Wireless live streaming video of surgical operations: an evaluation of communication quality

Armin Schneider*, Dirk Wilhelm*,†, Dietrich Doll†, Uwe Rauschenbach‡, Michael Finkenzeller‡, Helga Wirnhier*, Klaus Illgner‡ and Hubertus Feussner*†

*Workgroup MITI; †Department of Surgery, Klinikum r. d. Isar, Technische Universität München; ‡Siemens Corporate Technology, Munich, Germany

Summary
We evaluated a mobile video system for surgical teleconsultation. A video streaming server in the operating room transmitted video and audio to a hand-held computer (personal digital assistant [PDA]) over a wireless local area network. Two groups of 20 surgeons (each with 12 qualified surgeons and eight surgeons between the 2nd and the 4th year of training) participated in the tests. For voice transmission, correct understanding of numbers was achieved in 100% of the cases (n = 1000) and 98% of medical terms (n = 400). The quality of the video displayed on the PDA was assessed by the recognition of different operating room scenarios. Only 62% (SD 17) of the structures were identified clearly on the hand-held device (n = 400). The accuracy improved to 78% (SD 15) (n = 400) if the same scenario was observed on a larger (50 cm) video screen (P < 0.001). Accuracy was significantly better if audio conversation was possible. The quality evaluation by the consultants showed that the PDA display size and quality were sufficient for clinical use.

Introduction
Teleconsultation is already used for intraoperative consultation of external experts who are not physically present in the operating room.1–3 The main disadvantage is that consultants need appropriate equipment in their offices or must go to a room equipped with telemedicine facilities. To overcome these limitations and to allow spontaneous video communication during routine clinical activities, we have developed a mobile video consultation system based on a hand-held computer connected to a wireless local area network (WLAN). This enables audio–video transmission from the operating theatre to be established as required. The first studies have demonstrated that wireless live streaming is helpful in the health-care sector4,5 and can be useful for educational purposes.6
We have evaluated the use of wireless live streaming for clinical and surgical purposes.

Methods
Operating room equipment
A PC was installed as a streaming server, with a frame grabber board (Videum, Winnov, Santa Clara, California, USA) for capturing the audio and video data. The streamed video data were transmitted through a LAN at 100 Mbit/s. WLAN access points (Netgear MR314, Santa Clara, California, USA) were sited at various places and connected to the network. The access points were based on the IEEE 802.11b wireless standard and provided a connection speed of 11 Mbit/s. For security reasons, the 128-bit Wireless
Encryption Protocol between access points and WLAN controller was used. In addition, MAC Address Authentication over Access Control List was employed. In areas where the wireless signal was weak and installation of an access point to the wired LAN was impossible, wireless repeaters were set up.

For security purposes any connection to the wireless network was recorded in a log with date, time and connection duration together with the IP address, the MAC address of the network card and the name of the client.

The video streaming software (Siemens CTIC2, Munich, Germany) was developed to provide high-quality, live video transmission (in particular with low delay). Commercial streaming applications have the drawback of large buffers to compensate for packet timing jitter in the Internet. These produce long delays, which were not acceptable for our application.

The frame grabbing device provided a video resolution of 176 × 144 pixels (QCIF format) at 10 frames/s. Compression of the video was achieved by a proprietary MPEG-4 codec (Siemens Corporate Technology, Munich, Germany). In comparison to open source codecs, this special algorithm provided an enhanced prediction functionality to minimize delay and bandwidth. QCIF resolution was chosen in order not to consume the processing power of the PC and to leave some resources for the audio communication.

The video could be zoomed to full-screen mode by the client. The simple visual profile of MPEG-4 was used and the Group of Pictures size was set to 100. That meant that, after each intra-coded frame (I frame), 99 predicted frames (P frames) were encoded. This setting ensured good coding efficiency while still allowing from a transmission error in a maximum of 10 s. The video was encoded at variable bit rate, with a resulting bit rate of 450 kbit/s.

Audio connection to the remote consultant was established with the open source Voice over IP software (SJ Labs, Solon, Ohio, USA). The surgeon wore a headset with a microphone, a device which is routinely used for control of peripheral equipment in the operating room.7

**Client device**

To visualize the streamed video signal, we used a pocket PC (PocketLoox 600, Fujitsu Siemens Computers BV, Netherlands). It was equipped with a 9-cm display with a resolution of 320 × 240 pixels capable of displaying 65,000 colours (Figure 1). The overall size of the handheld device was 132 × 82 × 17 mm³ and it weighed 166 g. For connection to the wireless network, a WLAN adapter (Socket Communications Inc., Newark, California, USA) was installed in the Compact Flash slot of the pocket PC.

The video client software was based on the proprietary streaming protocol designed to minimize latency as mentioned above and decompress and render the video. It had to be configured with the IP address of the video server from which it requested the video stream. It supported scaling the video to the full display of the device.

For audio connection to the operating room, the pocket PC Version of SJPhone was installed. We configured the software to connect automatically to the identical Windows software on the streaming server in the operating room after start-up (Figure 2).
Technical evaluation

Signal strength and signal-to-noise ratio were analysed with special software (Ekahau Site survey 2.1, Ekahau Inc., Helsinki, Finland). Signal strength in the areas of interest (office floors) is shown in Figure 3.

Since delay is one of the most disturbing factors in live video communication, the delays were measured from the source in the operating room to the hand-held device via the WLAN. To determine the delay, a wireless access point was temporarily established in the operating room, creating a local loop. A videotape with an integrated time code was used as a source and streamed to the hand-held client. Both video screens (input to and output from the hand-held device) were recorded with a separate digital video camera for subsequent analysis. The distance from the access point to the hand-held device was extended in 2 m steps. This enabled us to detect whether the system lost frames or hung when the signal quality and thus connection speed of the wireless network was decreased.

Clinical evaluation

To our knowledge, no standardized tool is available to assess objectively the suitability of video communication procedures in clinical surgery. Therefore, a new approach was developed in order to test a surgeon’s ability to recognize typical operating room scenarios and anatomical structures.

Audio communication

The quality of voice transmission was assessed using test sets. Both the surgeon in the operating room and the remote consultant were asked to report with an established audio link 50 randomly generated numbers between 100 and 1000, as well as 20 pre-defined medical terms. At the two locations, an independent reviewer recorded whether the numbers and the terms were correctly identified.

Video transmission

The task was to identify important anatomical structures such as the recurrent nerve during re-section of a Zenker’s diverticulum or the cystic artery during laparoscopic cholecystectomy. In open surgery, tasks like the recognition of the carotid artery during dissection of the cervical oesophagus or the identification of the internal inguinal hernia ring in hernia repair were selected (Table 1). A situation similar to an intraoperative consultation was created.

The original video clips were first reviewed by five experienced surgeons (consultants), who did not take part in the evaluation study. All scenarios appeared to them easily recognizable. The original video clips were then transmitted to the hand-held device. Each participant had to decide what had been demonstrated within 20 s of the end of the scenario. The quality and speed of recognition were determined using a scoring system ranging from 0 (no recognition) to 3 points (immediate, precise identification of the scenario and anatomical structures). Immediately afterwards, each participant had to identify the same sequence on a standard laparoscopic video screen. The quality of recognition was determined in the same way.
Finally, a second sequence of video clips (sequence B) depicting the same (but not identical) surgical situations as described in Table 1, but from different patients, was presented in different order. A free dialogue was possible between the surgeon in the operating room and the test person using the hand-held device. The surgeon explained briefly the operative site. Then the test person was asked to identify the key structure.

Each of the groups consisted of 20 test persons. The training level of the surgeons in both groups was similar, each with 12 qualified surgeons and eight surgeons between the second and the fourth year of training.

### Results

Connection to the wireless network was always possible without any problems in the areas covered by the access points. Analysis of the connection protocols showed one unauthorized computer which unsuccessfully tried to connect to the network.

At the end of the covered WLAN area, the connection speed to the first access point was 11 Mbit/s within a range of 11 m. At a distance of 11–14 m to the access point, connection speed was decreased to 5.5 Mbit/s and at 14–16 m the speed without connection problems was reduced to 2 Mbit/s (Figure 4). These values were mapped with direct sight to the access point without any attenuating elements (doors or walls) in between the client and the access point.

Moving through the WLAN-covered area was possible without any connection losses to the streaming server. The live video was always visible without interruptions. Comparison of the live video and the hand-held device connected to the streaming server via the WLAN showed a time shift of eight frames only.

### Clinical evaluation

#### Voice transmission

Correct understanding of numbers was achieved in 100% of the cases ($n = 1000$). Medical terms were understood precisely in 98% (range 90–100%) of the instances ($n = 400$). Again, the results were similar in each of the groups.

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**Table 1** Intraoperative scenarios for visual evaluation

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario</th>
<th>Key finding/procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oesophagoscopy</td>
<td>Endoscopic view of an oesophageal clip</td>
<td>Identification of clip</td>
</tr>
<tr>
<td>Laparoscopic view of the upper abdomen</td>
<td>Reduction of a para-oesophageal hernia</td>
<td>Para-oesophageal hernia</td>
</tr>
<tr>
<td>Laparoscopic ultrasonography</td>
<td>Ultrasound of liver</td>
<td>Recognition of liver cirrhosis</td>
</tr>
<tr>
<td>Laparoscopic cholecystectomy</td>
<td>Positioning of clips on the cystic duct</td>
<td>Identification of the triangle of Calot</td>
</tr>
<tr>
<td>Laparoscopic exploration of the left upper quadrant</td>
<td>Examination of the spleen</td>
<td>Detection of a splenic cyst</td>
</tr>
<tr>
<td>Endoscopy of the stomach</td>
<td>Anterograde inspection of a submucosal tumour</td>
<td>Identification of the tumour site</td>
</tr>
<tr>
<td>Thoracoscopy</td>
<td>Oesophageal dissection</td>
<td>Identification of a leiomyoma</td>
</tr>
<tr>
<td>Laparoscopic fundoplication</td>
<td>Laparoscopic dissection of the hiatus</td>
<td>Identification of oesophagus and cardia</td>
</tr>
<tr>
<td>Laparoscopic wedge resection</td>
<td>View of the stomach and surrounding organs</td>
<td>Identification of stomach and left liver lobe</td>
</tr>
<tr>
<td>Extended diagnostic laparoscopy</td>
<td>Peritoneal spread of a gastric cancer</td>
<td>Identification of peritoneal tumour seeds</td>
</tr>
<tr>
<td>Laparoscopic appendectomy</td>
<td>Dissection of the mesappendix</td>
<td>Identification of the appendix and the colon</td>
</tr>
<tr>
<td>Exploration of the pelvis</td>
<td>Examination of the adnexes and the uterus</td>
<td>Recognition of a myoma</td>
</tr>
<tr>
<td>Herniotomy</td>
<td>Dissection of the hernia sac</td>
<td>Identification of the internal hernia ring</td>
</tr>
<tr>
<td>Dissection of the cervical oesophagus</td>
<td>Cervical anastomosis</td>
<td>Identification of carotid artery and cervical anastomosis</td>
</tr>
<tr>
<td>Merendino’s procedure</td>
<td>Anastomosis between stomach and small bowel</td>
<td>Identification of small intestine and gastric remnant</td>
</tr>
<tr>
<td>Small bowel resection</td>
<td>Skeletonization of the mesenterium</td>
<td>Recognition of vascular pedicle</td>
</tr>
<tr>
<td>Incision of the small bowel</td>
<td>Dissection of the antimesenterior of the jejunum</td>
<td>Identification of the small bowel</td>
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<tr>
<td>Preparation of a pedicled jejunal substitute</td>
<td>Closure of the mesenterial windows after anastomosis</td>
<td>Localization of the anastomosis</td>
</tr>
<tr>
<td>Re-section of a Zenker’s diverticulum</td>
<td>Mobilization of the diverticular sac</td>
<td>Identification of recurrent nerve</td>
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<tr>
<td>Radiofrequency ablation of the liver</td>
<td>Laparoscopic ultrasound of the liver for positioning of the probe</td>
<td>Identification of tumour and recognition of the tip of the probe</td>
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</tbody>
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**Figure 4** Decreasing transmission rate with increased distance to the access point
Almost all of these applications are for educational purposes. However, mobile teleconsultation using a hand-held device could be particularly valuable for surgical teleconsultation as well. This was pointed out by Banitsas et al., who evaluated the use of hand-held devices for real-time wireless teleconsultation. They assessed the communication quality of still images and of videoconferencing but, to our knowledge, not of surgical operations. Since little is known about the adequacy and suitability of mobile teleconsultation under real clinical conditions, we evaluated mobile teleconsultation in a realistic surgical setting.

It is comparatively easy to assess the technical accuracy and reliability of a communication system, but medical – or clinical – test procedures have not been available until now. In most studies, more or less subjective scoring systems or questionnaires are used to assess the opinion of the users about the quality of data transmission. Although the methodology of these subjective ratings has been significantly refined with the introduction of the Absolute Category Rating, which is still frequently used, there are no standardized tools to assess the objective effect of audiovisual communication. Therefore, we created a new test set depicting 20 different video segments of surgical intervention. All of them demonstrated a characteristic part of a well-defined video segments of surgical intervention. All of them demonstrated a characteristic part of a well-defined video segments of surgical intervention. All of them demonstrated a characteristic part of a well-defined video segments of surgical intervention. All of them demonstrated a characteristic part of a well-defined video segments of surgical intervention.

Discussion

Mobile telecommunication is increasing in importance in medicine. Even though a wide field of applications has been described, very few reports are available about mobile broadcasting of surgical operations. A Schneider et al. Video streaming of surgical operations

Figure 5 Accuracy of recognition of surgical scenarios (± SD): monitor audio: large video screen with vocal communication; PDA audio: hand-held device with vocal communication; monitor: large video screen (Mute); PDA: hand-held device (mute). Significance: monitor audio versus PDA audio: \( P < 0.001 \); monitor (mute) versus PDA (mute): \( P < 0.001 \)

Video transmission

The precise recognition of specific scenarios of surgical interventions without verbal comments on the hand-held device was low. Only 62% (SD 17) of the structures were identified clearly on the hand-held device \((n = 400)\). The accuracy improved to 78% (SD 15) \((n = 400)\) if the same scenario was observed on a larger (50 cm) video screen \((P < 0.001)\). In contrast, accuracy was significantly better if audio conversation was possible. The results achieved with the hand-held device were nearly equal to those obtained by watching the video screen (Figure 5).

The video quality assessment showed that 72% (SD 15) of the key structures were identified clearly \((n = 400)\). Nevertheless, teleconsultation with the large monitor and audio connection showed a higher accuracy, with 82% (SD 13) correct findings \((P < 0.001)\) \((n = 400)\).

Technically, establishing oral communication with the audio software from the hand-held device to the software installed in the operating room was always possible. The speech quality evaluated by 20 surgeons was found sufficient in all cases, although six surgeons were dissatisfied with the audio delay and the resulting interruption in communication.

Mobile telecommunication is increasing in importance in medicine. Even though a wide field of applications has been described, very few reports are available about mobile broadcasting of surgical operations.
both on the small PDA display as well as on the large monitor. However, the visual information on a PDA is still inferior to the full display on a standard monitor.

References