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A method for the estimation of the hemoglobin distribution in gastroscopic images

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Abstract

The assessment of blood flow in the gastrointestinal mucosa could be a useful indicator for the diagnosis and treatment of several diseases, such as ulcers, gastritis, colitis or early cancer. The quantity of blood flow is roughly estimated by computing the spatial hemoglobin distribution in the mucosa. The method presented here enables a practical realization by calculating approximately the hemoglobin concentration based on a spectrophotometric analysis of endoscopic true-color images, which are recorded during routine examinations. A system model based on the reflectance spectroscopic law of Kubelka-Munk is derived, which enables an estimation of the hemoglobin concentration by means of the color values of the images. Additionally, a transformation of the color values is developed, in order to improve the luminance independence. Applying this transformation and estimating the hemoglobin concentration for each pixel of interest, the hemoglobin distribution can be computed. The results obtained are mostly independent of luminance. An initial validation of the method is made by a quantitative estimation of the reproducibility.

Keywords: Blood flow; Distribution of hemoglobin; Endoscopic true-color images; Color image analysis; Reflectance spectrophotometry

1. Introduction

Blood supply to the gastrointestinal organs plays a vital role for physiological functionality [1]. Therefore, the relationship between 'blood flow and repair mechanisms in the mucosa is of current interest in gastroenterology. For example there is evidence that a reduced blood flow precedes the development of gastric ulcers in animal experiments [2]. Changes in blood supply to the mucosa in humans are also possibly linked to the development of gastric diseases [1,3]. Hence, an analysis of the blood flow distribution in the mucosa may promote a better understanding of these diseases and facilitate a reliable diagnosis.

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It is a long-term aim to establish a practical standard for a reliable and reproducible determination of mucosal blood flow. The technique employed must fulfil the following criteria: it should be safe, noninvasive, continuous, quantitative, accurate, and reproducible. It should measure the intramural flow distribution and should not alter the blood flow during the measurement [4]. Different approaches have been evaluated to measure local blood flow. Initially, measurements by means of hydrogen gas clearance were carried out [5–7]. This method turned out to be difficult to apply and to reproduce. Laser-Doppler measurements of the velocity of blood flow can be applied to measure blood circulation [6,8]. The precision of this method is limited because of errors due to instable positioning of the probe [8]. Another possibility to measure local blood flow is by means of a spectroscopic probe which is brought onto the mucosa using the instrument channel of an endoscope [2,9–11]. This method is very time consuming because several measurements have to be carried out to determine the hemoglobin distribution. A newer approach to assess mucosal flow is to inject fluorescein intravenously during endoscopy and to evaluate its temporal and spatial distribution. The amount of fluorescein at a particular position on the mucosa is correlated to blood flow at this point [12,13].

1.1. State of the art of established methods

The optimal method for the estimation of mucosal blood flow should be safe and noninvasive in its use, should gain quantitative, accurate and reproducible results, should measure the intramural blood flow distribution and should not alter circulation during measurement [4]. Different approaches have been applied for the local measurement of blood flow in humans during endoscopy:

1.1.1. Hydrogen gas clearance

This technique is based on the fact that inhaled hydrogen gas which accumulates in the gastric mucosa is removed from there only by the blood flow. Therefore, the speed at which hydrogen is removed from a specific location in the mucosa is correlated to the blood flow at this point. After inhalation of hydrogen gas, its concentration in the mucosa is measured by a platinum electrode which is set onto a point of interest. The dissociation of hydrogen at the surface of the platinum electrode into ions and electrons causes the generation of a current, which is correlated to the saturation of tissue with hydrogen at this location. The decrease in current should be proportional to the blood flow [1]. The hydrogen gas technique was broadly used to determine the mucosal blood flow in animal experiments. It is assumed that measurements by means of hydrogen gas clearance record the blood flow in the superficial layer of the mucosa [1]. It is not possible to measure the blood flow continuously by means of this technique. The results of this method are difficult to normalize, as there are discrepancies in the absolute values of mucosal blood flow in different laboratories [5,14,15].

1.1.2. Laser-Doppler velocimetry

This technique is based on the principle that the frequency of light which is scattered back by moving blood particles is shifted according to the Doppler effect. In order to measure blood flow in humans by means of Laser-Doppler velocimetry, a fiberoptic guide which conducts laser light onto the tissue is put endoscopically on points of interest on the mucosa. The laser light is scattered back by the moving blood particles, thereby experiencing a shift in its frequency, which is subsequently measured by a photodetector. By the means of this method, a continuous measurement of blood flow can be performed at a specific location of the mucosa obtaining the absolute amount of blood flow [1,6,8]. Nowadays many examinations are performed using this technique. However, up till now it has mainly been used for scientific purposes and not in routine medical practice. It is assumed that it measures blood flow at a depth of 0.5–1 mm. One problem with this method is the maintenance of a continuous contact between the optical probe and the tissue [1].

1.1.3. Reflectance spectroscopy

This technique determines substance concentration by measuring the amount of absorbed light at distinct monochromatic wavelengths. A

fiberoptic guide which is guided into the stomach using the instrument channel of an endoscope is set onto a point of interest on the mucosa and conducts monochromatic light onto the tissue. The amount of remitted light, which is measured by means of a photodetector, is used to compute the hemoglobin concentration. This technique also allows the determination of the concentration of oxygenated and deoxygenated hemoglobin separately at the same time. The depth of penetration of electromagnetic radiation into human skin (0.15 mm at a wavelength of 450 nm and 0.75 mm of a wavelength of 700 nm [16]) suggests that the hemoglobin concentration is measured in the superficial layer of the mucosa. Indeed, it was demonstrated that absorption is mainly influenced by hemoglobin in the mucosa [2].

A major source of error in the techniques mentioned above is that the blood flow may be altered through compression or mechanical stimulation when the probe is set onto the mucosa [1,4]. Another limitation for the assessment of mucosal blood distribution by these methods is the time needed to make several measurements at different locations. For hydrogen gas clearance 15–30 min are needed in order to make a single measurement, with the requirement that the blood flow stays constant during this time [4]. Therefore, this method is not suitable to determine mucosal blood distribution in humans.

Laser-Doppler velocimetry and reflectance spectroscopy allow a quicker assessment of single samples. However, in order to perform 20 different measurements on the mucosa at least 10–20 min are needed [9,17]. The extra time which is necessary in order to perform the described measurements during endoscopic examinations represents an additional strain for the patient. Furthermore, the inter- and intraobserver variability of the mentioned methods might be considerably large, because it is rather difficult to reposition the probe at the same position.

1.2. Objectives

It is the aim of this study to develop a method that fulfils the criteria mentioned above in an improved manner in order to enable an efficient application in routine examinations. Estimating the blood distribution in the mucosa by a spectroscopic analysis of endoscopic images recorded during routine examinations is a very practical and microinvasive approach [17–19]. A system model based on the reflectance spectroscopic law of Kubelka-Munk is derived, which enables an estimation of the hemoglobin distribution on the basis of the color values of such images. Furthermore, a transformation of the color values is presented, in order to improve luminance independence. Through the application of this transformation and the following estimation based on the transformed color values, a mostly luminance independent assessment of the hemoglobin distribution can be achieved.

2. Materials and methods

2.1. Recording endoscopic true-color images

In modern endoscopy CCD-chips located in the tip of an endoscope are used to record images of the interior of the body [20–22]. A CCD-chip consists of a multitude of CCD sensor elements that are arranged in matrix form. In one-chip video endoscopes there are two options to create color images. The first possibility is to sequentially create three color extracts in different spectral ranges by filtering the radiated light and subsequently amalgamate them into one color image. Another possibility is to cover discrete sensor elements with filters that are sensitive in different ranges of the visible spectrum [23]. In each case, the color value generated by each sensor element results from spectral integration of the respective frequency band of the incoming light at the considered pixel position. The signal of the CCD chip is subsequently transformed in the video processor. Since there are a multitude of different CCD chips and video processors available from various manufacturers and so many parameters surrounding the endoscopic equipment that can be changed by the examiner, a totally comprehensive modelling system including a completely automatic image analysis is not possible.

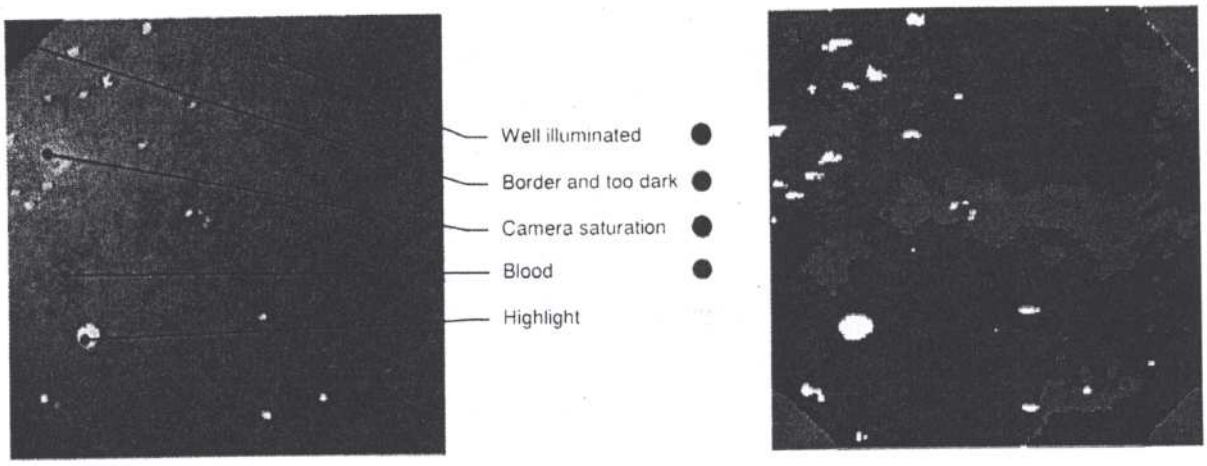

Fig. 1. Typical patterns in endoscopic images and segmentation result generated by a neural network. The left illustration (A) shows an endoscopic true-color image of the stomach with typical areas which have to be segmented. The segmentation result generated by a neural network is shown at the right side (B).

Endoscopic images are affected by a multitude of influences which may disturb subsequent analysis. For example, there are areas such as highlights and image borders and blood, succus, bile or the endoscope itself may cover the mucosa (Fig. 1A). In these image regions the hemoglobin concentration cannot be estimated reliably. Thus, they are not of interest for further analysis. The image properties are extensively influenced by luminance, as the brightness varies in different image parts due to different distances and angles between the endoscope and the mucosa. Moreover, CCD-sensor elements generally have a limited range to measure the intensity of the incoming light. If this intensity exceeds the maximal measurable light intensity, the camera cannot represent this information appropriately. This effect is called camera saturation (Fig. 1A and Fig. 2).

2.2. Segmentation

A segmentation of the images is necessary in order to exclude those areas in which the hemoglobin distribution cannot be estimated reliably. Additionally, it is necessary that the segmentation method creates uninterrupted image regions of the mucosa with smoothed boundaries. Segmentation procedures distinguish different image areas according to their underlying characteristic properties (Fig. 1B and Fig. 2B). For example, highlights, image borders and dark regions can be detected by means of their luminance. Therefore, a threshold segmentation method [24] on the basis of luminance values can be used to detect those regions. Other image regions such as blood or bile can be identified by their color information. Thresholds of the red, green and blue color values only allow discrimination of regions in the color space in planes that run in parallel to the coordinate axes (Fig. 2). In order to employ a more sophisticated discrimination of the 3D-color data, an artificial neural network — a one-layer perceptron [25] — has been used to assign each pixel to a segment (Fig. 3). This neural network is able to discriminate the RGB-color space by means of linear partitioning. Providing the net with the red, green and blue color value of each pixel as input vector, the neural network is able to assign each pixel to a segment. This applies to all mentioned segment types. Furthermore, we provided the neural network with color information of the environment of each pixel in order to obtain coherent image regions with smoothed boundaries. This environmental information consisted of frequency distribution of the red, green and blue color values of a square region (17×17 pixel for an image size of 256×256) surrounding each pixel (Fig. 3).

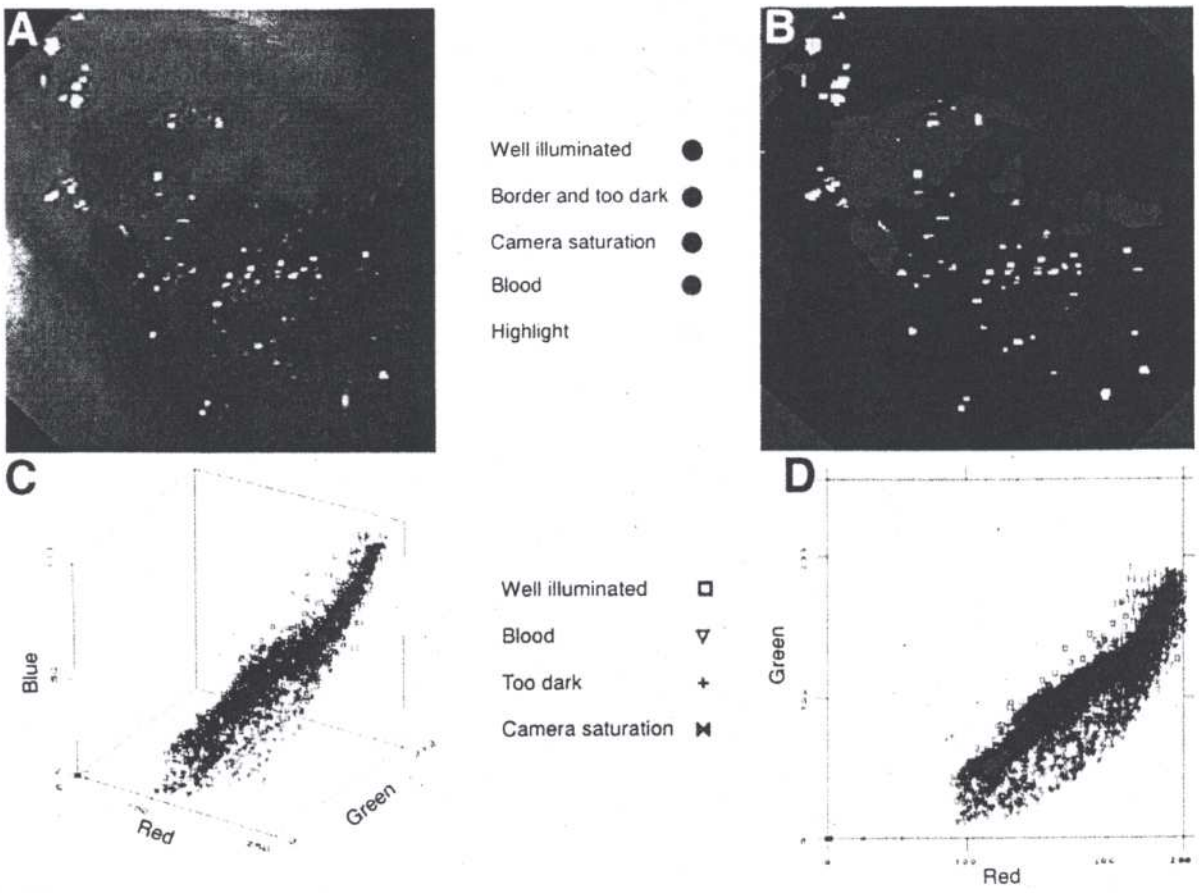

Fig. 2. Data discrimination shown at a typical example. Part (A) shows an endoscopic color image of a stomach with blood on the mucosa: in image (B) the a priori segmentation of (A) is presented. The distribution of the RGB-color values of certain segments in image (B) is visualized in a pseudo 3D-space (C). The projection of the same RGB-color data to a RG-color plane demonstrates the different distributions of several areas (D). The distribution of the areas caused by the camera saturation and covered with blood are well discriminated.

Neural networks adjust their parameters automatically by means of training processes in which the net is provided with a sufficiently large set of typical pairs of input and preclassified output values. Ten original endoscopic images with a size of 256 × 256 pixel combined with the corresponding a priori segmentations for each pixel position in the images were employed as a training set. They included different images of the esophagus, stomach and duodenum in order to enable a wide application of the method. Applying the presented segmentation method, those areas are excluded in which no hemoglobin concentration can be reliably calculated and no coherent image regions with smooth region boundaries are created (Fig. 1B).

2.3. Principles of spectrophotometric blood flow estimation

The accurate determination of substance concentration by means of spectroscopy using monochromatic light is well established. The method presented here estimates the hemoglobin distribution with the help of a spectrophotometric analysis of the color values of endoscopic images.

In order to compute an index which is linearly correlated with the hemoglobin concentration at a considered pixel position a formula is derived from the Kubelka-Munk equation applied in reflectance spectroscopy. The Kubelka-Munk equation describes the dependencies of reflection, absorption and scattering of light reflected from a surface [26,27]:

$$\frac{a_\lambda}{s_\lambda} = \frac{(1 - \frac{I_\lambda}{I_{\lambda 0}})^2}{2 \cdot \frac{I_\lambda}{I_{\lambda 0}}} \quad (1)$$

a_λ is the absorption coefficient of the pigment depending on the monochromatic wavelength λ, s_λ the scattering coefficient of the illuminated material, $I_{\lambda 0}$ the intensity of the radiated and I_λ the intensity of the remitted light of a certain wavelength λ. Among other assumptions, the application of the Kubelka-Munk equation assumes that the substance is diffusely illuminated and that no additional light is reflected directly at the surface. Sato et al. applied the principles of reflectance spectroscopy to the mucosa [2]. However, in their approach scattering effects were ignored.

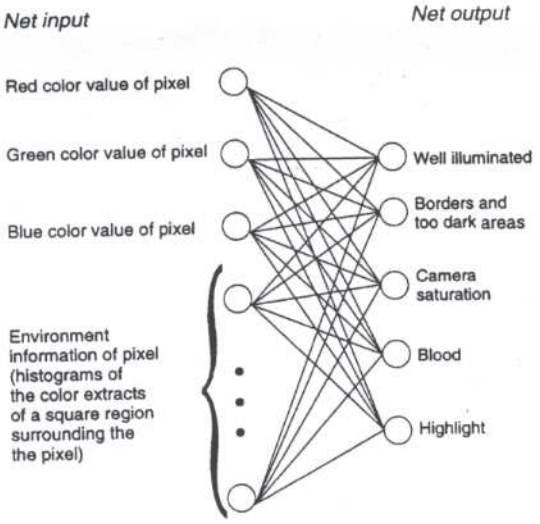

Fig. 3. Synthetic model of neural network used for the segmentation. The neural net assigns every pixel to a segment type according to its local and environmental color information.

Anderson and Parrish investigated light reflection from the human skin [16,28]. They concluded that the Kubelka-Munk equation which considers absorption, scattering and reflection delivers a reliable model for the underlying physical principles. According to Beer's law the absorption a_λ at a certain wavelength λ is correlated linearly with the concentration c of the absorbing substance:

$$a_\lambda = c\varepsilon_\lambda \quad (2)$$

where ε_λ is the extinction coefficient at a specific wavelength λ of the absorbing substance.

Combining Eqs. (1) and (2), a formula can be derived which accurately determines substance concentration c by means of the amount of the reflected light I_λ in relation to the radiated light $I_{\lambda 0}$:

$$c = \frac{(1 - \frac{I_\lambda}{I_{\lambda 0}})^2}{2 \cdot \frac{I_\lambda}{I_{\lambda 0}}} \cdot \frac{s_\lambda}{\varepsilon_\lambda} \quad (3)$$

If the light intensity $I_{\lambda 0}$ of the radiated light, the scattering coefficient s_λ of the mucosa and the extinction coefficient ε_λ of hemoglobin are known and the light intensity of the remitted light I_λ is measured, the hemoglobin concentration c can be calculated.

Usually, quantitative spectroscopic measurements are performed at a monochromatic wavelength where light absorption by the substance is maximal. For hemoglobin these maxima are reached in the green range of the spectrum at wavelengths 542 and 577 nm for the oxygenated and 556 nm for the deoxygenated forms (Table 1 and Fig. 4). However, color values of standard endoscopic images do not represent a monochromatic measurement, but rather an integrated sample of the incoming spectrum. In order to use Eq. (3) for the estimation of the hemoglobin concentration the green and red color values of endoscopic images are used, even although this use of polychromatic instead of monochromatic light introduces an error in the estimation.

Hemoglobin is the most abundant dye in the gastric mucosa (Table 1). Furthermore, the concentration of other pigments is not influenced by circulation and is approximately constant. These

Table 1
Concentration of the most important mucosal pigments (depicted from [18])

Pigment	Maximum of extinction at wavelength (nm)	Concentration (nmol/g)
Oxygenated hemoglobin	542, 577	> 140–180
Deoxygenated hemoglobin	556	
Cytochrome cyt aa_3	605	10
Cytochrome cyt b	560–565	10
Cytochrome cyt $c+c_1$	550–554	15
Catalase	500–600	10–20

The maximum of absorption lies in the green range of the visible spectrum for all relevant pigments.

Hemoglobin is the most abundant dye in the gastric mucosa (Table 1). Furthermore, the concentration of other pigments is not influenced by circulation and is approximately constant. These other pigments are nearly uniformly distributed in the gastrointestinal mucosa [29]. Consequently, the spectral composition of the remitted light and thus also the red and green color values are governed by the concentration of hemoglobin in the mucosa. Hemoglobin strongly absorbs green light and weakly absorbs red light (Fig. 4), therefore, the amount of remitted green light is assumed to be a good indicator for measurement with monochromatic light in the green range of the spectrum. The absorption of red light is almost independent of the concentration of any pigment, because all mucosal pigments absorb red light comparatively weakly. Hence, the red color value is used as a measure of the intensity of the illuminating light. Therefore, the following assumptions are made:

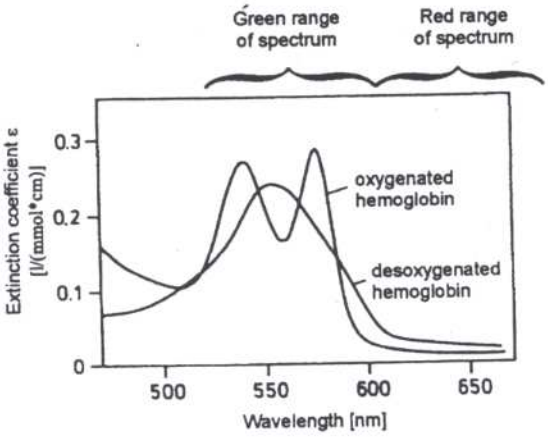

Fig. 4. Absorption characteristics of hemoglobin as shown by its extinction coefficient [31].

$$I_\lambda \cong G \qquad I_{0\lambda} \cong R \tag{4}$$

where G and R are the green and red color values, respectively. That means, that the green color values which are highly governed by the concentration of the hemoglobin are standardized by the red color values. The underlying assumption is that the red color value is used as a measure for the radiated light $I_{\lambda 0}$. Substituting I_λ and $I_{\lambda 0}$ in Eq. (3) using these assumptions and summarizing the constants, the following formula is derived to estimate the hemoglobin concentration for one pixel:

$$c = k \cdot \frac{(1-\frac{G}{R})^2}{\frac{G}{R}} \tag{5}$$

where k is a constant which has to be determined experimentally.

By means of this formula an index can be computed which should be linearly correlated to the hemoglobin concentration at a certain pixel position. A spatial representation of the hemoglobin concentration can be generated by visualizing the calculated estimations for all pixels of interest (Fig. 6B, 6D, 7B, 7D)

2.4. Transformation to ensure luminance independence

If the hemoglobin concentration is computed by applying Eq. (5) to the color values of original endoscopic true-color images, the results are still dependent on the luminance. The calculated hemoglobin concentration is higher in dark and lower in bright parts of the images compared to the average calculated hemoglobin concentration.

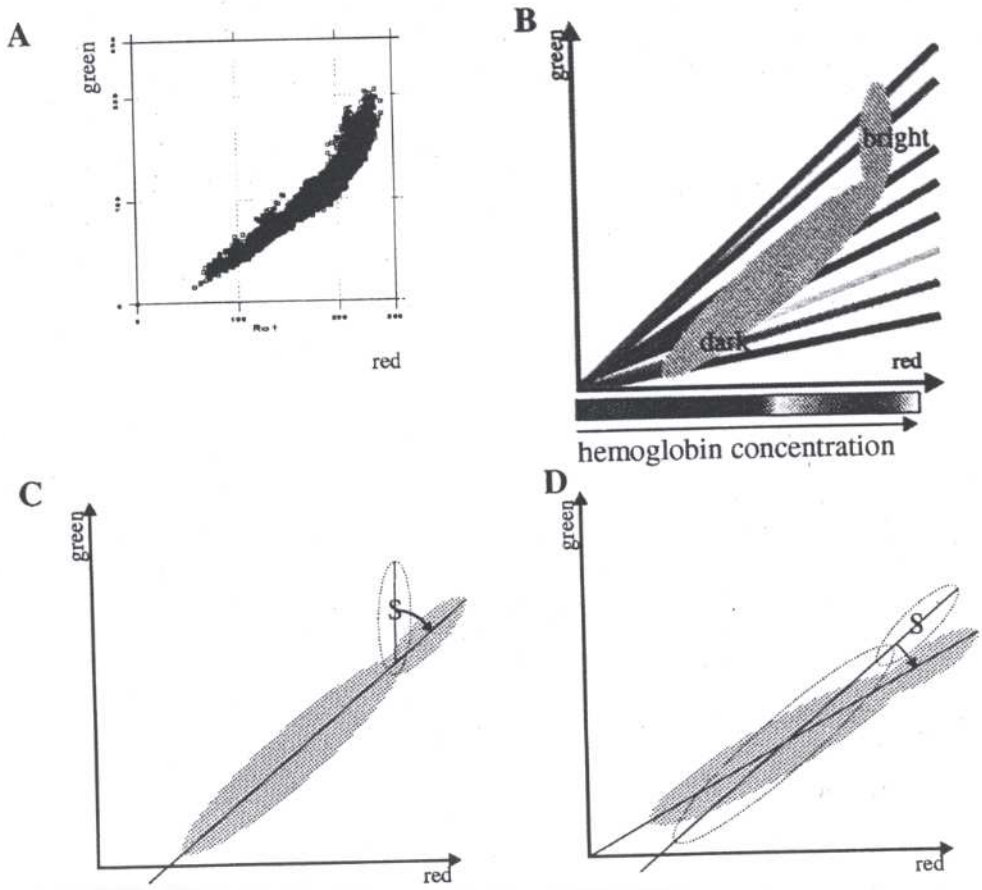

Fig. 5. Transformation of color image data in the RG-color plane. (A) Distribution of color data from an example of one endoscopic image in the RG-color plane with nearly the same hemoglobin content in the visible image part. (B) Diagram of calculated hemoglobin distribution in the RG data plane. The calculated hemoglobin concentration is higher in dark parts and lower in bright parts of the images. (C) Rotation of the distribution of those image parts that are influenced by saturation effects of the camera (s). (D) Rotation of the resulting distribution. Applying this transformation the computed hemoglobin concentration is uniformly distributed in dark and bright areas of the image data.

images due to camera saturation. Additionally, the regression line of the distribution which is not influenced by camera saturation does not intersect the origin. For this reason, an algorithm was developed which transforms the image data in the RG-color plane to improve luminance independence. This algorithm is based on the assumption that in general hemoglobin is uniformly distributed in various bright areas of the image.

Theoretically, those pixels in the RG-color plane corresponding to the same hemoglobin concentration are situated on a line which intercepts the origin (Fig. 5B). Furthermore, the color image data of endoscopic images has to be uniformly distributed in various bright regions in the RG-color plane in which the same hemoglobin concentration is calculated. Therefore, a method was developed which transforms the image (red and green colour) data in such a way that it fulfils this requirement. In a first step, the distribution is linearized by rotating the part of the distribution which results from camera saturation (area S in Fig. 5C). Subsequently, the entire resulting distribution is transformed. Initially, this was done by shifting the distribution so that its regression line intercepts the origin. In this case, the resulting

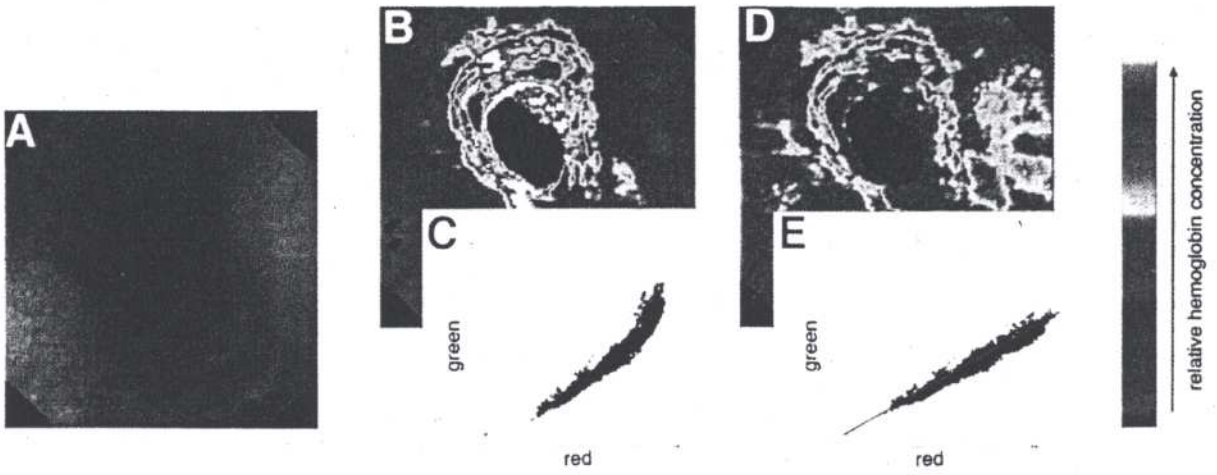

Fig. 6. Demonstration of the applied method providing the luminance independence. Endoscopic color image of a normal esophageal mucosa (A) in which the segmented areas are excluded (black image parts). The presented mucosa is approximately uniformly supplied with blood (preclassified visually by medical experts). RG-projection of the data distribution of the remaining color values before any transformation (C). RG-projection of the same data after applying the presented transformation algorithms (E). Visualization of the spatial representation of the calculated hemoglobin indices at each pixel position before (B) and after (D) applying the transformation algorithms. The transformation of the color values improves the luminance independence.

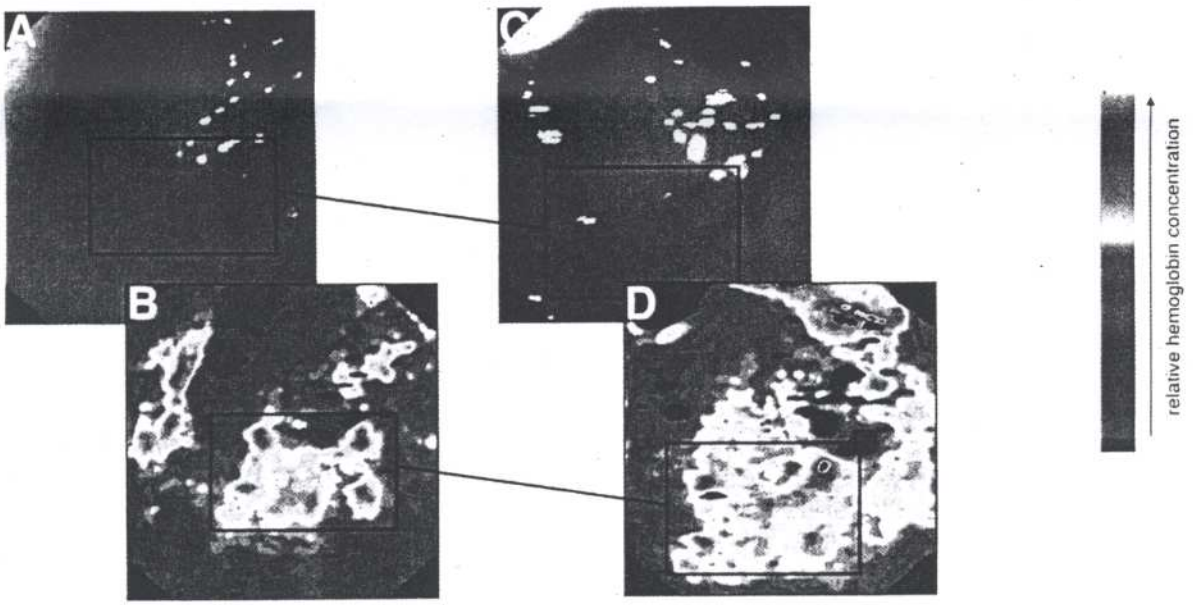

Fig. 7. Demonstration of the reproducibility of the presented procedure. Two endoscopic images showing the same mucosal surface of the stomach recorded from different distances and angles of view (A,C). Within the corresponding region of interest (black rectangle in B and D) comparable patterns of the underlying circulation are observed. (B) and (D) are visualizations of the calculated hemoglobin estimations at each pixel position after the transformations.

Table 2
Statistical pixel-based evaluation of the reproducibility of the described method

	Same distances and angles of view	Different angels of view	Different distances and angles of view
Number of image pairs n	5	2	1
Average deviation of the mean estimated hemoglobin concentration in correspondent regions of images of the same mucosa	5%	28%	63%

The mean relative hemoglobin concentration was calculated in corresponding regions (15 × 15 pixels – 30 × 30 pixels) of images that show the same mucosa.

hemoglobin distribution is luminance independent, but different mean hemoglobin concentrations are calculated for images of the same mucosal surface. Therefore, this approach results in poor reproducibility. In order to improve the reproducibility, a transformation of the distribution was developed which rotates the distribution in such a way that the regression line of the distribution intersects the origin (Fig. 5D). By means of this transformation a mostly luminance independent hemoglobin distribution can be computed with a comparable mean concentration in images showing the same mucosal surface.

The estimation of the hemoglobin distribution is performed by means of Eq. (5) on the basis of the transformed color values. By introducing the described transformation method, the reproducibility of the method can be significantly improved, as the results are mostly independent of luminance (Fig. 6).

3. Evaluation of experimental results

To evaluate the luminance independence the method was applied to 13 endoscopic images of regions in which the hemoglobin distribution is approximately uniform (preclassified visually by medical experts), yet showed varying luminance in different areas of the image. A uniform blood supply in the esophagus was proven with images recorded at different heights, which were weaker illuminated in those parts which were further away from the endoscope (Fig. 6A). The application of the presented method to parts under comparable luminance conditions confirmed an uniform blood supply. This was also confirmed by the application of the presented method based on the transformed color values (Fig. 6).

An initial statistical evaluation of the reproducibility of the method was performed. For this evaluation the mean values of the estimated hemoglobin concentration of corresponding regions of different endoscopic images were compared quantitatively. This was done by computing the average deviation of the mean estimated hemoglobin concentration in corresponding regions of images showing the same mucosal surface. Until now we have investigated 10 patients with multiple endoscopic examinations and it was demonstrated that the reproducibility is good for images under similar luminance conditions. The deviation is greater in images under different luminance conditions. However, it has to be taken into account that identifying the same region in different endoscopic images recorded at a different angle of view is rather difficult. Additionally, the small number of images available did not allow a complete evaluation of the reproducibility of the method and secondly there exists no golden standard for a quantitative determination of the hemoglobin distribution (Table 2, Fig. 7).

4. Discussion

4.1. System model

Analysis of the color values of endoscopic images with regard to the blood distribution was

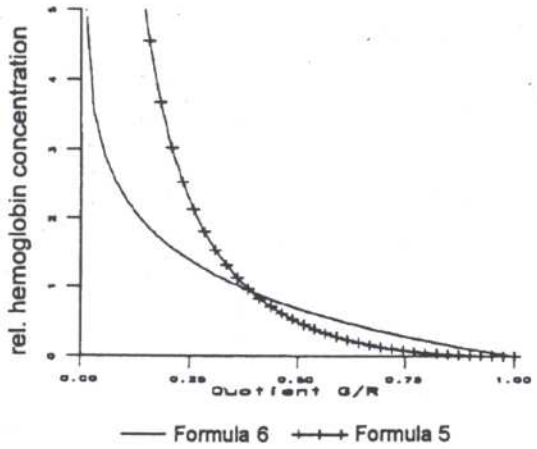

Fig. 8. Comparison of the two system models. Function plots corresponding to Eqs. (5) and (6) derived from system models with and without consideration of scattering are shown. It is observed that the calculated hemoglobin concentration has similar linear properties for low hemoglobin concentrations (high G/R ratio) but is diverging for high hemoglobin concentrations (low G/R ratio). k and k' are not determined. Therefore, they are both set to 1.

introduced by Tsuji et al. in 1988 [17–19]. They assumed that scattering effects in the mucosa could be ignored [18]. If there is no scattering, a logarithmic dependence is derived from the Kubelka-Munk approach. In principle, this reflects the properties of transmittance spectroscopy, which are described by Lambert-Beer's law. Using substitutes (4), the approach of Tsuji et al. provides the following formula:

$$c = k'(\lg\frac{R}{G}) \qquad (6)$$

where k' is set to 32 [17–19]; R and G are the red and green color values. However, it was never proven by Tsuji et al. that scattering could reasonably be ignored. The precision of this alternative method will depend largely on the influence of light scattering in the mucosa. The comparison of the two different approaches shows that, theoretically, quantitatively similar results should be obtained in areas where blood circulation is weak (high G/R ratio) and differing results in areas with an increased blood flow (low G/R ratio, Fig. 8). Using monochromatic light, Sato et al. reported a linear correlation between the extinction of the light and the hemoglobin concentration up to 150 nmol/g mucosa [2]. Theoretically, their observation may be due to the fact that according to the function plots in Fig. 8 the neglect of scattering causes a deviation from the hemoglobin concentrations at high levels (i.e. low G/R ratios). Consequently, a more accurate determination should be possible using a system model according to formula [5].

4.2. Transformation for luminance independence

The described transformation of the color image data plays an important role in the luminance independent estimation of the hemoglobin distribution, because in routine endoscopic images luminance varies due to changing distances and angles of view. Of course, when endoscopic images are recorded in order to estimate the blood flow, the examiner will try to position the endoscope strictly at a right angle to the mucosa. Tsuji et al. [17–19] do not report on luminance dependence. This might be due to the fact that they use mainly images with homogenous luminance. However, due to the anatomy of the gastrointestinal tract, it is sometimes difficult to obtain images that are uniformly illuminated. Luminance will influence image properties in many images, hence, the presented transformation is beneficial to ensure luminance independence and to improve the quality of the method.

In order to improve luminance independence, the color image data have to be transformed in such a way that they are uniformly distributed in various bright regions in the RG-color plane. This can be accomplished either by a geometric translation or by rotation. The geometric translation of the distribution was first employed. Thereby, it was observed that the results of this method were mostly luminance independent but weakly reproducible, as different mean hemoglobin concentrations were calculated for images that show the same area on the mucosa. Therefore, the rotation of the distribution was used to achieve luminance independence. By means of this technique the reproducibility of the method could be significantly improved. The choice of the rotation center is the main problem, as this choice influences the

calculated mean hemoglobin concentration. This determination is done empirically and still needs to be optimised. A transformation, based on a combination of geometric translation and rotation was not employed, because the simultaneous determination of three free parameters — the amount of translation, the rotation center and angle — is very complex. As described above, typical distributions of the color values in the RG color plane deviate from the theoretically expected pattern in two aspects: firstly, the non-linearity in bright parts, resulting from camera saturation and secondly, the shift of the regression line out of the origin. The latter is probably due to the linearization of the non-linear characteristic curves of the three different color channels. Those influences vary for different endoscopic equipment and are partly changeable by the examiner. As the corresponding parameters are difficult to define at computation time, it is a more practical approach to find the transformation algorithm empirically.

4.3. Technical realization

The images were obtained with an Olympus video endoscope GIF-100 and a video processor EVIS-100. The video signal was digitized by means of the documentation system ENDOBASE® (Olympus Opticals, Hamburg) using a frame grabber card. For the digital image processing the UNIX software KHOROS® (University of New Mexico) and the graphical user interface CANTATA were employed. Programming was performed in C. Currently the algorithms are ported to a PC-based system. Segmentation will be optimized using method of mathematical morphology [30] instead of including the environmental information of each pixel in the input vector of the neural network. Moreover, the neural network will be included in the image processing environment. After optimization a complete calculation should be performed within 5–20 s by a solely software solution.

Analyzing endoscopic true-color images is a very practical and microinvasive approach to estimate the hemoglobin concentration in the mucosa. Images that have been recorded during routine examinations can be used to calculate a two-dimensional estimation of the mucosal hemoglobin distribution. This is an advantage over methods that measure blood flow locally, where several measurements have to be performed in order to enable an estimation of the blood distribution. Also, blood flow is not altered, because no probe has to be set onto the mucosa, that could possibly change blood flow in this region. The measurement depth of the presented method should be similar to the one in reflectance spectroscopy (<1 mm, see above). Furthermore, a far better resolution quality for the measurement of regional mucosal blood flow is obtained (ca. 30 000 pixels per image). However, the use of polychromatic rather than monochromatic measurements introduces a considerable error in the measurements obtained. The accuracy and reproducibility of the method in comparison to established techniques is still under investigation. In summary, the presented method fulfils well most of the criteria mentioned above, provided it meets the expectations with respect to accuracy and reproducibility. According to the investigations of Tsuji et al. [17] the accuracy of blood flow estimation in gastroscopic true-color images compares well with measurements by reflectance spectroscopy. The introduction of an improved system model as described and a transformation for luminance independence should further improve these results. A clinical evaluation is currently in progress.

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