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Operational effectiveness of three-dimensional flexible endoscopy: an *ex vivo* study using a new model

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Abstract

Background and objectives Two-dimensional (2D) images lack depth information and thus provide probabilistic recognition that do not completely match the actual three-dimensional (3D) information. Here, we investigated the operability of 3D endoscopes.

Methods A 3D operation model was developed by passing 20 silk threads through upper and lower plates at 2-mm intervals in front and back rows separated by 1 mm. We evaluated accuracy and time of operating an electrosurgical knife. A successful operation was defined as pulling only a front-row thread; an unsuccessful operation was defined as pulling no thread (miss) or simultaneously pulling front- and back-row threads. Endoscopists (four experts, six trainees) repeated the operation under 2D and 3D conditions until individually accumulating 10 successful attempts under each condition.

Results Operation accuracy was significantly higher for 3D compared with 2D in all endoscopists (88.5% vs. 61.3%; $p < 0.01$) and in both experience groups (trainees: 84.5% vs. 61.2%; experts: 95.2% vs. 61.5%; both $p < 0.01$). Operation time was significantly shorter for 3D compared with 2D in all endoscopists (12.5 ± 4.1 s vs. 14.8 ± 4.7 s; $p < 0.01$) and in both experience groups (trainees: 12.8 ± 4.2 s vs. 15.2 ± 4.9 s; experts: 12.1 ± 4.0 s vs. 14.3 ± 4.3 s; both $p < 0.01$).

Discussion Compared with 2D endoscopy, 3D endoscopy significantly improved operation accuracy and shortened operation time, suggesting that 3D endoscopy enables accurate operation by depth information, aiding spatial recognition.

Keywords Three-dimensional imaging (3D) · 3D endoscope · Operation · Endoscopic procedure

Conventional endoscopic imaging relies solely on two-dimensional (2D) information, and therefore lacks depth information. Recent studies have reported the investigation and utility of three-dimensional (3D) endoscopic systems in surgery [1–3], but only a few have reported on the use of flexible 3D endoscopes [4]. Against this background, using neoplasm specimens dissected by endoscopic submucosal dissection (ESD), we have reported that 3D endoscopes improve recognition for lesions compared with 2D endoscopes [5, 6]. In the present study, we investigated the utility of the 3D endoscope to improve endoscopic operability when used under 3D conditions compared with 2D conditions.

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Materials and methods

Endoscopic imaging and observation

The dimensions of the newly developed 3D prototype endoscope (GIF-Y0083) were outer diameter at the tip of the scope, 12.2 mm; maximum diameter of the scope, 14.1 mm; length of the scope, 1030 mm; and the diameter of the channel, 2.8 mm. Although magnification is not feasible, the endoscope is equipped with narrow-band imaging and water jet technologies. This newly developed 3D prototype endoscope was used along with an endoscopic system identical to that used in surgery: EVIS EXERA III Video System Center, 3D Visualization Unit (CV-190), and EVIS EXERA

III Xenon Light Source (3DV-190), and EVIS EXERA III (CLV-190) (all from Olympus) as well as 3D Medical Display (LMD-3251MT; Sony). Images are obtained through each lens and sent to each video processer as an electrical signal. Each video processer changes the electrical signal to video signal similar to the working of the conventional endoscope. Each video signal is send to a 3D video processer and synthesized as a 3D image. Finally, 3D image is visualized using 3D monitor and 3D glasses [7]. In these systems, 2D mode can be switched to 3D mode and vice versa with one button.

Methods

To evaluate endoscopic operability, a 3D operation model was developed by placing two metal plates (upper and lower) 30 mm apart and passing 20 red silk threads through the two plates at 2-mm intervals in two rows (front and back) separated by 1 mm (20 silk threads/row × 2 rows = 40 silk threads in total) (Fig. 1A). Because 3D samples cannot be displayed without a 3D monitor and 3D glasses, only 2D samples are shown in Fig. 1B. The operation model was used to evaluate accuracy and time of operating the HookKnife™ electrosurgical knife (KD-620QR; Olympus, Japan). The operation was considered successful when only front-row threads were pulled, but was considered unsuccessful when no thread was pulled (miss) or when both front- and back-row threads were pulled simultaneously.

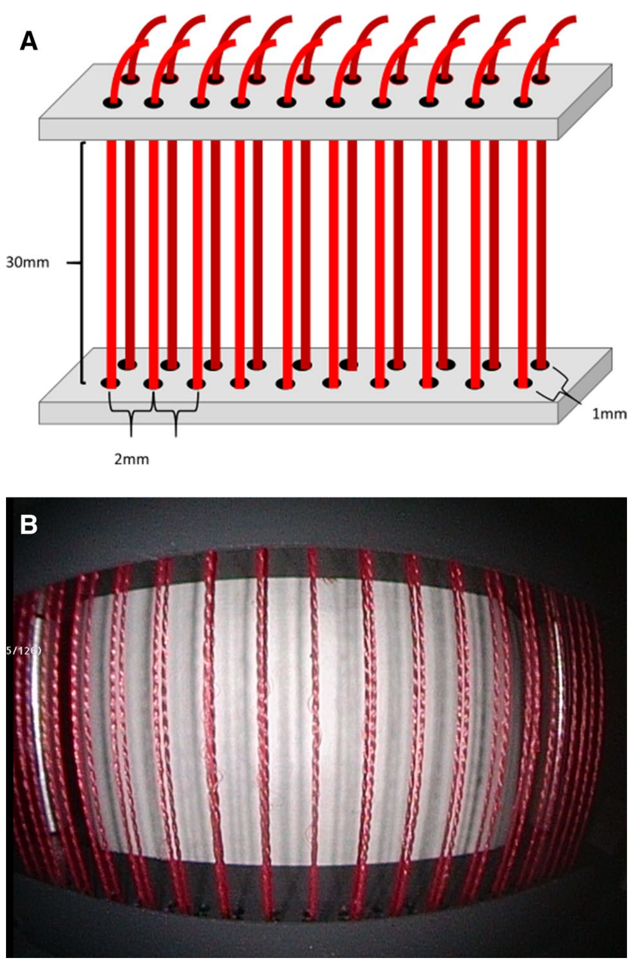

Fig. 1 **A** Schematic diagram of the operation model. **B** Two-dimensional endoscopic images generated using the operation model

Design

Ten endoscopists (four experts, six trainees) repeated the operation under 2D and 3D conditions until they individually had ten successful attempts under each condition. An expert was defined as an endoscopist with more than 10 years of experience in endoscopy. To reduce bias due to technical familiarity, a crossover study was performed by dividing the ten endoscopists equally into two experimental groups (the 2D-first group and 3D-first group), each including two experts and three trainees (Fig. 2).

Statistical analysis

Operation time are presented as mean ± standard deviation. Statistical analysis was performed using the χ^2 test and paired t test. All statistical analyses were performed using Stata version 14 (StataCorp, College Station, TX, USA) and a p value of < 0.05 was considered to be statistically significant.

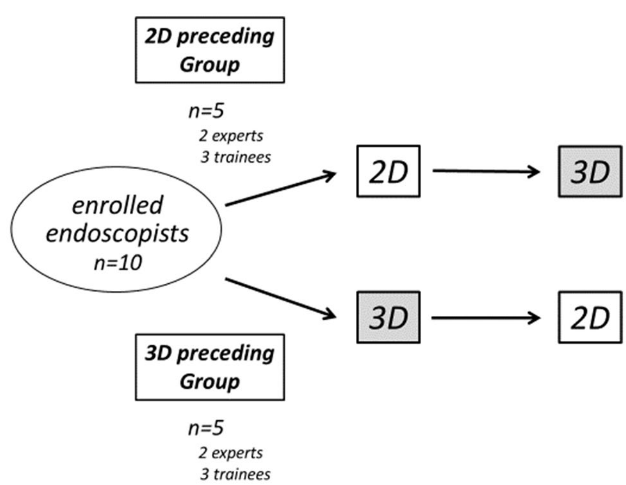

Fig. 2 Flow diagram of the study

Results

Operation accuracy

Operation accuracy was 61.3% under 2D conditions and 88.5% under 3D conditions, with a significantly higher number of unsuccessful attempts under 2D conditions ($p < 0.01$, Table 1). Operation accuracy was significantly and comparably higher under 3D conditions in both the 2D-first and 3D-first groups, indicating the absence of bias. Analysis of unsuccessful attempts revealed that the incidence of misses was 22.7% and 3.5% and that of simultaneous pulling was 16.0% and 8.0% under 2D and 3D conditions, respectively (Table 2). Analysis by experience showed that operation accuracy under 2D and 3D conditions was 61.2% and 84.5% in trainees and 61.5% and 95.2% in experts, respectively (Table 1).

Operation time

Operation time was 14.8 ± 4.7 s under 2D conditions and 12.5 ± 4.1 s under 3D conditions, showing that 3D endoscopy significantly shortened operation time ($p < 0.01$, Table 3). Operation time for 3D endoscopy was significantly and equally shorter in both the 2D-first group and the 3D-first group, again indicating that no bias was involved (Table 3). Analysis by experience showed that operation time under 2D and 3D conditions was respectively 15.2 ± 4.9 s and 12.8 ± 4.2 s among the trainees and 14.3 ± 4.3 s and 12.1 ± 4.0 s among the experts, showing that 3D endoscopy significantly shortened operation time in both groups (Table 3).

Discussion

The brain has the stereoscopic ability to convert flat 2D images into 3D images. The parallax that exists between visual information entering from the eyes is converted into 3D information in the brain to perceive depth of view or the dimension of objects. With the use of special glasses, modern 3D technology allows the addition of depth to 2D images taken with twin lenses and displayed on a 2D monitor. Three-dimensional technology has been applied in various fields including cinematography. In recent years, the application range of 3D technology is also steadily expanding in the medical field. In conventional laparoscopic surgery, which relies on 2D information displayed on the monitor, the lack of depth information makes it difficult to determine the location of organs and the depth of the surgical field. Because a 3D endoscopic system can compensate for this type of drawback, many studies have investigated 3D endoscopy and reported its utility and safety [8–13]. With expectations for the improved accuracy of endoscopic diagnosis through the addition of 3D information, we previously reported the utility of 3D endoscopy in the diagnosis of superficial gastric tumor [6]. The present study investigated the operability of the 3D endoscope. This is the first report to investigate the operability of a flexible 3D endoscope.

In this study, compared with 2D endoscopy, 3D endoscopy significantly improved accuracy and time of operation. Both results were significant regardless of years of experience. No significant differences in recognition/diagnostic accuracy for lesions were noted among experts with many years of experience in endoscopy in previous studies [5, 6]. This might have been because they had recognized 3D objects/structures from 2D images based on their experience. In the present study, however, endoscopic operability improved significantly under 3D conditions even among experts. Under 2D conditions, endoscopists could see red silk threads in only the front row, despite the presence of two rows in the operation model (Fig. 1B). However, under 3D conditions, they could carry out the operation in the front

Table 1 Operation accuracy

	2D (%)	3D (%)	p
All endoscopists	61.3	88.5	< 0.01
2D-first group	64.1	92.6	< 0.01
3D-first group	58.1	84.7	< 0.01
Trainees	61.2	84.5	< 0.01
Experts	61.5	95.2	< 0.01

Table 2 Analysis of unsuccessful attempts

	2D (%)	3D (%)
Miss	22.7	3.5
Simultaneous pulling	16.0	8.0

Table 3 Operation time

	2D	3D	p
All endoscopists (95% CI)	14.8 s (13.9–15.7)	12.5 s (11.7–13.3)	< 0.01
2D-first group (95% CI)	13.5 s (12.4–14.7)	12.5 s (11.2–13.7)	< 0.01
3D-first group (95% CI)	16.1 s (14.8–17.4)	12.5 s (11.5–13.6)	< 0.01
Trainees (95% CI)	15.2 s (13.9–16.4)	12.8 s (11.7–13.9)	< 0.01
Experts (95% CI)	14.3 s (12.9–15.6)	12.1 s (10.8–13.3)	< 0.01

row while paying attention to the back-row threads, which were visible owing to the parallax generated by twin lenses used in 3D endoscopy, thereby improving the accuracy and time of the operation. 3D depth information is expected to be useful in therapeutic endoscopy that involves highly delicate procedures, such as ESD and endoscopic mucosal resection.

Some challenges associated with 3D endoscopy may be symptoms, such as eyestrain and headache, due to the use of 3D glasses. These symptoms are said to occur because the brain is confused by two distinct images entering the eyes simultaneously through the glasses. Similarly, several endoscopists complained of eyestrain after 3D endoscopy in this study, suggesting that further study is needed to investigate eyestrain and establish appropriate countermeasures.

This study has some limitations. One is the small sample size ($n = 10$), which may mean that this study lacked sufficient statistical power. In addition, the study was designed with a special focus on depth information. We plan to perform and compare 2D and 3D endoscopy during actual ESD in the future.

In conclusions, the newly developed 3D endoscope enabled significantly improvements in operation accuracy and operation time in endoscopy. In 3D endoscopy, the parallax generated by twin lenses provides depth information and eases spatial recognition, thereby improving operation accuracy. We expect the application of 3D endoscopy for therapeutic uses in the future.

Compliance with ethical standards

Disclosures Kosuke Nomura, Daisuke Kikuchi, Mitsuru Kaise, Toshiro Iizuka, Yorinari Ochiai, Yugo Suzuki, Yumiko Fukuma, Yasutaka Kuribayashi, Masami Tanaka, Yosuke Okamoto, Tsukasa Furuhata, Satoshi Yamashita, Akira Matsui, Toshifumi Mitani, Shu Hoteya have no conflicts of interest or financial ties to disclose.

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