results of all 14 physicians for the evaluation of the image pairs. For color normalization all mean values were positive, but interestingly the value for color impression was the smallest one (we expected this value to be larger than the other image quality criteria). The results for equalization were as expected: the mean values for better/worse and distortions were 0.43 and 0.52 whereas the other two values were close to zero. For temporal median filtering with size 3 the mean values of all criteria were close to zero which means the physicians did not see any difference between the original and the processed images. For temporal filter size 5, the original images were evaluated as the better ones (mean values of better/worse –0.21 and sharpness –0.25, other two criteria near zero). The reduction of the sharpness of the image can be explained because a hand-held endoscope will usually not remain truly steady during the number of frames contributing to the temporal filtering (especially edges are blurred in this case).

Table 3 shows the evaluation results for the image pairs split into experienced (n = 7) and inexperienced (n = 7) physicians. Equalization and temporal filtering results are the same in both groups. The only distinction is the highly significant ($p < 0.005$) difference in color impression between experienced and inexperienced evaluating persons. The inexperienced group preferred the color normalized images (MV 0.28) whereas the experienced group favored the original images (MV –0.24). This may be due to the fact that the inexperienced were not already used to (or confident with) the colors of a "normal" endoscopic image.

Table 4 illuminates the evaluation of image sequences done by the physicians. It became apparent during the evaluation of single images that it is very hard to observe

Table 2 Evaluation results (image pairs) for the 14 physicians altogether: Mean values (MV) and standard deviation (SD) for criteria better/worse, sharpness, distortion, color impression applied for the 4 methods color normalization (CN), equalization (EZ) and temporal median filtering with sizes 3 (TF 3) and 5 (TF 5).

Method	Criteria	Mean Value	Standard Deviation
CN	better/worse	0.28	0.87
	sharpness	0.17	0.85
	distortion	0.08	0.60
	color impression	0.02	1.01
EZ	better/worse	0.43	0.71
	sharpness	-0.06	0.52
	distortion	0.52	0.82
	color impression	-0.02	0.25
TF 3	better/worse	-0.07	0.65
	sharpness	-0.08	0.68
	distortion	-0.04	0.39
	color impression	-0.03	0.32
TF 5	better/worse	-0.21	0.71
	sharpness	-0.25	0.78
	distortion	-0.06	0.44
	color impression	-0.04	0.29

Table 3 Evaluation results (image pairs) split into experienced (7 altogether) and inexperienced (7 altogether) physicians. Mean values (MV) and standard deviation (SD) for criteria better/worse, sharpness, distortion, color impression applied for the four methods color normalization (CN), equalization (EZ), temporal median filtering with sizes 3 (TF 3) and 5 (TF 5). The grey fields show the highly significant ($p < 0.005$) difference in color impression between experienced and inexperienced physicians.

Method	Criteria	Mean Value		Standard Deviation	
		Unexp.	Exp.	Unexp.	Exp.
CN	better/worse	0.40	0.16	0.87	0.87
	sharpness	0.28	0.06	0.93	0.74
	distortion	0.15	0.01	0.75	0.39
	color impression	0.28	-0.24	1.13	0.97
EZ	better/worse	0.41	0.46	0.73	0.68
	sharpness	-0.07	-0.06	0.38	0.64
	distortion	0.46	0.58	0.90	0.72
	color impression	-0.01	-0.02	0.29	0.21
TF 3	better/worse	-0.10	-0.04	0.68	0.62
	sharpness	-0.11	-0.05	0.71	0.66
	distortion	-0.05	-0.03	0.45	0.32
	color impression	-0.03	-0.03	0.33	0.30
TF 5	better/worse	-0.17	-0.24	0.74	0.69
	sharpness	-0.26	-0.24	0.82	0.74
	distortion	-0.01	-0.10	0.47	0.40
	color impression	-0.05	-0.03	0.36	0.21

Table 4 Evaluation results (image sequences) for the physicians altogether.

	Color Normalization (3 movies)		
	Processed movie better	Original movie better	No difference
Evaluation (42 possible)	26	13	3
	Temporal Filtering (2 movies)		
	Filter size 3 better	Filter size 5 better	Original = Processed
Evaluation (28 possible)	8	16	4

the reduction of small flying particles by comparing image pairs (whereas the reduction can easily be seen in image sequences). Therefore two pairs of temporal filtered sequences (one sequence pair processed with filter size 3 and the other one processed with filter size 5) and three pairs of color normalized sequences were evaluated by the 14 surgeons, each pair comparing processed sequences with original sequences. In the color normalization movies, the physicians voted that the processed image was better 26 times. They voted 13 times for the original image. Concerning temporal filtering only in 4 of the 28 cases was the original sequence chosen as the better one, 8 of the times the processed sequence with time filter size 3 was chosen, and 16 times the processed sequences with time filter of size 5 were evaluated to be better (nobody decided that two sequence pairs looked the same). These results lead to the assumption that, regarding image sequences, the reduction of small flying particles can clearly be seen and is more important to the physician than maintaining the sharpness.

4. Conclusion and Discussion

Currently, standard video endoscopic systems offer only a few hardware-based image enhancement methods to adjust the images and to keep this good setting in the course of the operation. White balancing is applied to the endoscopic camera at the beginning of the intervention. In newer systems, an image processing unit allows for the digital increase of sharpness of edges, more precisely an increase of contrast. The basic colors red, green and blue can be modified with a controller at the monitor within close limits. None of the available standard video endoscopic systems allow for software-assisted image processing.

Through use of the established image processing methods, it is possible to reduce disturbances of endoscopic images by computer vision methods: temporal color median filtering (filter sizes 3 and 5) is used to eliminate small flying particles, color normalization corrects color errors and after calibrating the camera equalization eliminates lens distortion effects. Although these methods aim at an improvement of the images, it was necessary to clarify if the processing is a real enhancement for video endoscopy in minimal invasive surgery. Discussions with the participating surgeons led to the choice of certain criteria (better/worse, sharpness, distortion, color impression). The influence of names and order of the criteria could be an approach for further research because, for example, the placement of the better/worse decision (i.e. atop or below of the other criteria) seems to have an important effect on the overall result. The evaluation of the methods showed that the enhanced images (or image sequences in case of temporal filtering) were preferred by the physicians. As a result, further evaluations will attach more importance to image sequences than to single images, as this is closer to the real situation during surgical interventions. It will also be interesting to examine if the weighting of the image processing methods or the combination of the different methods lead to other results. Equalization and temporal filtering can already be applied in real-time. Color normalization should be accelerated by a factor of 4. Decreasing the required processing time could for example be reached by normalizing color only in parts of the image (e.g., the periphery). In addition to the applied and already evaluated image processing methods, new methods will be evaluated, e.g., highlight-reduction or temporal filtering of smoke.

Altogether the results obtained in this present evaluation emphasise that the applied image processing methods can significantly improve the quality of video endoscopic images. As a result of this the necessary lavages of the operated area can be reduced which leads to saving time and a better overview and orientation for the surgeon can be reached.

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