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Image-guided preparation of the Calot's triangle in laparoscopic cholecystectomy

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Abstract— **Laparoscopic cholecystectomy is the most common way to remove the gallbladder nowadays. Compared to open surgery, laparoscopy results in shorter hospital stays, reduced postoperative pain, and smaller incisions. Proper localization of the cystic artery is of great importance in laparoscopic cholecystectomy in order to ensure safe stapling and avoiding injury to the artery. In this study, we evaluate an image-guided method for artery detection. The performance of this method was evaluated in detecting arteries in 35 laparoscopic cholecystectomy patients. This method uses the artery's pulse to distinguish it from veins and biliary ducts. By subtracting the systolic and diastolic images, the change regions are detected and shown on a monitor. In 35 laparoscopic cholecystectomy procedures the method can correctly detect all arteries that are not too deep and can move superficial tissues with zero false-negative and 12% false-positive rates. Using the second mode of the method that needs more time for processing, the false-positive rate decreased to 4% with zero false-negative. The image-guided technique is a sensitive, noninvasive, and cost-effective method to detect arteries in laparoscopic cholecystectomy, even if it is covered with fat or other tissues. It is possible to install the program on any ordinary laparoscopy set and it displays the artery's region on the monitor.**

I. Introduction

LAPAROSCOPIC cholecystectomy has replaced open cholecystectomy since the late 1980s. It is now the gold standard to remove the gallbladder. The laparoscopic approach is used in 75% to 95% of cases for management of symptomatic gallstone disease [1]-[3]. There is overwhelming evidence that laparoscopic cholecystectomy offers patients less pain, shorter hospitalization, and faster recovery [4]. Laparoscopic cholecystectomy is the most common operation performed laparoscopically worldwide. When it was first introduced, there were some concerns about its safety owing to its rapid adoption by untrained surgeons. However, when a careful, correct technique is employed, the operation is extremely safe [5].

Calot's triangle is bordered by the cystic artery, the cystic duct, and the hepatic duct. A potentially serious complication with the laparoscopic cholecystectomy is injury to the cystic artery, which is between 0.85% and 2.84% [6], [7]. Uncontrollable bleeding from cystic artery is one of the various reasons for conversion in laparoscopic cholecystectomy. In an evaluation study on 176 cases, cystic artery injury occurred in 5 (2.84%) cases. Bleeding could be controlled in 3 (1.70%) cases whereas 2 (1.14%) cases were converted [6]. Hemorrhage during laparoscopic cholecystectomy is usually more difficult to control than that during open cholecystectomy as blood tends to obscure the operative field [7]. Identification of the cystic artery is a time-consuming procedure especially for less experienced surgeons. Assessing technical skill during 30 operative procedures in a study showed that 5 (17%) procedures did not successfully complete all steps. In three of these patients, the step not completed was identification, ligation, and transection of the cystic artery [8].

Proper localization of the cystic artery can be helpful in laparoscopic cholecystectomy for proper alignment of other important structures including the cystic duct [9].

Injury to major vessels in laparoscopic surgery is reported in several patients. An accidental injury to a blood vessel may cause serious complications and could result in changing from a laparoscopic procedure to open surgery. Moreover, distinguishing arteries from veins is necessary in all surgical cases [10].

Different advanced methods are applied in laparoscopic surgeries for detection of the blood vessels. These methods are complicated, and need expensive and highly technical medical equipments [9], [10]. The endoscopic pulse detector is a device that has been especially developed for detecting arteries in laparoscopy by an accelerometer on its tip. It is inexpensive and simple to use but requires the surgeon to temporarily stop the procedure and insert the device into the body and detect the artery [9].

In this study, we evaluate an image-processing method for artery detection that would be useful during laparoscopic cholecystectomy. It is a noninvasive, reliable, and cost-effective way. This is the first method reported that can continuously detect the arteries without interrupting the laparoscopic surgery. It is possible to install the program on any ordinary laparoscopy set and it displays the artery's region on the monitor.

II. Materials and Methods

In this study, we evaluated the method that uses a pulse to detect arteries covered by other tissues and to differentiate between the arteries and veins by image-processing techniques. The method senses the movement of tissues over

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the artery due to the artery's pulse. To evaluate the performance of the method, we considered a data set corresponding to 35 patients underwent laparoscopic cholecystectomy. This technique was evaluated for its performance in detecting arteries and the ability to differentiate between arteries and other structures (veins or biliary ducts) in these surgeries.

A. Procedural steps

The laparoscopies were carried out on 7 males and 28 females. The clinical diagnoses were cholecystitis in 19 patients (54.3%), biliary colic in 15 patients (42.9%), and biliary pancreatitis in 1 patient (2.8%). Underlying diseases in these patients were rheumatic fever, hypertension, diabetes mellitus, hyperlipidemia, coronary artery disease, thalassemia minor, and mitral valve prolapse.

The method senses the movement of tissues over the artery based on the artery's pulsatile movement. The magnitude of superficial tissue movement is affected by changes in blood pressure, pulse rate, vessel geometry, arterial depth, and the texture of overlying tissue - all of which are important in the evaluation of this method. Even special circumstances such as the age of patient and preexisting medical conditions such as diabetes or arteriosclerosis that change artery elasticity should be taken into consideration [10]. The Olympus laparoscopic system (Tokyo, Japan) with OTV-S6 camera system, CLV-S30 Xenon light source, and UHI-2 insufflator was used for our laparoscopic surgeries.

To perform a laparoscopic cholecystectomy, after general anesthesia, four trocars were placed through the abdominal wall. This technique was evaluated for its performance in detecting arteries and the ability to differentiate between arteries and veins in these surgeries. Eighty sequential pair images were extracted according to systolic and diastolic times. The measurements of both the detection of the artery and the ability to differentiate between arteries and veins were evaluated.

B. Change Detection Algorithm

The algorithm that is behind this method is a change detection algorithm. A pair or a set of images of the same scene at systolic and diastolic times is obtained. The objective of the algorithm is to extract the set of pixels that are significantly different between the last image of the sequence and previous sampled images. This algorithm has two modes: the first mode uses a pair image according to systolic and diastolic times and the second mode uses three pair images according to three nearby pulses. Although more sample images will result in a more precise output, it needs more calculation time. Capturing two images at systolic and diastolic times result in a maximum change between two images. Ideally, plain intensity changes at a pixel resulting from laparoscope motion alone should not be detected as artery regions. Therefore, a necessary preprocessing step is accurate image registration, the alignment of two or several images into the similar coordinate frame. The method performs an unsupervised registration algorithm to correct for the geometric differences of the input image with respect to the reference image by increasing the accuracy level of the registration and reducing computational time. Mathematical modeling techniques are used to correct the geometric changes like translation, scaling, and rotation of the input image with respect to those of the reference image so that these images may be used in change detection. The image registration algorithm that is used in this method uses a fast Fourier transform (FFT) method for registering two images. This algorithm considers a model that combines a 2D affine transformation and an illumination change [10], [11].

The FFT-based method that operates in the frequency domain was chosen, as it had short computational time and was sufficiently precise. In contrast, the nonlinear local registration method omitted the artery pulse [11]. Unwanted tissue movements caused by surgical devices, were eliminated in post-processing.

The FFT-based automatic registration algorithm is based on the Fourier shift theorem. When two images differ only by a shift, then their Fourier transforms are related by the following equation.

$$F(\xi,\eta) = e^{-j2\xi(x\xi+y\eta)} F1(\xi,\eta) \tag{1}$$

where $F(\xi,\eta)$ and $F1(\xi,\eta)$ are Fourier transforms of two images.

The ratio of two images is defined as:

$$R = \frac{F1(\xi,\eta)conj(F(\xi,\eta))}{abs(F1(\xi,\eta))abs(F(\xi,\eta))} \tag{2}$$

where *conj* is the complex conjugate and *abs* is the absolute value. By taking the inverse Fourier transform of R, the resulting function is approximately zero everywhere except for a small region around a single point. This single point is where the absolute value of the inverse Fourier transform of R reaches its maximum value. The location of this point is exactly the displacement, which is used to optimally register the images [10]-[12]. Then converting these images from rectangular coordinates to log-polar coordinates makes it possible to represent both rotation and scaling as shifts [10], [13].

C. Pulse Detection and Post-processing

The changed parts are calculated by image differencing. It requires only calculating the absolute values of the difference between the corresponding pixels in two registered images, and high values in the difference map indicate the locations of change. To define a threshold value, a generic methodology for target-detection performance evaluation is employed. Given a threshold value for a change, the proposed method calculates false detection (false positive) and false rejection (false negative) regions using reference image pairs. By varying the threshold from zero to some maximum value, a curve of false negative probability versus false positive probability can be determined. We adjusted the threshold to different values for different frames of surgeries, based on the average intensity change in each surgery and zero false negative. In this way, we could be sure to detect all arteries.

Changes due to pulse motion in laparoscopic image sequences arise from the appearance of motion of an artery in a specific size range with continuous, differentiable boundaries. Therefore, the change detection algorithm matches the change mask to these expectations in the post-processing step. The color of each detected region should be within the range defined for arteries and the length of the minor axis should not be greater than the diameter of the artery. The computational time was about 4-5 seconds on a 3.6 GHz computer with a 2 GB RAM. It is possible to decrease the calculation time using a digital signal processor or parallel processing which meets real-time conditions. The flowchart of the method is shown in Fig. 1.

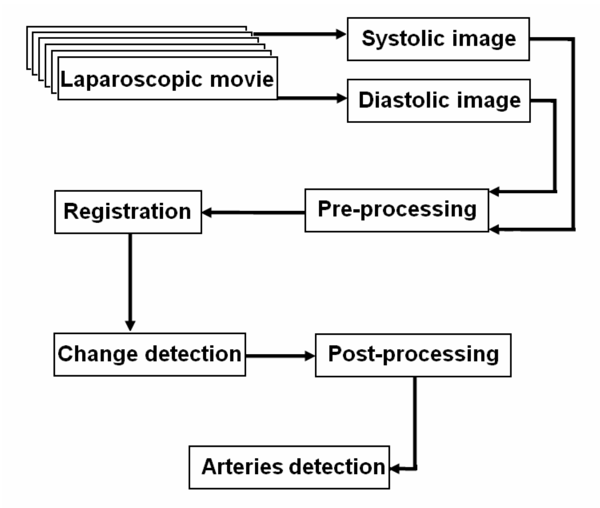

Fig. 1. Flowchart of artery detection algorithm.

III. Experimental Results

This program works in parallel with laparoscopic procedure and does not interrupt the procedure. The detected artery can be displayed on a monitor in a near real-time manner over the ordinary laparoscopic monitor screen. Performance criteria for artery detection are false negative rate (FNR) and false positive rate (FPR). When a region is detected as a non-artery region, the detection is a false negative if the region is an artery region on the hand-created map. FNR is defined as the number of false negatives divided by the total number of arteries on the hand-created map. When a region is detected as an artery region, the detection is a false positive if the region is non-artery region on the hand-created map. FPR is defined as the number of false positive pixels divided by the total number of non-vessel pixels.

The performance of this technique to detect all the arteries in the field of surgeries and its ability to differentiate between arteries and veins in laparoscopic surgery is evaluated. All the arteries that are exposed in these procedures are evaluated for detection by the method. The method could detect all the arteries include the cystic arteries. One sample of systolic and diastolic frames and detected artery is shown in Fig. 2. A checkerboard image is created by combining alternating squares from systolic and diastolic images to enhance the difference between to images. As is shown in this figure the algorithm does not detect the exact margin of the artery. The method is evaluated in its two modes: first mode that is faster and second mode that is more precise.

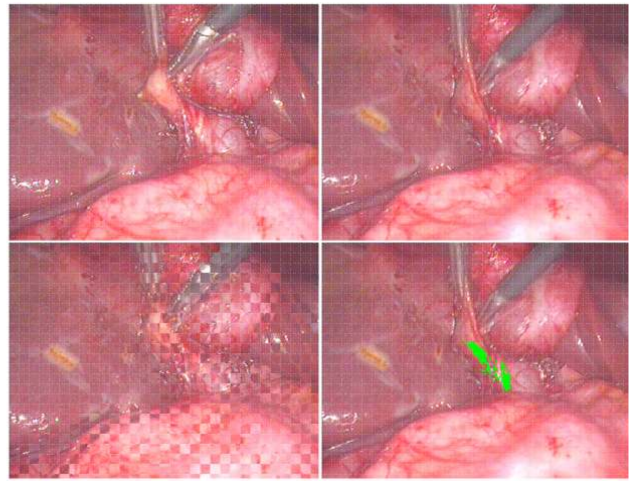

Fig. 2. Laparoscopic images of the laparoscopic cholecystectomy; left-up image is the systolic image with a grid; right-up image is the diastolic image with a grid; left-down is a checkerboard image is created by combining alternating squares from systolic and diastolic images; right-down image is the detected artery, using the proposed method.

Eighty sequential pair images were extracted according to the systolic and diastolic times. For these paired laparoscopic images, the FPR value is 12% that offers a specificity of 88% for detecting arteries. The FNR value is 0% that offers a sensitivity of 100% for detecting the arteries. For the second mode, the FPR value decreases to 4% that offers a specificity of 96% for detecting arteries. The FNR value is 0% that offers a sensitivity of 100% for detecting the arteries. These results are shown in Table I.

TABLE I
EVALUATION RESULTS

	FPR	FNR	Specificity	Sensitivity
First mode	12%	0%	88%	100%
Second mode	4%	0%	96%	100%

FPR = false positive rate, FNR = false negative rate.

The method is relatively safe and no extra devices have to be inserted into the body. Therefore, it does not increase the risk of infection or risk of radiation and does not require extra time for application.

IV. Discussion

Laparoscopic surgery is done by making a few small incisions to insert a laparoscope and other surgical devices. The laparoscope takes images and sends them to the monitor. The surgeon can see the operation field using this monitor. Due to the lack of tactile sensation and three-dimensional visual feedback, it is difficult to identify blood vessel position intraoperatively. In almost all laparoscopic procedures, surgeons face the problem of detecting and localizing blood vessels, either to avoid them or to allow their ligation. A noninvasive, reliable, and cost-effective method to detect blood vessels would be useful during laparoscopic and endoscopic procedures [10].

In laparoscopic cholecystectomy, dissection of cystic pedicle is a critical part of the surgery. A misunderstanding of anatomy can result into injury to the common bile duct or the blood vessels. The cystic pedicle is a triangular fold of peritoneum containing the cystic duct and artery, the cystic node and a variable amount of fat. It has a superior and an inferior leaf, which are continuous over the anterior edge formed by the cystic duct. An important consideration is the frequent anomalies of the structures contained between the two leaves (15-20%). There are a few anomalies in cystic artery include: short cystic artery arising from looped right hepatic artery, latter liable to be mistaken for cystic artery or damaged with bleeding during dissection of cystic duct; early division of the cystic artery, risk of bleeding usually from the posterior branch if this is overlooked; and anomalous origin of the hepatic or right hepatic artery from the superior mesenteric artery [5].

Various methods are designed for studying the vascular system. Angiography, laser Doppler flowmetry, color Doppler ultrasonography, speckle methods, optical coherence Doppler tomography, functional imaging and monitoring of blood oxygenation in human tissues by means of time and spatially resolved near-infrared reflectance spectroscopy, computed tomography angiography, magnetic resonance angiography, are methods for evaluating the vascular system [14]. All these methods are complicated, time-consuming, need expensive and highly technical medical equipment and expertise, and are not readily available for ordinary laparoscopic surgery [9], [10].

V. Conclusion

The image-guided method can detect all arteries with 100% sensitivity without interruption of the procedure. The method does not entail any type of radiation or risk exposure to the patients. This method is the first method that can continuously detect the arteries without interrupting the laparoscopic surgery. All of the previous methods required a surgeon's attention to a special region and use of highly technical equipment to detect arteries or to differentiate between arteries and veins. Using the proposed method the risk of arterial injuries during laparoscopic cholecystectomy would diminish and surgeons can localize the artery easier than before.

None of previous strategies guarantees safe removal of the gallbladder in all situations. Especially in difficult cases, such as anatomic variations, fusion of dissection planes, or poor visualization could force the surgeon to change the laparoscopic procedure to open surgery. This conversion invariably leads to longer operative and hospitalization times with higher morbidity compared to successful laparoscopic surgery. It is possible to convert the output image into an audio signal which can alarm the surgeon if approaching an artery. In addition, this method has the potential to be used for other clinical applications.

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