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Seven Years of Clinical Experience With Teleconsultation in Craniomaxillofacial Surgery

Rolf Ewers, MD, DMD, PhD, Kurt Schicho, DSc,†*
Arne Wagner, MD, DMD,‡ Gerhard Undt, MD, DMD, PhD,§
Rudolf Seemann, MD, MS,‖ Michael Figl, MS, DSc,¶ and
Michael Truppe, MD#

Purpose: In this work the experiences from 50 telemedically supported treatments in craniomaxillofacial surgery are summarized and different setups for their technical realization are described. Furthermore, for the first time the innovative UMTS (universal mobile telecommunication system) is applied for the transmission of arthroscopic videos of the temporomandibular joint and other craniomaxillofacial structures.

Materials and Methods: The combination of computer-assisted navigation technology in augmented reality environments with telecommunication is used for execution of interactive stereotaxic teleconsultation. Furthermore, treatments without navigation are telemedically supported. This study is composed of 4 technical system configurations: *1*) integrated services digital network (ISDN)-based videoconferencing without remote control of the navigation computer; *2*) transmission control protocol/internet protocol (TCP/IP)-based interactive teleconsultation via bundled ISDN lines (including remote control of the navigation computer); *3*) TCP/IP-based interactive teleconsultation via network; *4*) combination of TCP/IP-connection and ISDN-based videoconferencing. The telemedically supported treatments are: orbitozygomatic osteotomies, positioning of the mandibular condyle in orthognathic surgery, insertion of implants, positioning of the maxilla in orthognathic surgery, distraction osteogenesis, arthroscopies of the temporomandibular joint, and operation simulations on stereolithographic models. The surgical interventions are evaluated on a 5-level system performance scale from the technical point of view. In a separate trial 20 videosequences of arthroscopies of the temporomandibular joint are transmitted via UMTS cellular phones and independently evaluated by 3 experts (ie, a total of 60 streamings) to investigate feasibility of this technology in the field of craniomaxillofacial surgery.

Results: In the years from 1996 to 2002 a total of 50 treatments were telemedically supported. All intraoperative applications were successfully finished; 48 of 60 UMTS transmissions were finished without any interruptions in constant quality, slight interruptions were observed in 8 tests, and a complete breakdown was observed during 4 streamings that required a restart of the transmission. Resolution was sufficient to diagnose even tiny anatomic structures inside the temporomandibular joint, but orientation was hardly recognizable.

Conclusion: In many applications telecommunication technology can contribute to a quality improvement in cranio- and maxillofacial surgery because of the global availability of specialized knowledge. The

*Clinic Head, University Hospital of Cranio-Maxillofacial and Oral Surgery, Medical University of Vienna, Vienna, Austria.

†Staff Scientist, University Hospital of Cranio-Maxillofacial and Oral Surgery, Medical University of Vienna, Vienna, Austria.

‡Professor, University Hospital of Cranio-Maxillofacial and Oral Surgery, Medical University of Vienna, Vienna, Austria.

§Professor, University Hospital of Cranio-Maxillofacial and Oral Surgery, Medical University of Vienna, Vienna, Austria.

‖Staff Scientist, University Hospital of Cranio-Maxillofacial and Oral Surgery, Medical University of Vienna, Vienna, Austria.

¶Staff Scientist, Center for Biomedical Engineering and Physics, Medical University of Vienna, Vienna, Austria.

#Director, Karl Lansteiner Institute Biotelematics, Vienna, Austria.

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Address correspondence and reprint requests to Dr Schicho: University Hospital of Cranio-Maxillofacial and Oral Surgery, Medical School University of Vienna, Waehringer Guertel 18-20, 1090 Vienna, Austria; e-mail: kurt.schicho@meduniwien.ac.at

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required technical expenditure for teleconsultation crucially depends on the infrastructure that is already available at the clinic and the remote site. UMTS is a promising technology with the potential to be valuable in numerous craniomaxillofacial applications.

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Application of computer technology in the field of cranio- and maxillofacial surgery opened new perspectives in the preoperative planning and accurate intraoperative realization of treatment concepts. In addition to powerful imaging techniques such as computed tomography (CT) and magnetic resonance imaging, computer-assisted navigation technology is a development milestone. In navigation systems, so-called "augmented reality" environments are applied to complement visual information acquired by imaging techniques concerning the patient's actual anatomic conditions with additional "artificial" (ie, computer-generated) information.[1-4] Into this augmented reality the operation (OR) site is intraoperatively integrated by means of tracking systems that fulfill the task of continuous spatio-temporal registration of positions of the patient and the surgical instruments.[5,6] Computer-assisted navigation technology with augmented reality, however, can not only contribute to quality improvement of the therapy, but also fulfills the preconditions for telemedicine applications.[7-9] The integration of additional experts into the surgical intervention via teleconsultation can be interpreted as direct advancement of the computer-aided surgery concept, because—generally speaking—the "information space" of the augmented reality environment is again being extended by information contributed by "remote experts." Nevertheless, telemedicine applications in the field of craniomaxillofacial surgery are not limited to operations with navigation technology. Also, conventional audiovisual transmissions of operations without navigation, which are much less complex from the technical point of view, are a kind of telemedicine.[8] Teleconsultations, during which remote experts can directly control and modify the procedure, are of special interest (in contrast to pure transmissions). This modification of the transmitted treatment can take place directly (eg, by remote access to the navigation computer via the internet) or indirectly (eg, by verbal communication via telephone or a videoconferencing system connecting the persons involved in the OR site with the remote experts). Operations with navigation are ideally suited for interactive teleconsultation. The initial report on navigated arthroscopies of the temporomandibular joint (TMJ) with interactive teleconsultation by Wagner et al[9,10] is an example of telemedicine in craniomaxillofacial surgery.

In 1993, the new medium of the internet became publically accessible. This was also a milestone and a new dimension in telemedicine.[11-13] Since the beginning of the new century the third generation of mobile communication was introduced, called IMT-2000 (International Mobile Telecommunication). In Europe this standard is addressed as UMTS (universal mobile telecommunication system). It is intended to provide higher bandwidths for data transmission.

At our hospital numerous telemedical applications have been accomplished routinely in different technical setups since 1996. This study will summarize the experiences from 50 teleconsultations performed since that time. The technical requirements and expenditure will also be discussed and described in detail, providing information for clinics that are planning to start their own teleconsultation projects. Additionally, preliminary results from a recent study are mentioned that investigated the feasibility of UMTS for arthroscopic craniomaxillofacial interventions.

Materials and Methods

Teleconsultation in craniomaxillofacial surgery can be accomplished in numerous different technical setups. The system configurations applied for this purpose have changed greatly during the last few years because of rapid technical advancements. In principle, we have to differentiate between telemedical applications that are exclusively a transmission (one-way), and transmissions of treatments with full interaction (interactive teleconsultation). Further transmissions of operations with computer-assisted navigation technology and operations without navigation are to be differentiated. In this study all of these variants are included.

COMPUTER-ASSISTED NAVIGATION TECHNOLOGY

The VirtualPatient System and MedScanII software (both from MedLibre Inc, Munich, Germany) are used for intraoperative navigation. As navigation computers, the Apple PowerMac G3 and G4 workstations (or earlier top range types; Cupertino, CA) are applied. The navigation computers are connected with optoelectronic tracking systems ProReflex Motion-Capture MCU240 (Qualisys Inc, Gothenburg, Sweden), Polaris (NDI Northern Digital Inc, Waterloo, Ontario, Canada), and FlashPoint 5000 3D Localizer (Image Guided Technologies Inc, Boulder, CO). For visualization of

the surgeons' information, the computer screen of the navigation system is usually complemented by semitransparent head-mounted displays to ensure an unhindered, continuous view onto the OR site.

TELECONSULTATION

In the initial phase (during the mid 1990s), when there were no efficient network connections (ie, networks providing sufficient bandwidths) available in the operating theater, exclusively ISDN lines served as pathways for data transmission. Today there are 10/100 Mbit/s network connections additionally installed in the operating theater.

TCP/IP-BASED TELECONSULTATION

For TCP/IP-based transmissions in the early years (when the 10/100 Mbit/s network connections were not yet available) up to 4 ISDN lines with 2 B channels each (B channels are the lines of the ISDN connection) are bundled by means of a router. One B channel provides a bandwidth of 64 kbit/s, enabling a total bandwidth of up to 512 kbit/s. CT data are preoperatively transmitted to the remote site to allow for interactive teleconsultations during live transmissions of surgical interventions at such limited bandwidths. Thus, a sufficient intraoperative transmission capacity is available to exchange data (primarily coordinates of the patient and of surgical instruments) between the navigation computer and the remote-control computer with minimum time delays. The teleconsultation module is integrated in the navigation software, MedScanII. Connection to the remote control computer is built up directly by entering the remote site's IP address (Fig 1). Because 10/100 Mbit/s network connections are now available, these have replaced the other connections for TCP/IP-based transmissions.

CONVENTIONAL (ISDN-BASED) VIDEOCONFERENCING AND COMBINED SETUPS

Alternatively, the ISDN lines can be used for conventional videoconferencing systems (eg, by Polycom, Pleasanton, CA). A 512 kbit/s connection allows for a transmission with up to 30 frames per second and full-duplex audio. At the present state of technical development (as mentioned previously) TCP/IP-based teleconsultation is performed via 10/100 Mbit/s network connections in the operating theater, while ISDN lines are exclusively applied for conventional videoconferencing. Furthermore, system configurations that combine TCP/IP-based remote control of the navigation computer with conventional videoconferencing via ISDN connections are used. The diagram of this *optimum* realization of interactive teleconsultation is illustrated in Figure 2. All technical setups covered by this study are summarized in Table 1.

TELEASSISTED THERAPIES

A total of 50 teleassisted treatments performed from 1996 to 2002 were the basis of this review. The technical solutions presented in this work are not limited to an application in the context of these specific medical treatments described here. The "telemedical component" (ie, the technical part, the telecommunication per se) can be used to contact remote experts within other fields of medicine as well. Therefore, in principle, any of the 4 technical configurations can be applied for any therapy in this study. The telemedically supported treatments accomplished in the period comprised in this study are: I, orbitozygomatic osteotomy; II, positioning of the mandibular condyle in orthognathic surgery; III, insertion of implants; IV, positioning of the maxilla in orthognathic surgery; V, distraction osteogenesis; VI, arthroscopy of the TMJ; and VII, other (such as OP-simulation on a stereolithographic model). Table 2 summarizes all telemedicine applications from the years 1996 to 2002 considered in the evaluation (with and without navigation). Those aspects of the telemedicine applications that are directly referring to the transmission (ie, not the surgical intervention or the navigation system per se) are evaluated by means of a 5-level system performance scale (5, optimum performance: no critical phases with increased risk of breakdowns, constant quality of audio and video transmission, constantly high resolution of the picture; 4, good performance: but slight shortcomings such as short periods with noise in the video or audio signal, high resolution but at slightly lower level than at level 5; 3, sufficient performance: mentionable technical problems, special technical skills required to finalize the transmission, perceptible noise in the video and/or audio signal, but nevertheless sufficient quality to enable the remote audience to follow the main parts and aspects of the intervention; 2, insufficient performance: resolution not sufficient, noisy video and audio signal, the complete intervention [but parts of it] could not be watched and analyzed by the remote experts; 1, complete breakdown).

PRELIMINARY UMTS STREAMING EXPERIMENTS

Twenty arthroscopic video streams showing sequences from craniomaxillofacial interventions such as arthroscopies of the TMJ or treatments of a fractured mandibular condyle are hosted on a server and analyzed on a UMTS cell-phone handset (Siemens U10; Siemens, Erlangen, Germany). Quality and stability of the transmission are documented as well as perceptibility of defined anatomic details. All streamings are encoded in the H.263 standard. A resolution of 176 × 144 pixel and a bandwidth of 55 kbit/s are selected. Each of the 20 arthroscopic video sequences was independently evaluated by 3 medical experts,

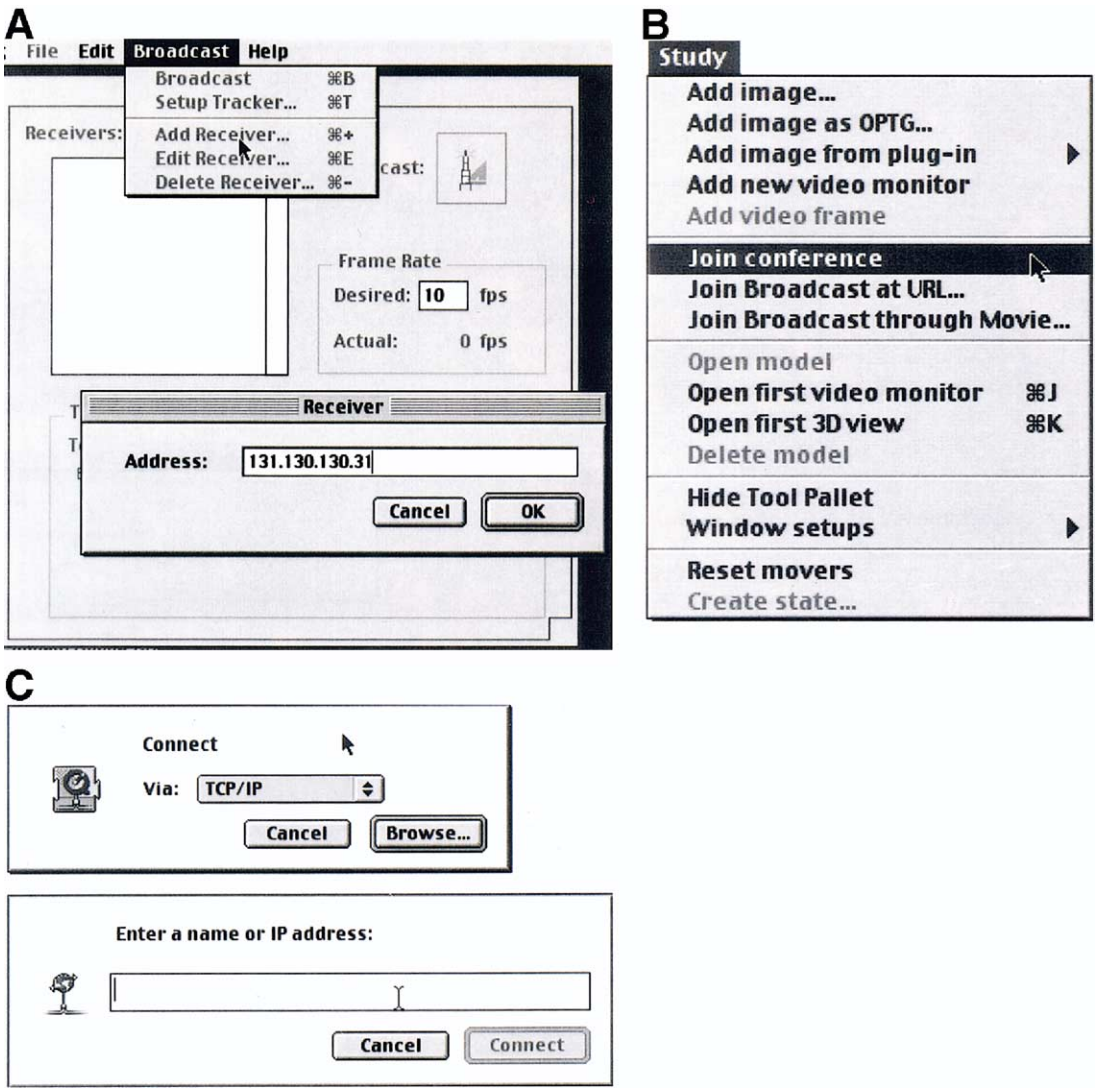

FIGURE 1. Interactive teleconsultation in MedScanII. *A*, The conference starts by entering the IP address of the remote site. *B*, The remote computer is "called up," and (*C*) informed of the IP address of the navigation computer.

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who document whether they agree or disagree with the information about the video or state that they can not make a decision based on the transmitted movie. Stability of the transmission, interruptions, and breakdowns are registered also.

Results

STATISTICAL DATA AND EXPERIENCES FROM 1996 TO 2002

In the years 1996 to 2002, a total of 50 treatments were supported telemedically. The number of teleconsultations per year is summarized in Figure 3, the applied system configurations are listed in Table 2. The number of teleassisted therapies in the distinct groups of treatments is depicted in Figure 4. An average of 7 teleconsultations per year were accomplished in this period (minimum, 1; maximum, 15). All intraoperative teleconsultations were finished successfully. Considerable technical problems occurred during the transmission process in only 2 cases of preoperative teleconsultation in the context of an operation simulation at a stereolithographic skull model. The arithmetic mean on the 5-level system performance scale amounts to 4.14. The results of the evaluation by means of this scale are given in Table 3. A comparison of the technical complexity and a rough comparison of the costs for routine clinical application are listed in Table 4. However, it has to be taken into account that the technical complexity in routine clinical application after initial implementation of a system configuration has only

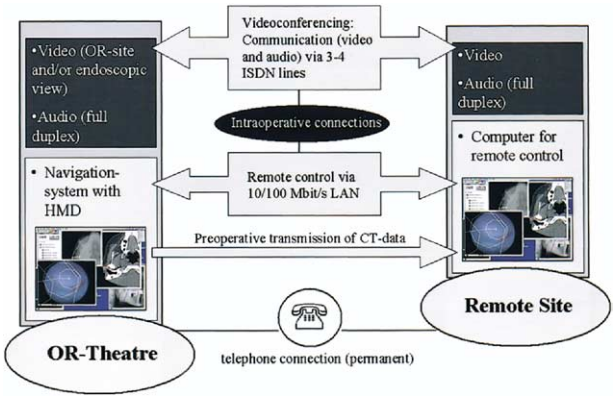

FIGURE 2. Schematic representation of configuration D (according to Table 1), which is the most sophisticated setup in this study. ISDN-based videoconferencing for verbal communication and transmission of an endoscopic (or arthroscopic) videostream is combined with TCP/IP-based remote control of the navigation computer. Additionally, a conventional telephone connection between the OR and the remote site is available. The other setups listed in Table 1 are part of this configuration.

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small effects on the practical execution of the teleconsultations.

PRELIMINARY RESULTS OF THE UMTS STREAMINGS

Forty-eight of 60 UMTS transmissions were finished without any interruptions in constant quality. Slight interruptions were observed in 8 tests and a complete breakdown occurred during 4 streamings, requiring a restart of the transmission. Resolution was sufficient to diagnose even tiny anatomic structures, but orientation was barely recognizable. The buffering time (ie, the time delay for the start of the video streams) ranges from 4 to 6 seconds.

Discussion

The experiences from the 50 teleconsultations described in this work show that developments in telemedicine, and in particular the availability of the medium internet, allow for a broad pallet of applications in the field of craniomaxillofacial surgery. Because of synergies resulting from a combination of computer-assisted navigation technology with teleconsultation, the interventions remote experts can directly participate in surgical intervention within an augmented reality environment (interactive stereotaxic teleconsultation). In 1993 the internet was opened for public use, 3 years later (in 1996) at the University Hospital of Cranio-Maxillofacial and Oral Surgery Vienna the first live transmission of an operation via the internet was successfully accomplished. At this time barely efficient local area networks were available in the operating theaters; therefore, the internet had to be joined by means of bundled ISDN lines (system configuration B). Because the large data sets of the CT scans were preoperatively transmitted to the remote site, an altogether satisfying intraop-

Table 1. SURVEY OF TECHNICAL SETUPS APPLIED FOR INTRAOPERATIVE TELECONSULTATION IN THIS STUDY

Configuration	Description	Technical Setup
A	ISDN-based videoconferencing without remote control of the navigation computer	• Conventional videoconferencing system (eg, by Polycom, Pleasonton, CA) • Connection via 3–4 ISDN-lines • Bandwidth ≤512 kbit/s • ≤30 fps • Audio: full duplex • Standards: eg, H.263+, H.320
B	TCP/IP-based interactive teleconsultation via bundled ISDN lines (including remote control of the navigation computer)	• Teleconferencing with direct remote control of the navigation computer at the OR site • Software: MedScanII (Artma Medical Technologies AG) • Connection via 3–4 bundled ISDN-lines • Bandwidth ≤512 kbit/s • Additional telephone connection for verbal communication required • CT data transmitted preoperatively • Intraoperatively: transmission of real-time positional data (surgical instruments, modifications of preplanned portals), arthroscopic live video stream
C	TCP/IP-based interactive teleconsultation via network	• Similar to configuration B • Bundled ISDN lines are substituted by a 10/100 Mbit/s network connection
D	Combination of TCP/IP connection and ISDN-based videoconferencing	• Components as described at configurations A and C • Arthroscopic video stream, live videos of the OR site, and verbal communication are transmitted via ISDN-based videoconferencing • Remote control of the navigation computer is performed by means of the TCP/IP connection

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Table 2. TELEMEDICALLY SUPPORTED SURGICAL INTERVENTIONS WITH AND WITHOUT NAVIGATION IN THE YEARS 1996 TO 2002: THERAPIES AND APPLIED TECHNICAL SETUPS

Year	Therapies	System Configuration	Navigation (yes/no)	No. of Interventions	Total Number/Year
1996	I	B	No	2	2
1997	I	B	No	3	15
	II	B	Yes	2	
			No	1	
	III	B	No	2	
	IV	B	Yes	1	
			No	2	
	V	B	Yes	1	
			No	3	
1998	II	B	Yes	3	12
		C	No	2	
	III	C	Yes	4	
			No	2	
	VII	C	Yes	1	
1999	I	C	Yes	1	6
	VII	C	Yes	4	
			No	1	
2000	III	A	Yes	1	4
			No	1	
	V	A	Yes	1	
	VI	C	Yes	1	
2001	III	A	Yes	3	10
	VI	D	Yes	2	
		A		4	
	VII	A	Yes	1	
2002	VII	A	Yes	1	1
				Total 1996–2002	50

NOTE. System configuration no. according to Table 1. I, Therapies: orbitozygomatic osteotomy. II, Positioning of the mandibular condyle in orthognathic surgery. III, Insertion of implants. IV, Positioning of the maxilla in orthognathic surgery. V, Distraction osteogenesis. VI, Arthroscopy of the TMJ. VII, Other, such as OP simulation on a stereo lithographic model.

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erative performance could be achieved despite the limited bandwidths. The transmission of position data (ie, coordinates) can be carried out without considerable time delays (ie, with small latencies). For the kind of applications described in this work the latencies are of minor relevance because of generally slow movements. But in the context of future applications of robots, latencies during data transmission would be a crucial criterion, giving rise to the demand of higher standards concerning connection capacities.[14-18]

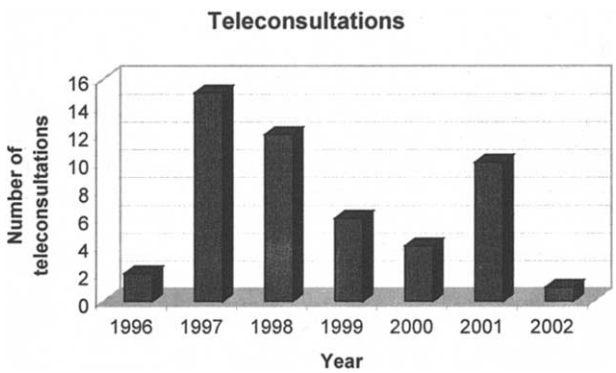

FIGURE 3. This graph depicts the number of teleconsultations performed from 1996 to 2002.

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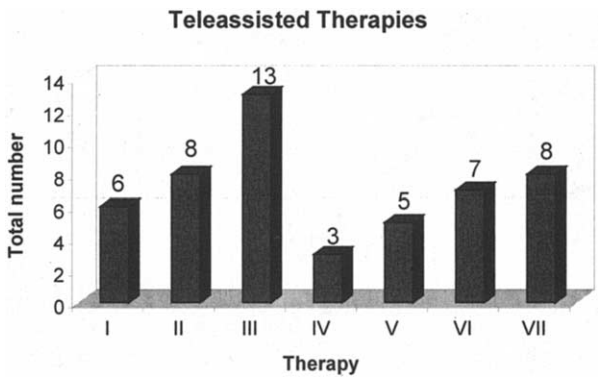

FIGURE 4. Total number of teleassisted cases from 1996 to 2002 for therapies I through VII (legend as in Table 2).

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Table 3. EVALUATION OF ALL TELEASSISTED SURGICAL INTERVENTIONS

Therapy SPS	I	II	III	IV	V	VI	VII
5	1	3	8	1	2	5	2
4	4	4	4	1	1	2	3
3	1	1	1	1	2	0	1
2	0	0	0	0	0	0	1
1	0	0	0	0	0	0	1
Mean SPS	4.0	4.25	4.54	4.0	4.0	4.71	3.5

NOTE. For each level of the system performance scale (5, optimum performance; 4, good performance; 3, sufficient performance; 2, insufficient performance; 1, complete breakdown) the number of cases is listed separately for the 7 groups of therapies. Insufficient performance or complete breakdown only occured in 2 cases where OP simulations were transmitted. Intraoperative teleconsultations (live OPs) were not interrupted by technical problems.

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Among all the applications described in this work, particularly for the arthroscopy of the TMJ (therapy no. VI), support via teleconsultation is beneficial. For example, during the introduction phase of this very specific operation technique at a remote hospital, experts can intraoperatively supervise the treatment in a cost-saving manner. In navigated dental implantology, the benefit of teleconsultation is to be expected in the context of preoperative planning of the intervention rather than in an intraoperative supervision. Optimal planning of positions of dental implants requires specialized knowledge, which is available in centers of excellence and could be made accessible independently of geographic location via teleconsultation over the internet. The technical expenditure for preoperative teleplanning would be smaller than that of the technical configurations described in this work because no live video and audio signals would need to be transferred. Only CT datasets combined with planning data would be sent as conventional attachments in e-mail programs.

The other teleassisted therapies and surgical interventions examined in this work are sophisticated from the technical point of view and contributed to considerable progress in the adaptation of extended teleconferencing techniques for intraoperative application. The presented procedures for teleconsultation are not restricted to craniomaxillofacial surgery and can be seen as promising technology in general (particularly because of the high stability and secure system performance). The temporal and financial expenditure for the realization of the described procedures can hardly be evaluated directly because it crucially depends on the already available infrastructure. In general, teleconsultation requires high infrastructure investments, whereby the expenditure for the infrastructure can usually not be exclusively related to teleconsultation. This applies in particular to local area networks, which today are standard infrastructure also used for data exchange in administration. However, in routine application, teleconsultation allows for a substantial increase of efficiency and thus for cost reductions of treatment. The expenditure for the preparation of an intervention decreases significantly after an appropriate time (eg, a so-called "learning curve").

Altogether, an evaluation of telemedical applications should also cover the aspect of quality control and quality improvement. Future developments in craniomaxillofacial surgery will depend crucially on the availability of new data communication technologies (broadband network connections). Apart from medical, technical, and economic criteria, legal aspects (eg, responsibility of remote experts participating in the therapy, data security) are an important factor in telemedicine.

The high degree of correspondence between the diagnoses of the arthroscopic videos transmitted via UMTS and the diagnoses based on the original arthroscopic screen indicates that the third generation of mobile communication is also a promising technology in the field of craniomaxillofacial surgery. Our preliminary results indicate that sufficient stability for routine clinical application can be expected. Nevertheless, orientation is nearly impossible without additional information. This aspect encourages the combination of UMTS-arthroscopy with computer-assisted navigation to supply the remote experts with position data of the surgical instruments relative to the patient's anatomy.

Table 4. SURVEY OF TECHNICAL COMPLEXITY AND RUNNING COSTS FOR ROUTINE CLINICAL APPLICATION (CONNECTION FEES) OF SYSTEM CONFIGURATIONS A–D

Configuration	Technical Complexity	Costs for Routine Application (Connection Fees)
A	Low	High (respectively, no costs for the local site, when the remote site builds up the connection)
B	Average	Average/high (depending on required bandwidth)
C	Average	Very low (no additional connections fees when a LAN is available at the operating theater)
D	high	High (respectively, no costs for the local site, when the remote site builds up the connection)

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Our experience of many years shows that modern telecommunication technologies allow for numerous applications in craniomaxillofacial surgery. In many cases the integration of remote experts proves to be an efficient approach for quality control and quality improvement of the therapy. By means of telemedicine, specialized knowledge can be made globally available and accessible in principle. The current state of development enables intraoperative application of teleconsultation not only for research purposes, but also in clinical routine. By combining teleconsultation with computer-assisted navigation technology, remote experts can be directly involved in the operation process (interactive stereotaxic teleconsultation). An evaluation of the expenditure for teleconsultation depends on the telecommunication infrastructure available at the hospital. Availability of UMTS and therefore the relevance of this technology is increasing rapidly, while costs are decreasing. A great potential for applications in minimally invasive surgery can be expected and should be investigated in further studies. Based on these experiences, we are now developing a universal telenavigation client, usable on any computer platform, based on open source software development (www.biotelematics.at). This will be subject to future studies.

Acknowledgments

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