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NEW TECHNOLOGY

Ultrahigh sensitivity endoscopic camera using a new CMOS image sensor

Providing with clear images under low illumination in addition to fluorescent images

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Abstract

Background We developed a new ultrahigh-sensitive CMOS camera using a specific sensor that has a wide range of spectral sensitivity characteristics. The objective of this study is to present our updated endoscopic technology that has successfully integrated two innovative functions; ultrasensitive imaging as well as advanced fluorescent viewing.

Methods Two different experiments were conducted. One was carried out to evaluate the function of the ultrahigh-sensitive camera. The other was to test the availability of the newly developed sensor and its performance as a fluorescence endoscope. In both studies, the distance from the endoscopic tip to the target was varied and those endoscopic images in each setting were taken for further comparison.

Results In the first experiment, the 3-CCD camera failed to display the clear images under low illumination, and the target was hardly seen. In contrast, the CMOS camera was able to display the targets regardless of the camera-target distance under low illumination. Under high illumination, imaging quality given by both cameras was quite alike. In the second experiment as a fluorescence endoscope, the CMOS camera was capable of clearly showing the fluorescent-activated organs.

Conclusions The ultrahigh sensitivity CMOS HD endoscopic camera is expected to provide us with clear images under low illumination in addition to the fluorescent images under high illumination in the field of laparoscopic surgery.

Keywords CMOS · Fluorescent image · Laparoscopic surgery · High sensitivity

Since the first report of laparoscopic cholecystectomy in 1986, indications for laparoscopic surgery have been widely spread [1]. Three-charge-coupled device (CCD) camera system has been increasingly accepted as the standard video-system in the field of advanced endoscopic surgery [2–4]. The 3CCD system, however, currently has four disadvantages. First, the 3CCD system requires high illumination using xenon light for imaging. Furthermore, this system occasionally causes misleading the images with unnatural color tone, especially in cases of intraoperative bleeding. Second, because of the light intensity required for sufficient illumination, the diameter of the scope is as large as 10 mm. Third, potentially indispensable double cables, one for the light source and the other for CCU are often felt as a nuisance in endoscopic manipulation. Lastly, current CCD systems are not equipped with the ability to intraoperatively switch the standard mode to the fluorescence camera mode. In recent years, intraoperative identification of the sentinel lymph nodes as well as the biliary system using fluorescence light has been increasingly required [5–10].

We developed a new ultrasensitive complementary metal-oxide-semiconductor (CMOS) camera that is likely

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to promote endoscopic surgery, by making it possible to view the surgical targets even under the low illuminations and to display those targets fluorescently. We believe that this newly developed system will be the standard in the near future for less invasive endoscopic surgery including sentinel navigation procedure in laparoscopic gastrectomy with lymph node dissection. In this article, we describe our neo-CMOS endoscopic camera system, especially in terms of its updated technology, surgical utility and prospects.

Materials and methods

In our newly developed camera for laparoscopic surgery, a CMOS image sensor was used as an imaging device. This CMOS image sensor was 2/3 inches format color image sensor. The output pixel was 1.47 million pixels. This sensor had a wide range of spectral sensitivity characteristics. The camera head size was 45 (W) × 45 (H) × 50 (D) mm and weight was 170 g. It could be mounted on all kinds of rigid endoscope. In this experiment a 10-mm and 30-degree rigid scope was used. As a light source, a cable of xenon light was connected to the scope (Fig. 1). Also the camera head was connected to the camera control unit for imaging (CCU) (Fig. 2).

CCDs are most commonly used as the image sensor in laparoscopic surgery. Table 1 shows the comparison between a CMOS image sensor and a CCD image sensor, in regard to the cost, noise, and their performances. A CMOS image sensor has an advantage of low power consumption that only demands a single power supply. On the other hand, a CCD image sensor requires the multiple voltages on the chip for efficient charge transfer. The electric source for the CCD should thus be multiple and complicated. With regard to the cost, the CMOS image sensors are basically cheaper than CCDs. This is because more than 90 % of the manufacturing process of the CMOS is the one that the semiconductor products commonly use. On the other hand, the CCD image sensor requires specialized expensive processes, pushing up its cost. The CCD image sensor has high quantum efficiency, high fill factor, and the low level of noise. On other hand a CMOS system produces the high level noise in general. The level of noise is dependent on the sensitivity. Increasing the sensitivity results in the increased level of noise. When using high illumination like in the laparoscopic surgical field, the level of noise is not a matter of concern [11–13].

We conducted two different experiments. One was carried out to evaluate the function of the new system as the ultrahigh-sensitive camera. The images of the target were taken by our new CMOS HD (high-definition) camera and conventional 3CCD camera to compare the sensitivity. Figure 3 shows images of the CMOS and 3CCD camera heads. A xenon light source was used as the standard and an light emitting diode (LED) light was used as a new light source in some experiments (Fig. 4). The other experiment was conducted to test the ability of the two systems as a

Table 1 Comparing CCD and CMOS image sensor

	CCD image sensor	CMOS image sensor
Electric Power	CCD > CMOS	
Manufacturing line	Exclusive use	General-purpose
cost	CCD > CMOS	
noise	CCD < CMOS	

Fig. 1 CMOS camera mounted on 10 mm rigid scope with xenon light cable

Fig. 2 CMOS camera control unit

Fig. 3 Images of 3CCD/CMOS camera heads *above* : 3CCD camera head *below* : CMOS camera head

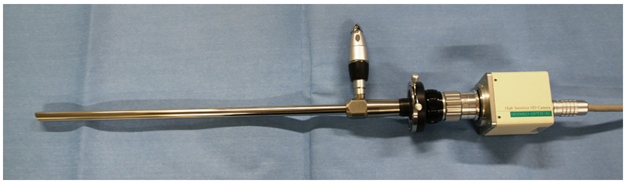

Fig. 4 CMOS camera with LED light

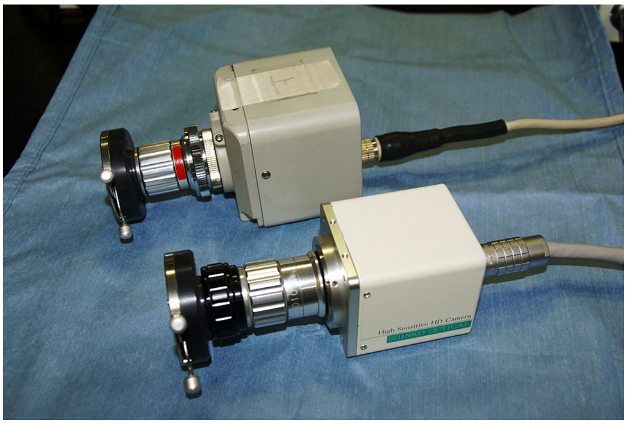

Fig. 5 Images of EM-CCD/CMOS camera heads *above* : EM-CCD camera head *below* : CMOS camera head

fluorescence endoscope. The fluorescent images were taken by CMOS HD camera and electron multiplying charge-coupled device (EM-CCD) camera. Figure 5 shows images of CMOS and EM-CCD camera heads. These experiments have been carried out in laparoscopic surgery settings. All images were taken using a training box system. Table 2 summarizes the specifications of each camera.

Experiment 1

To evaluate the function of ultrahigh-sensitive camera, the excised swine organs were set in the training box. The distances from the tip of the scope to the target (15, 10, 5, and 2 cm) were set respectively and the endoscopic images were taken using two kinds of the camera system. One was the 3CCD camera system and the other was the one with CMOS. A xenon light source was used as in usual abdominal surgery. The amount of light illumination was individually adjusted to low illumination or high illumination for taking images with auto-gain system. Low/high illumination can be adjusted on the camera control unit. With auto-gain system, fine adjustment is automatically controlled according to the difference in brightness of surgical field. This experiment was carried out with auto-gain system especially when using CMOS camera, because there are negative effects that make it difficult to see the target under high illumination without auto-gain system. For example, when auto-gain was not used and when the intensity of the xenon light was strong, the target would be shinny white and recognition of the detail of the target would become difficult.

As a new trial, the LED light was used as the light source.

Experiment 2

Experiment 2 was intended to test the ability of CMOS camera as a fluorescence endoscope. This experiment was designed to compare the EM-CCD camera and CMOS camera. Currently EM-CCD camera is available as the fluorescent endoscope. As a fluorescent target, the excised swine gallbladder was used. The indocyanine green (ICG) solution (ICG + 5 % Albmin) was injected into the gallbladder and it was placed in the dry box. The fluorescent gallbladder images were taken at the distances of 20, 15, 10, and 5 cm using CMOS camera or EM-CCD camera, respectively. With standard light source, this camera displays the target, and when fluorescent images are needed, the camera system can be switched to a fluorescent endoscope by only pushing a button.

In an additional experiment, we observed the fluorescent gallbladder under the liver parenchyma. A surgical forceps was pointing the border line of the liver and the gallbladder under visible light. Then the xenon light was turned off and fluoroscopic observation was conducted to see how the gallbladder under the liver parenchyma looks like.

Table 2 Characteristics of CMOS camera and 3CCD/EM-CCD camera

	3CCD camera standard type	CMOS camera ultrahigh sensitivity type (SKD-1057)	EM-CCD camera standard type (SK-1057-EMS)
Image sensor	1/3 in. format CCD × 3	2/3 in. format color CMOS	2/3 in. format EM-CCD
Output pixel	0.41 million pixels × 3	1.47 million pixels	0.33 million pixels
Camera head	38 (W) × 48 (H) × 55 (D)mm	45 (W) × 45 (H) × 50 (D)mm	65 (W) × 65 (H) × 65 (D)mm
Head weight	100 g	170 g	218 g
Cooling system	Unnecessary	Unnecessary	Necessary

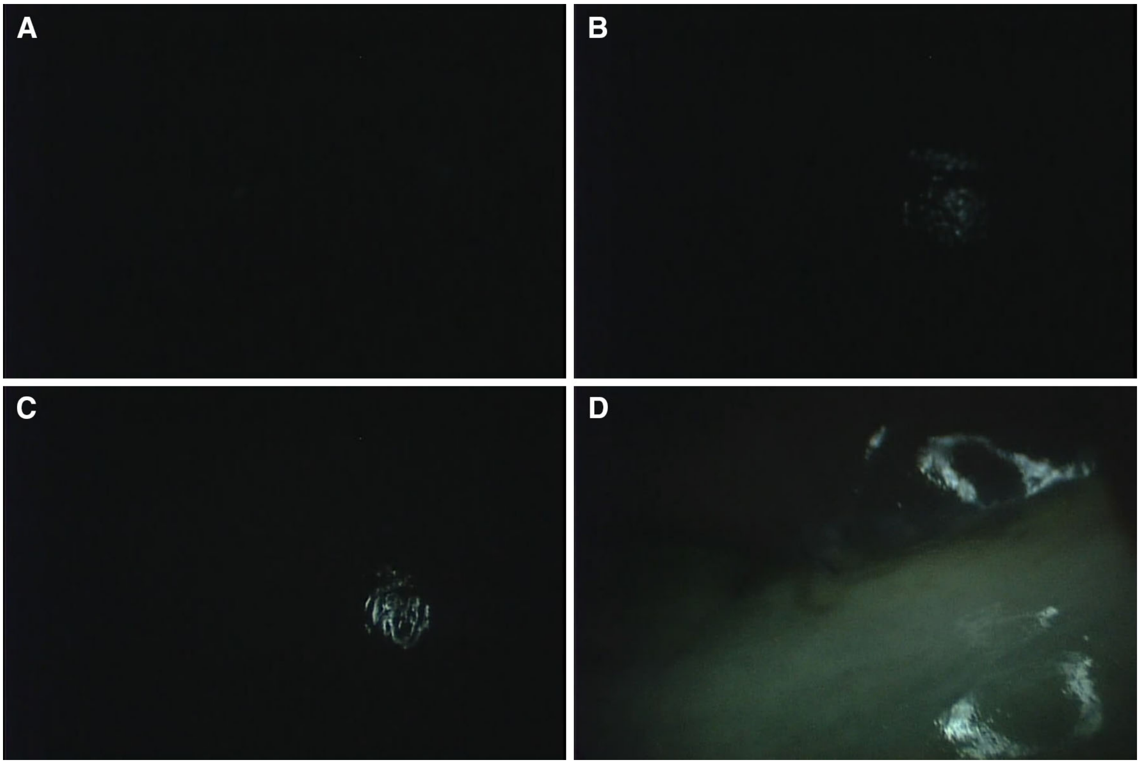

Fig. 6 Images of gallbladder and liver of swine were taken using 3CCD camera with low illumination with auto-gain. **A** The distance from the tip of the camera to the target was set to be 15 cm. **B** The distance from the tip of the camera to the target was set to be 10 cm. **C** The distance from the tip of the camera to the target was set to be 5 cm. **D** The distance from the tip of the camera to the target was set to be 2 cm

Results

Experiment 1

The xenon light images of the excised liver and gallbladder of the swine in the dry box taken by 3CCD and CMOS camera were shown in Fig. 6. When the 3CCD camera was used under low illumination with auto-gain system, it was hard to view the target in the distance range between 15 and 5 cm. When the distance was set 2 cm away, the target could be barely recognized (Fig. 6). In brief, the 3CCD camera failed to display clear images under low illumination.

In contrast, when the CMOS system was employed, the target could be distinctly observed regardless of the camera-target distance (Fig. 7). Especially when the distance was set to be 2 cm away, the target could be clearly recognized like the image was taken under high illumination.

Under high illumination, both 3CCD and CMOS cameras could display similar imaging quality (Figs. 8, 9).

Then an LED light was used in place of the xenon light. Surprisingly enough, it is possible to recognize the target at a distance of 15 cm with the CMOS system even when just a single LED light was used (Fig. 10).

Experiment 2

The images of the fluorescent gallbladder were taken using the EM-CCD camera at the distances of 20, 15, 10, and 5 cm, from the tip of the camera to the gallbladder. Before the experiment, the image of fluorescent gallbladder was taken under visible light. The fluorescent gallbladder was only visible when the distance was 5 cm (Fig. 11). However, when the CMOS camera was used, it was possible to clearly see the organ even 20 cm away (Fig. 12).

Figure 13 shows that the additional experiment revealed the fluorescent gallbladder can be observed even through the liver parenchyma. A surgical forceps was pointing the border line of gallbladder under visible light. Under the fluorescent observation, it was confirmed that the border line of the fluorescent area and non-fluorescent area was different from the pointing line by the forceps. It means that it was possible to recognize the fluorescent areas through the parenchyma.

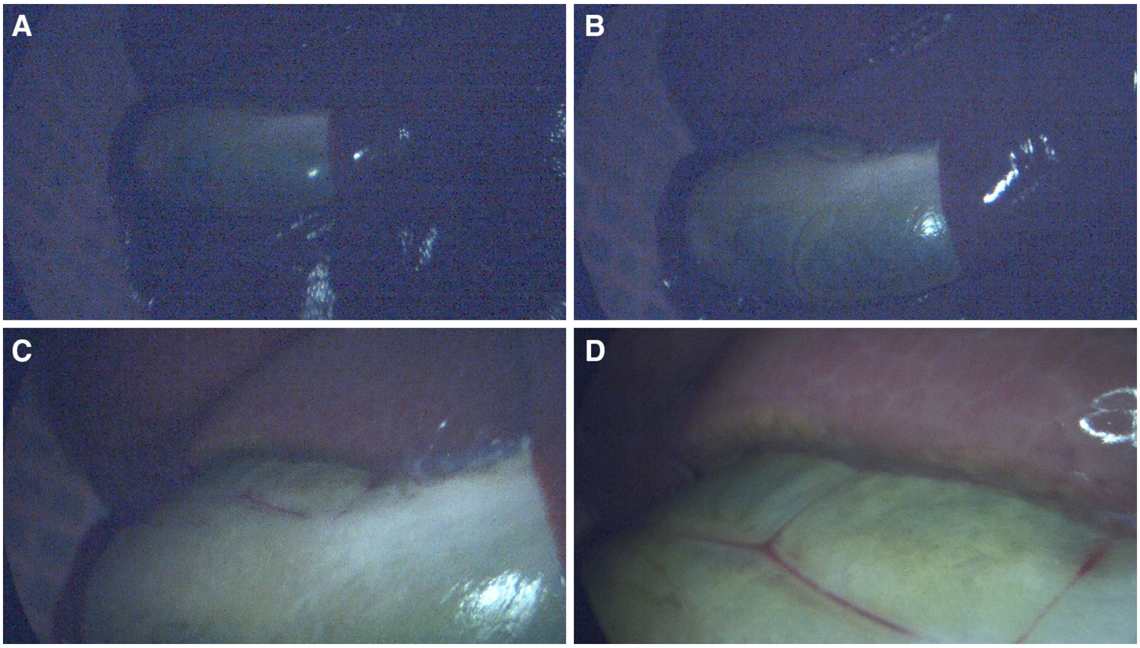

Fig. 7 Images of the gallbladder and liver of swine were taken using CMOS camera with low illumination with auto-gain. **A** The distance from the tip of the camera to the target was set to be 15 cm. **B** The distance from the tip of the camera to the target was set to be 10 cm. **C** The distance from the tip of the camera to the target was set to be 5 cm. **D** The distance from the tip of the camera to the target was set to be 2 cm

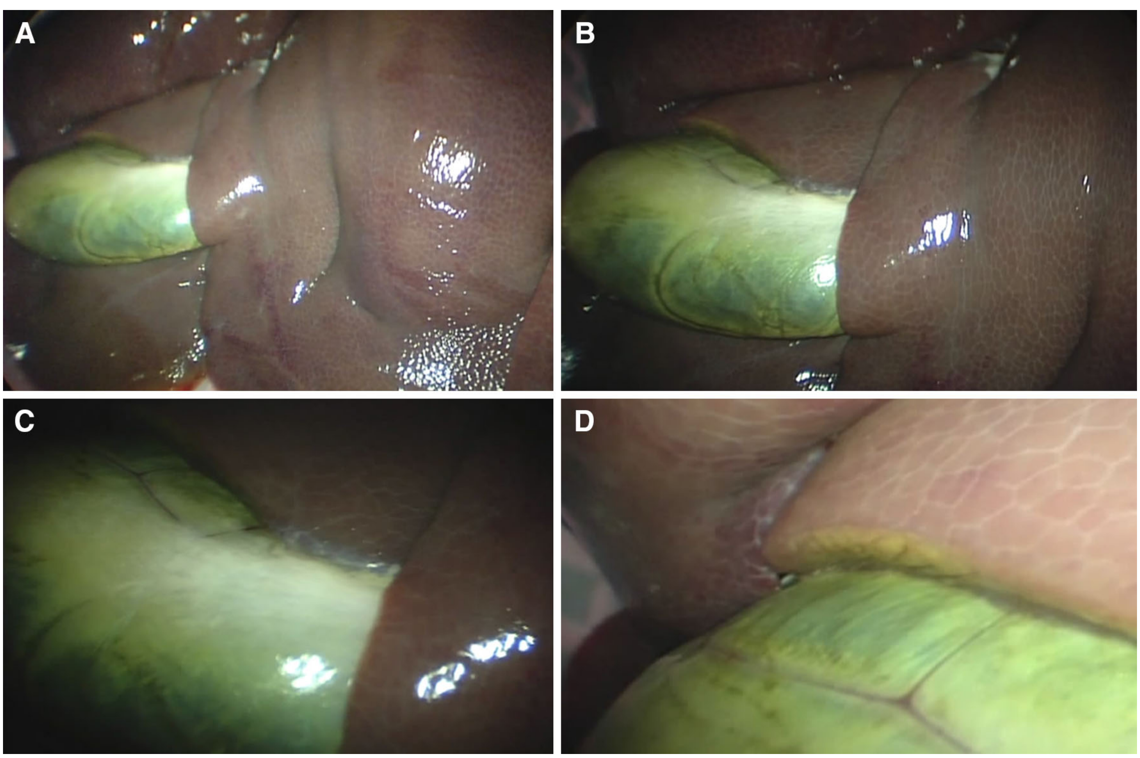

Fig. 8 Images of the gallbladder and liver of swine were taken using 3CCD camera with high illumination with auto-gain. **A** The distance from the tip of the camera to the target was set to be 15 cm. **B** The distance from the tip of the camera to the target was set to be 10 cm. **C** The distance from the tip of the camera to the target was set to be 5 cm. **D** The distance from the tip of the camera to the target was set to be 2 cm

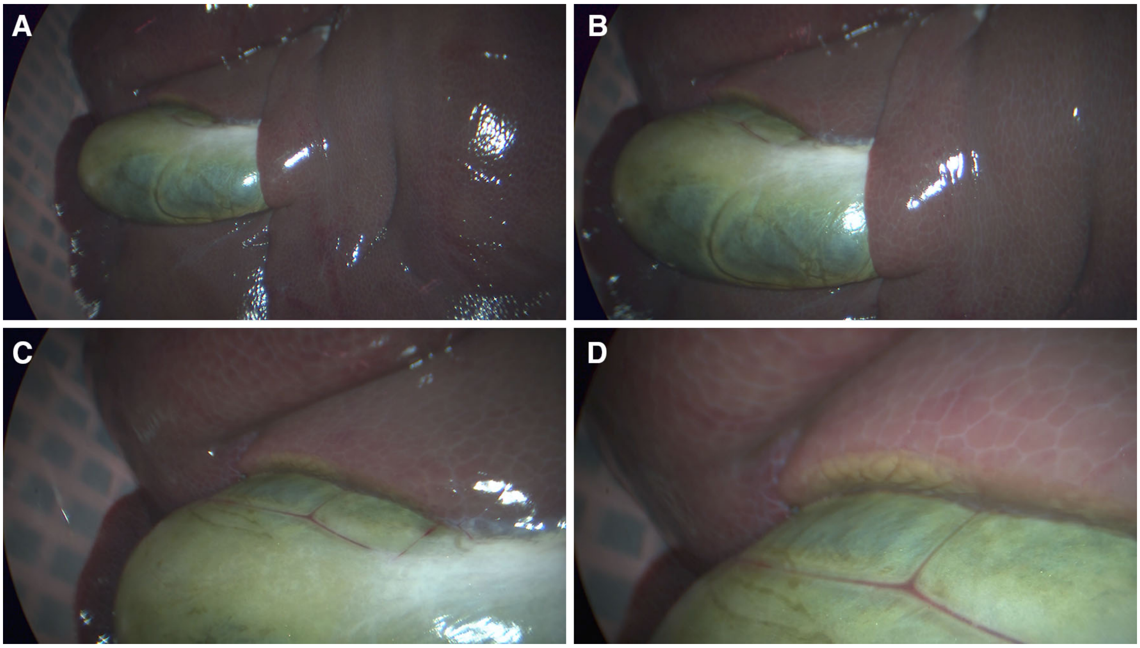

Fig. 9 Images of the gallbladder and liver of swine were taken using CMOS camera with high illumination with auto-gain. **A** The distance from the tip of the camera to the target was set to be 15 cm. **B** The distance from the tip of the camera to the target was set to be 10 cm. **C** The distance from the tip of the camera to the target was set to be 5 cm. **D** The distance from the tip of the camera to the target was set to be 2 cm

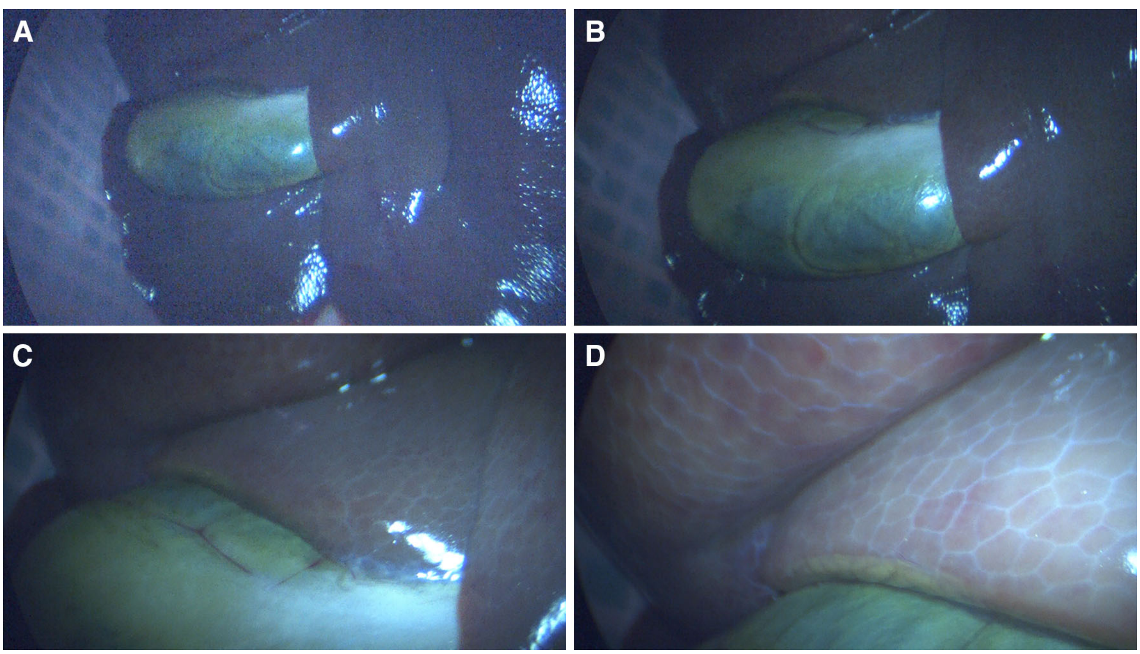

Fig. 10 Images of the gallbladder and liver of swine were taken using CMOS camera with single LED light. **A** The distance from the tip of the camera to the target was set to be 15 cm. **B** The distance from the tip of the camera to the target was set to be 10 cm. **C** The distance from the tip of the camera to the target was set to be 5 cm. **D** The distance from the tip of the camera to the target was set to be 2 cm

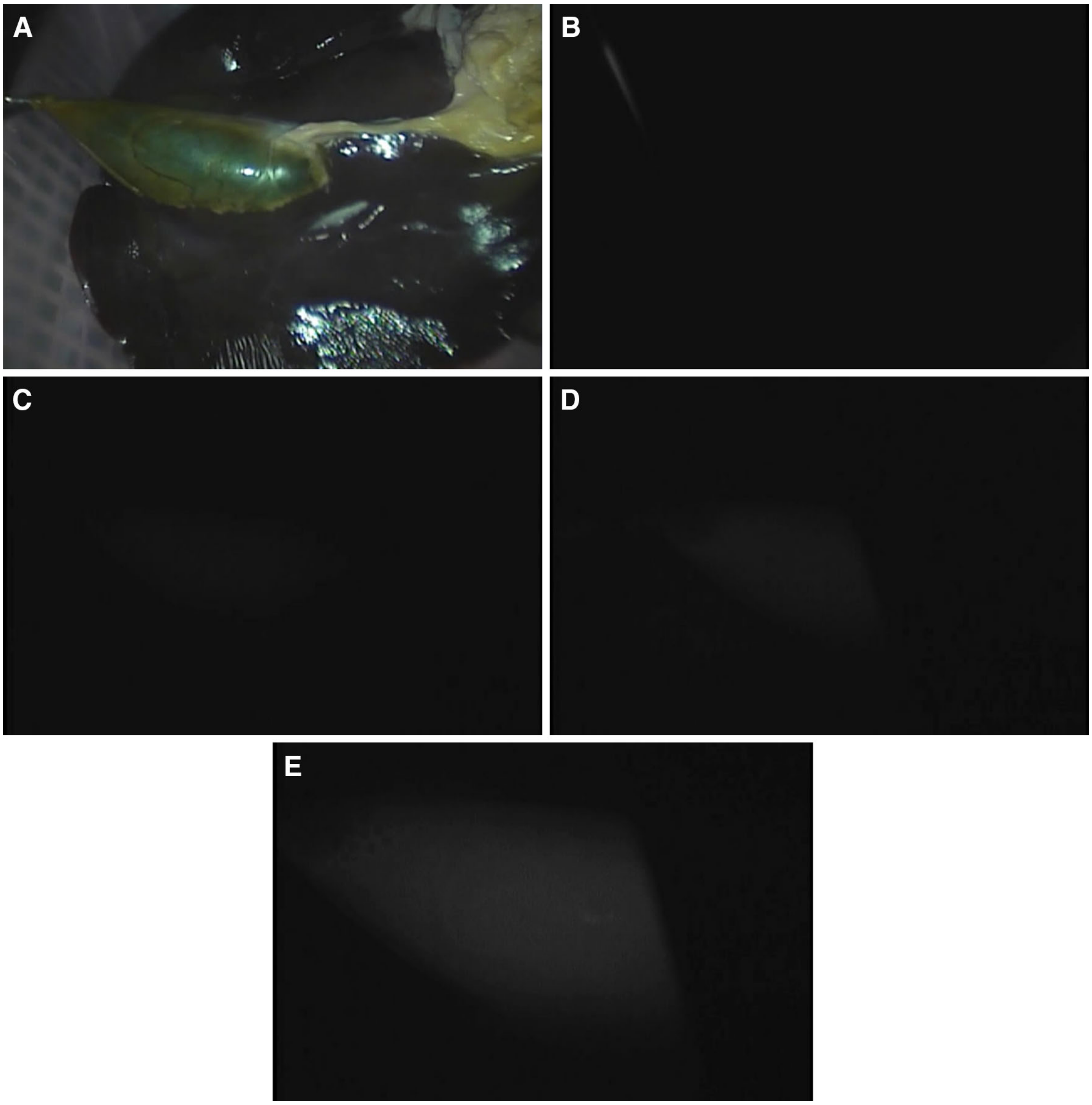

Fig. 11 Images of the fluorescent gallbladder of swine were taken using EM-CCD camera. **A** Image of fluorescent gallbladder under visible light. **B** The distance from the tip of the camera to the target was set to be 20 cm. **C** The distance from the tip of the camera to the target was set to be 15 cm. **D** The distance from the tip of the camera to the target was set to be 10 cm. **E** The distance from the tip of the camera to the target was set to be 5 cm

Discussion

We could successfully reveal that our ultrasensitive CMOS camera has several advantages over the current 3-CCD camera system, which has been already accepted in a wide range of medical fields [1–4]. It is because the current 3-CCD camera system has the following essential disadvantages: First, it requires high illumination for imaging. Second, because of the light intensity required for sufficient illumination, the diameter of the scope is as large as 10 mm and this intensity of the light may potentially induces intraoperative thermal tissue injuries especially at the tip of the light cable [14]. Third, it always needs double cables, one for hooking the scope up to the xenon light source and the other for transmitting the endoscopic images to the monitoring display. Lastly, these current CCD systems cannot work both in visible light and in fluorescence light modes to produce clinically helpful fluorescence images.

Of keen note, in recent years, the use of fluorescence endoscopic images for intraoperative accurate identification of the tiny bile ducts and lymphatic channels as well as sentinel lymph nodes has been increasingly required for less invasive but more definitive surgery for treating hepatobiliary diseases and a wide range of human cancers. In

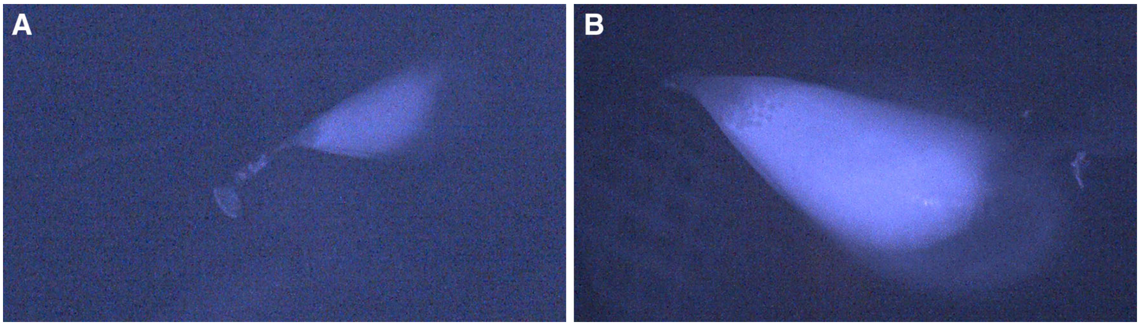

Fig. 12 Images of the fluorescent gallbladder of swine were taken using CMOS camera. **A** The distance from the tip of the camera to the target was set to be 20 cm. **B** The distance from the tip of the camera to the target was set to be 5 cm

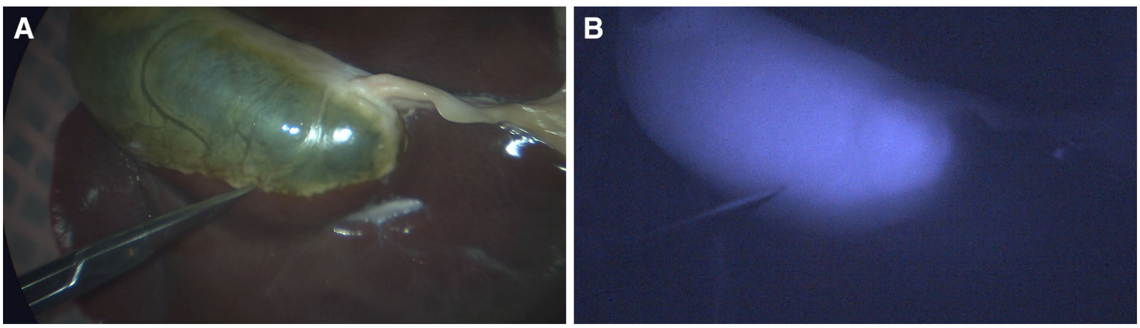

Fig. 13 **A** The difference of the border line between visible light and fluorescent observation using CMOS camera. A surgical forceps was pointing the border line of the liver and the gallbladder under visible light. **B** The difference of the border line between visible light and fluorescent observation using CMOS camera. The border line of the fluorescent area and non-fluorescent area under the fluorescent observation was different from the pointing line by forceps under visible light

fact, Miyashiro et al. reported that detection of the sentinel nodes in gastric cancer surgery using the ICG fluorescence imaging system was useful for laparoscopic surgery. In their reports, however, some lymph vessels and nodes could be hardly recognized by ICG green color [8]. Subsequently, Tagaya et al. reported in 2009 that fluorescence observation was performed by a laparoscope for the evaluation of the fluorescence imaging of the biliary system using a couple of the swine models [9]. In this report, they described that this method, although still unsatisfactory, was safe and easy for identification of biliary anatomy without the need for cystic duct cannulation followed by injection of x-ray contrast media or radioactive materials. In the field of urological surgery,as well as the field of gastrointestinal surgery, the fluorescent image is reportedly useful for the navigation [15].

On the other hand, in the field of fetal surgery, Harada et al. reported that the ICG fluorescence endoscope can visualize the placental vascular network in the fetoscopic laser treatment for twin–twin transfusion syndrome (TTTS) [16]

In our study using the new CMOS camera equipped with just a single LED light, we conducted an experiment to eliminate the xenon light source for endoscopic lightening, and demonstrated that this CMOS camera system enabled us to well visualize the endoscopic target without ordinary high illumination. In contrast, the current CCD camera system failed to give clear images with low illumination in this experiment. In addition, this study showed the CMOS camera was able to display the targets even in the dark regardless of the camera-target distance. Practically, if the CCD camera was used, the target was visible only when the distance from the tip of the scope to the target was around 2 cm or less. When the CMOS camera was tested, however, we could clearly observe the target organs even in a situation where they were 20 cm distant. Furthermore, our CMOS system could substantially overcome the frustrating problems of unnatural color tone especially associated with the intraoperative bleeding and so on.

The image quality of both systems in a high illumination is comparable, not only in impression, but also in the specification (1.47 million pixels for the CMOS camera and 1.23 million pixels for the 3CCD camera, respectively). Furthermore, this study was not intended to compare the fine image differences in both the systems, which is largely the surgeons' preference. We would predict that the high sensitivity CMOS laparoscope holds the future for its sensitivity in a compromised situations and the versatility as a fluorescent camera system. In our experiments, under low illumination, the increased level of noise made the image on the monitor flickering, and the quality of image was thus compromised. In low illumination where this flickering became problematic with the CMOS camera system, the CCD camera system cannot even display the images on the monitor. When using high illumination like in the laparoscopic surgical field, the level of noise is not a matter of concern so far.

Based on these new technological developments, we are sure to achieve an advanced surgery using high definition, ultrahighly sensitive endoscope potentially eliminating the above-mentioned double cables (light and image transmission) mounted on the endoscope, restraining its free manipulation. These endoscopes are likely to be much smaller and safer (reduced risk of accidental thermal injuries)and much less expensive ones. They could be also quite acceptable in terms of their well-coordinated color tones and feasibility as well-functioning fluorescence endoscopes. In the future, they will be usable as non-cable (cordless) endoscopes with free manipulation with the fluorescence-activated clear images by the CMOS camera hopefully superimposed in real time onto the ordinary visible images of the same camera system.

In conclusion, we developed an ultrahigh-sensitive endoscope camera system using a new-CMOS image sensor. The data shown in this paper may suggest that this system could be the new eyes of the surgeons, who routinely perform advanced procedures for malignant disorders, where the visualizing ability in a bled surgical field and sentinel nodes navigation is more likely to be appreciated.

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