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Basic research and 12 years of clinical experience in computer-assisted navigation technology: a review

R. Ewers, K. Schicho, G. Undt, F. Wanschitz, M. Truppe, R. Seemann, A. Wagner
University Hospital of Cranio-Maxillofacial and Oral Surgery, Medical School, University of Vienna, Waehringer Guertel 18-20, 1090 Vienna, Austria

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Abstract. Computer-aided surgical navigation technology is commonly used in craniomaxillofacial surgery. It offers substantial improvement regarding esthetic and functional aspects in a range of surgical procedures. Based on augmented reality principles, where the real operative site is merged with computer generated graphic information, computer-aided navigation systems were employed, among other procedures, in dental implantology, arthroscopy of the temporomandibular joint, osteotomies, distraction osteogenesis, image guided biopsies and removals of foreign bodies.

The decision to perform a procedure with or without computer-aided intraoperative navigation depends on the expected benefit to the procedure as well as on the technical expenditure necessary to achieve that goal. This paper comprises the experience gained in 12 years of research, development and routine clinical application.

One hundred and fifty-eight operations with successful application of surgical navigation technology—divided into five groups—are evaluated regarding the criteria ''medical benefit'' and ''technical expenditure'' necessary to perform these procedures. Our results indicate that the medical benefit is likely to outweight the expenditure of technology with few exceptions (calvaria transplant, resection of the temporal bone, reconstruction of the orbital floor). Especially in dental implantology, specialized software reduces time and additional costs necessary to plan and perform procedures with computer-aided surgical navigation.

Key words: computer-assisted navigation; augmented reality; arthroscopy; dental implantology; biopsies; distraction osteogenesis.

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Nineteenth-century surgery is primarily based on the knowledge of the anatomy of the region of interest. The discovery and application of X-rays marks the beginning of medical imaging, a revolutionary development still continuing. The use of imaging techniques allows preoperative evaluation of pathology and anatomy, but it is required that the surgeon transfers this visual information to the actual operation site just in imagination. Consequently the wish to have a ''glasslike patient'' arises, where relevant information from preoperative imaging is directly available to the surgeon's perception.

This can be achieved with the application of ''augmented reality''[3,4,7,25]. This technique allows to merge information as computer generated overlay-graphics (the mathematical term could be ''information-space'') into the surgeons field of view. In contrast to ''virtual reality''-technology, ''augmented reality'' does not rely solely on artificially generated environments but expands the real world with additional elements (information content)[5,22]. Spatial and temporal linking of the operation-site with computer-generated additional information can be achieved by using tracking-technology, which continuously registers the position of patient and surgical tools by means of special sensors (''computer-aided navigation'').

Navigation technology is already tested and established by many research groups and clinical physicians in numerous applications. Verstreken et al. state that computer-assisted planning in oral implant surgery ''... largely outperforms the manual planning practice based on two-dimensional dental computerized tomographic images printed or on film ...''[19] and that ''... the improvements often avoid complications such as mandibular nerve damage, sinus perforations, fenestrations, or dehiscences''[20]. Siessegger et al. report on successful navigation in dental implantology and conclude that ''the use of an image-guided navigation system provides a valuable tool in implant dentistry and proved superior to conventional implant surgery especially in difficult anatomical regions''[18]. Cavalcanti et al. have investigated the precision and accuracy of three-dimensional multislice spiral CT imaging for implant planning and find that it ''... allows highly accurate measurements for dental implant placement...''[4]. Ishimaru et al. describe computer-based simulations of arthroscopies of the temporomandibular joint (TMJ) ''... to observe the presence of a partial defect in the articular disc and an osteophyte on the condyle ...''[10], Wagner et al. have published the initial report on intraoperative navigation during TMJ arthroscopies, also in combination with interactive teleconsultation[28,29]. The wide range of CAS (computer-assisted surgery)-applications furthermore covers skull-base surgery and osteotomies[8,13], removal of foreign bodies[12,17], and the treatment of cranio-maxillofacial tumors. Schramm et al. conclude that ''... intraoperative navigation makes radical tumor surgery more reliable ...''[16].

Over the past 12 years our department has been conducting extensive basic research and computer-aided navigation-technology was employed intraoperatively in a wide range of indications. This paper gives an overview of computer-aided navigation technology in craniomaxillofacial surgery, summarizes the most important applications and assesses technical expenditure as well as clinical relevance. It also presents perspectives of future developments in computer-aided navigation-technology (teleconsultation, open-source-software).

Material and methods

Imaging systems

The basic principle for application of augmented reality and computer-aided navigation in craniomaxillofacial surgery is the visualization of two- and three-dimensional views of the surgical site superposed on the real image of interest. In most cases computertomographic images are used (CT), but conventional X-rays, magnetic resonance imaging (MRI) or fusion of CT and MRT images are also available for special indications.

The two- and three-dimensional images of the real anatomical situation are complemented with graphical structures like points, lines and planes made during the course of preoperative planning, helping to define the optimal entrance and direction of arthroscopes and other surgical tools. These landmarks can also be used to visualize the planes of symmetry, osteotomy-lines, contours of tumors or positions of dental implants[15,23,30,33–36] (''overlay-graphics'', Figs 1 and 2).

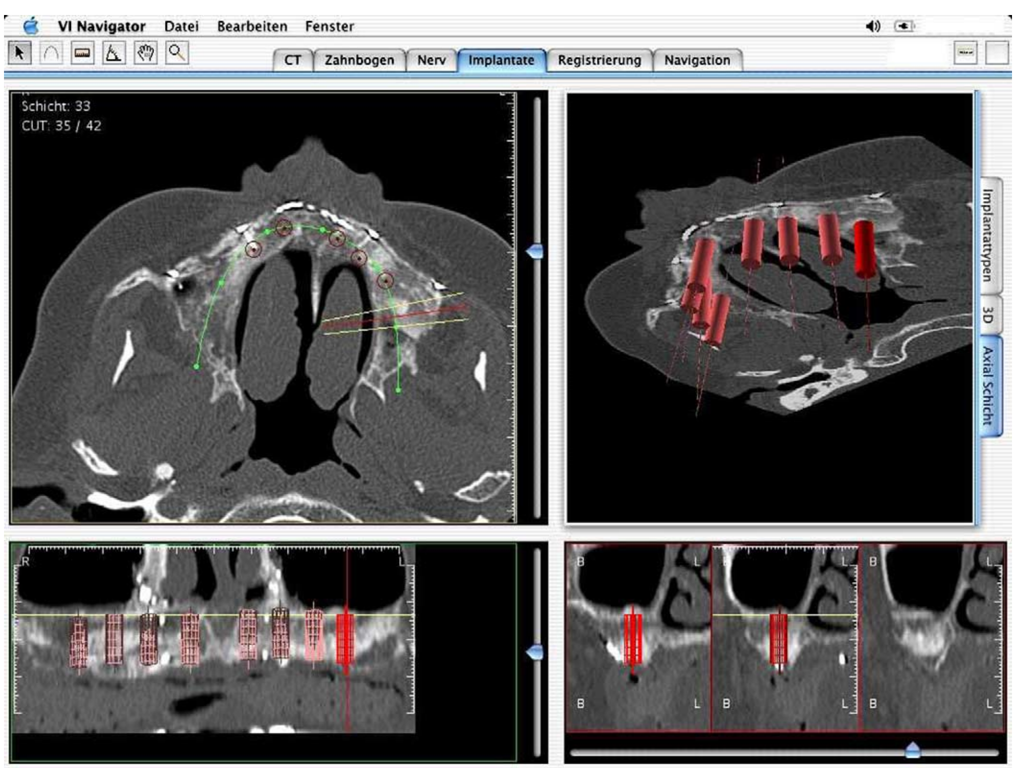

Fig. 1. Preoperative planning in computer-assisted dental implantology. Figure shows two- and three-dimensional visualization of planned implant positions. (Software: Artma Virtual Implant™.)

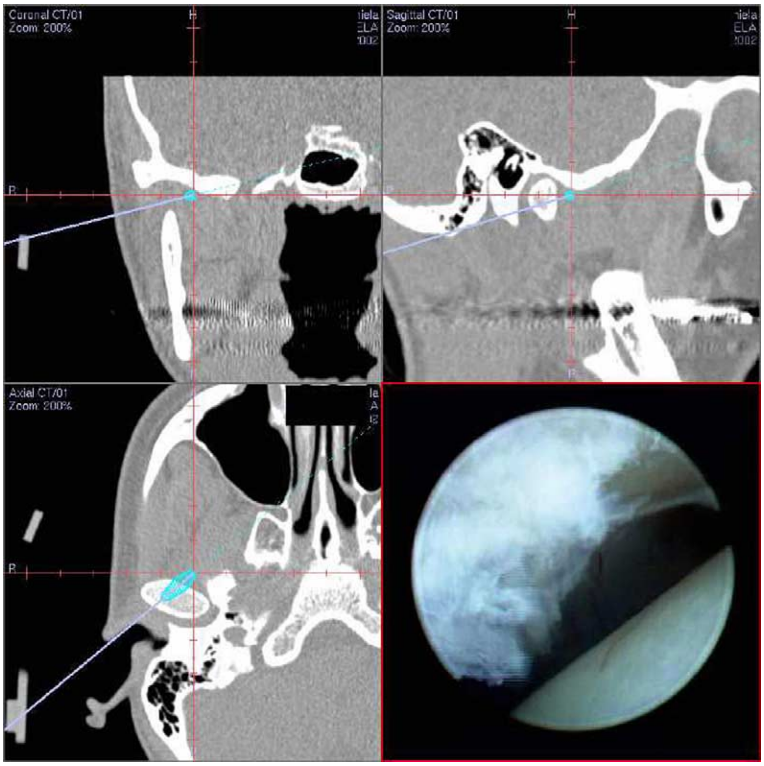

Fig. 2. Intraoperative screen during a navigated arthroscopy of the temporomandibular joint. The right lower window displays the arthroscopic video stream, the other windows line out the orientation of the arthroscope relatively to anatomical structures. (Software: Stryker Navigation system.)

The surgical procedure can be simulated on stereolithographic models in order to obtain planning data (Laserform Modellbau GmbH, Vienna). This is done especially for osteotomies and distraction osteogenesis[11] (Fig. 3). The data are merged with the ''real'' image of the patient, whose position is continuously tracked during the procedure. This process is called ''registration''. It can be performed using ''fiducial markers'', which are inserted to the patient when obtaining the CT-scan images, by using anatomical landmarks or by ''surface matching''. Position sensors mounted on the surgical instruments allows to visualize these almost in real time. Tracking systems are picking up the position of the patient and the surgical tool and transfer these data to the central processing unit[6,26] (Fig. 4).

Basic research has been carried out since 1992 at our department (software development in cooperation with Artma Medical Technologies, Vienna, preclinical studies, evaluation of accuracy). Routine clinical application of augmented reality technology began in 1995, using various types of navigation software (Virtual Vision™, MedScanII™, Virtual Implant™, Artma Medical Technologies, Vienna). VISIT is a modular surgical planning and navigation system for computer-aided surgery, developed by Birkfellner at the Department of Biomedical Engineering and Physics, Vienna General Hospital[2]. Recently the Stryker Navigation System by Stryker-Leibinger Inc., Freiburg, Germany has been used especially for arthroscopies of the temporomandibular joint.

The hardware components used in the Artma-System respectively in VISIT are:

- optoelectronic tracking systems: ProReflex™ Motion-Capture MCU240 (Qualisys Inc., Sweden), Polaris™ (NDI Northern Digital Inc., Canada), FlashPoint 5000™ 3D Localizer (Image Guided Technologies Inc., USA).
- Electromagnetic systems (since 1999 only used for research purposes): Polhemus Isotrac II™ (by Polhemus Inc., USA) and Aurora™ (NDI Inc., Ont., Canada), Fastrak™.
- Computers used for navigation: Apple PowerMac™ G3 and G4 workstations, SGI O2 RS12000 workstation (SGI, Mountain View, CA).

The information is usually displayed on a computer screen outside the operative field, but can additionally be displayed in a semitransparent head mounted display, enabling the surgeon to view planning data in the surgical field (Fig. 5). The head mounted display can also be equipped with position sensors, which allows stereoscopic projection of planning data into the surgeons field of view[1,31].

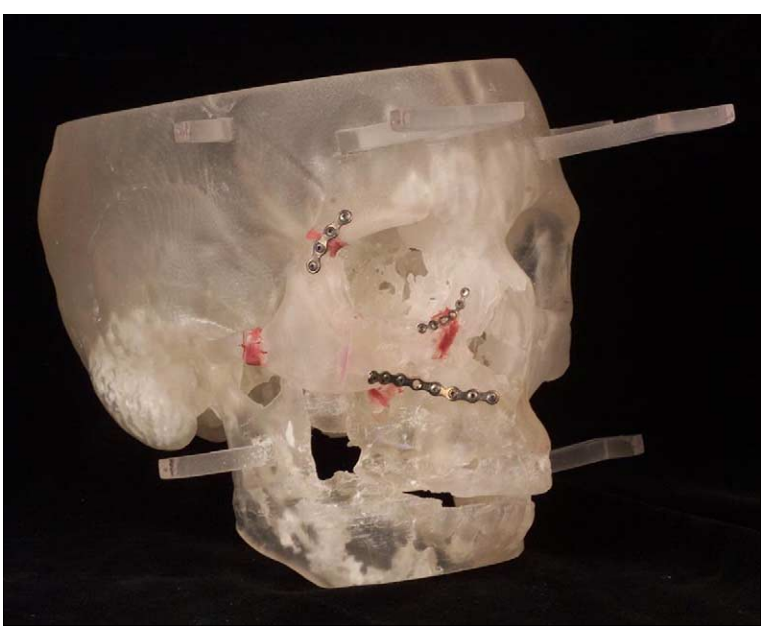

Fig. 3. Simulation and planning of operations by means of stereolithographic skull-models. Markers attached to the skull-model are corresponding to fiducial markers on a registration splint fixed to the patient during the CT-scan. These points are used for registration of the model for preoperative planning.

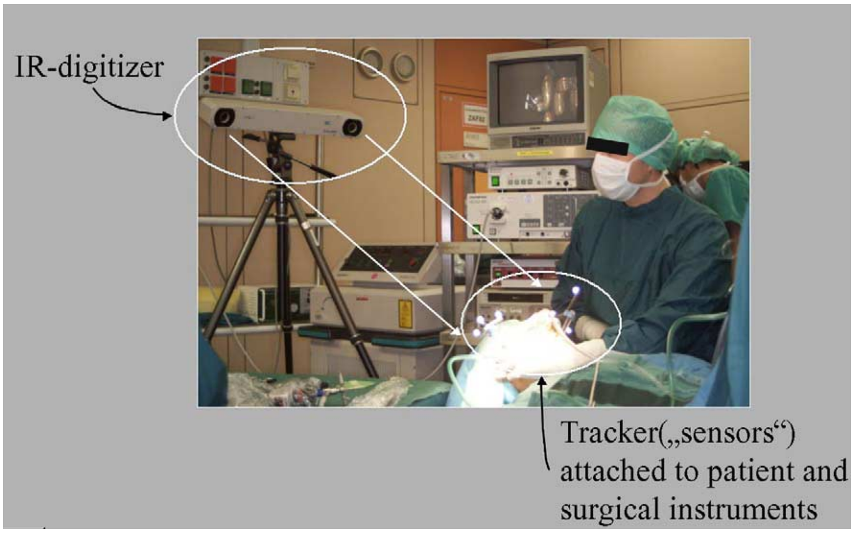

Fig. 4. Setup in the operating theatre. Positions of the patient and of surgical instruments are registered by means of an IR-digitizer, equipped with two IR-sources and IR-sensors. These sensors register the IR-radiation reflected by retroreflective marker spheres on rigid-body-tools, which are attached to the patient and to the surgical instruments.

Surgical procedures

This study presents the results based on 158 surgical procedures successfully performed from 1995 to 2003. Cases in which any kind of technical problems or system-failures occur are excluded from this review, because these operations have to be finalized in a conventional way without navigation. Due to technical progress during this period the system configurations underwent substantial changes (i.e., improved hard- and software, increased precision of the tracking systems, optimized geometry of sensors, high-speed network connection for telemedical applications, software-updates via internet). The surgical procedures are divided into five groups and discussed separately.

The groups are: (I) positioning of dental implants; (II) arthroscopies of the temporomandibular joint and intraoperative optoelectronical axiography (a newly developed method for recording movements of the temporomandibular joint[24,27]); (III) osteotomies of the facial skeleton (orbito-zygomatic osteotomies, orthognathic osteotomies, posttraumatic corrections, distraction-osteogenesis); (IV) removal of foreign bodies, image guided biopsies, punctures of the trigeminal ganglion (Ggl. Gasseri); and (V) other procedures: (a) resection of the temporal bone, (b) tumor resection and reconstruction with calvarial transplant, (c) reconstruction of the orbital floor, (d) positioning of positioning-screws (e.g., after vestibuloplasty).

Because this long-time review does not provide an explicitly investigated and separately defined control group for each of these groups, all evaluations and statements concerning comparisons with the corresponding surgical interventions without application of navigation technology are based on the experience of the involved surgeons and provide qualitative, descriptive information.

The intraoperative axiography (group II) was recently developed at our department. A software module integrated into the navigation system allows to record axiographic curves of passive (guided) joint movements intraoperatively and to compare pre- and postoperative joint function directly[24,27] (Fig. 6).

The above mentioned procedures supported with intraoperative navigation technology were qualitatively evaluated according to the following criteria: (1) empirical estimation of ''medical benefit''; and (2) ''expenditure''. ''Medical benefit'' describes the qualitative improvement of the procedure achieved by using navigation technology and is based on following criteria: (a) increased safety of the procedure (like avoiding nerve damage), (b) supporting the surgeon to achieve optimal esthetic and functional results (just ''measured'' qualitatively, i.e., registered by the surgeons by means of descriptive empirical comments), and (c) the increased morbidity of implementing surgical navigation (e.g., by mounting the fiducial markers and the tracking sensor to the patient).

Evaluation was performed by applying a three-step scale: ''excellent''—application of navigation technology is likely to allow substantial improvement of quality and intraoperative safety;

Fig. 5. Glasses with LCD-displays enable the surgeon to ''receive'' the information from the preoperative planning in the surgical field intraoperatively.

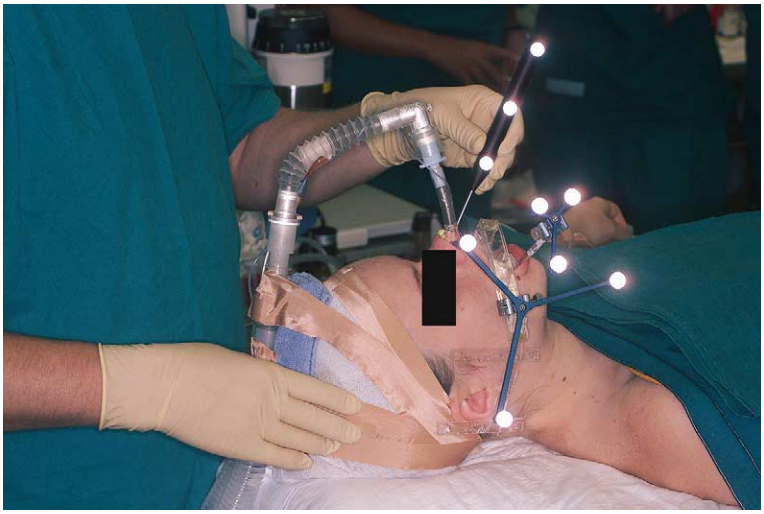

Fig. 6. Optoelectronic axiography enables intraoperative functional investigation of the temporomandibular joint. Pre- and postoperative joint function can be compared directly.

‘‘fair’’—navigation is helpful when routinely applied; ‘‘moderate/poor’’—navigation seems to be not recommendable for routine application and has some advantages only practical in special cases.

‘‘Expenditure’’ describes additional personal, technical and temporal resources necessary for preparation and performance of surgical procedures supported by intraoperative navigation technology (compared to the corresponding surgical interventions without navigation) as well as their ‘‘complexity’’.

The criteria refer explicitly to procedures performed with up-to-date technology and knowledge and do not include the efforts necessary during the phase of research and introduction of this technology to the operating theatre.

Evaluation is again performed on a three-step scale: ‘‘minor’’—navigation technology is easily integrated into clinical routine; ‘‘average’’—high expenditure compared to procedures without navigation, but still acceptable in clinical routine; ‘‘major’’—enormous expenditure, specialist knowledge necessary to perform navigation.

Results

Group I (positioning of dental implants) included 72 patients (395 implants), group II (arthroscopies of the temporomandibular joint and intraoperative optoelectronic axiographies) 26 patients, group III (osteotomies and distractions) 33 patients, group IV (removal of foreign bodies, image guided biopsies, punctures of the trigeminal ganglion) 19 patients and group V (other procedures) 8 patients. A chronological synopsis is given in Table 1 and Figs 7 and 8.

Groups I–IV (after thorough preclinical evaluation) had a favorable ratio between medical benefit and technical expenditure when applying navigation technology. Group V (a–d) needed average (V (a, b and d)) or considerable (V (c)) technical expenditure giving only small medical benefit.

The technical expenditure in group I (dental implantology) was essentially depending on the software used. Dedicated software optimized for dental implantology (Virtual Implant™, VISIT) needed much less technical effort than software non optimized for this task (MedScanII™). The medical benefit for group I was considered ‘‘excellent’’, especially in difficult implantological situations.

The medical benefit in group II (arthroscopies of the temporomandibular joint and intraoperative optoelectronical axiographies) was also conside— red ‘‘excellent’’. The technical effort (‘‘minor’’ to ‘‘average’’) depended on the goal: To navigate the arthroscope into the correct position did not need much technical effort, whereas navigation in the arthroscopic video and the visualization of a second pathway (troquar) required higher effort.

The technical effort in group III-procedures (osteotomies of the facial skeleton, posttraumatic reconstruction, orthognathic surgical procedures, distraction-osteogenesis) was ‘‘considerable’’ due to varying preoperative planning procedures (visualization of symmetry-planes, osteotomy-lines, etc.). The medical benefit was ‘‘fair’’.

Table 1. Number of surgical interventions performed from 1995 to 2003 using intraoperative navigation technology: group I—positioning of dental implants; group II—arthroscopies of the temporomandibular joint and intraoperative optoelectronical axiographies; group III—osteotomies and distractions; group IV—removals of foreign bodies, image guided biopsies, punctures of the trigeminal ganglion; and group V (a) resection of the temporal bone, (b) tumor resection and reconstruction with calvarial transplant, (c) reconstruction of the orbital floor, (d) positioning of marker-screws

	Year									
Group	1995	1996	1997	1998	1999	2000	2001	2002	2003	Total/group
I	2	–	1	10	2	8	21	11	17	72
II	–	–	–	2	3	3	10	8	–	26
III	–	3	6	14	–	2	3	3	2	33
IV	–	6	7	2	1	–	1	2	–	19
V (a)	1	–	–	–	–	–	–	–	–	1
V (b)	–	–	1	–	–	–	–	–	–	1
V (c)	–	–	–	–	2[a]	–	–	–	–	2
V (d)	–	–	–	1	–	1	2	–	–	4
Total/year	3	9	15	29	8	14	37	24	19	158

[a] Posttraumatic reosteotomy of the zygoma and reconstruction of the orbital floor.

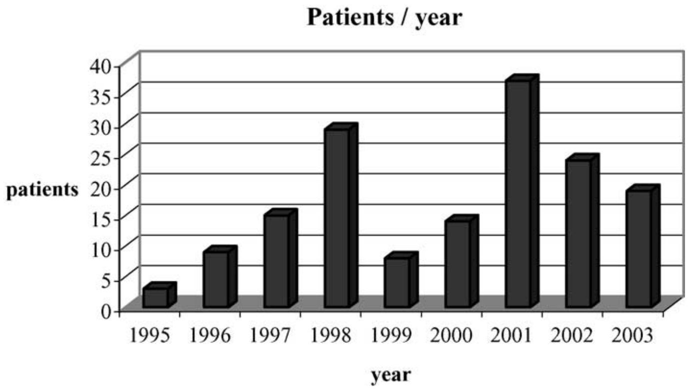

Fig. 7. Diagram is showing the number of patients operated on with support of intraoperative navigation technology from 1995 to 2003.

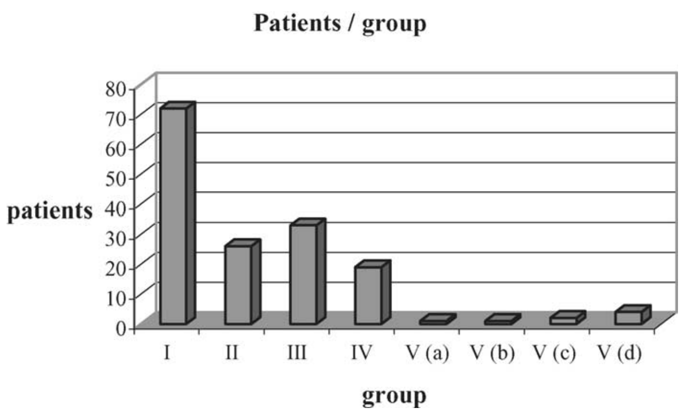

Fig. 8. Diagram depicts number of patients in groups I–V.

In group IV (removal of foreign bodies, image guided biopsies, punctures of the trigeminal ganglion) ''fair'' or ''excellent'' medical benefit could be achieved with minor technical effort (definition of a target structure), especially when removing foreign bodies in difficult accessible localizations. Table 2 depicts the results of the evaluation of all 158 cases.

The evaluation of 158 surgical interventions performed between 1995 and 2003 shows, that using computer-aided navigation technology in clinical routine is helpful in most indications.

Discussion

Basic research and routine clinical application of computer-aided navigation technology conducted over the past 10 years have proved that the application of this technology offers essential improvement in outcome and intraoperative safety in a wide range of craniomaxillofacial procedures. The 158 procedures discussed in this paper were performed with varying system-configurations within the groups due to ongoing technological progress. Each developmental step was tested before clinical application on models (mainly plastic ''phantom''-skulls) but was also evaluated for stability of hard- and software and accuracy[32,35]. Due to this thorough preclinical check-up technical problems or system-failures occurred in only 5% of all procedures. These cases were not included in this paper and all enrolled procedures were performed with satisfactory outcome and without increased risk for the patient.

Application of navigation technology in dental implantology is expected to increase in the near future since commercial systems are available that are easy to use and offer increased safety (avoiding lesions to the inferior alveolar nerve, etc.) and improved outcome with little preoperative preparation.

In TMJ arthroscopies (in combination with intraoperative axiography) the technical effort is small if there is no need to navigate relative to the arthroscopic video using defined target structures and entrance pathways. Pathways and target structures are visualized in the computertomographic images, where also the position of the permanently tracked arthroscope is shown. Navigation relative to the arthroscopic video is possible[29], but needs considerable efforts for implementation.

Osteotomies of the facial skeleton, posttraumatic reconstruction, orthognathic surgical procedures and distraction-osteogeneses (group III) can be planned precisely preoperatively. The planning parameters on screen or from simulated surgery on stereolithographic models can be transferred with high precision to the operating site, resulting in precise surgical displacement of the osteotomized bones. The technical effort necessary to plan and perform such procedures is considerable. Each case has to be treated individually, so the workflow cannot be standardized to the same degree like, for example, in dental implantology.

Image guided biopsies, punctures or removal of foreign bodies (group IV) have similar technical demands, i.e., the definition and finding of target structures. This task can be managed with little effort. The medical benefit is especially high in cases of small foreign bodies that are difficult to localize and are situated close to critical anatomical structures.

The procedures summarized in group V were all performed successfully with computer-aided navigation, but the achieved medical benefit does not justify

Table 2. Empiric estimation medical benefit and technical expenditure for all procedures in groups I–V

Group	Medical benefit	Technical expenditure
I	Very high	Low/considerable[a]
II	Very high	Low–average
III	High	Considerable
IV	High–very high (dependent on the indication)	Low
V (a)	Low	Average
V (b)	Low	Average
V (c)	Low	High
V (d)	Low	Average

[a] The technical effort in navigated dental implantology substantially depends on the navigation software used. Special software optimized for dental implantology reduces expenditure significantly.

the necessary effort. For example, the positioning of a calvarial transplant can be done with sufficient precision without navigation.

A distinct trend in computer-assisted surgery is the deployment of navigation technology in telemedical applications. Interactive teleconsultation offers new perspectives in medical training and (cost-)efficient support by remote experts in complex procedures[14,21,28].

The navigation-software presently available has already a high technical level. At our clinic current research is focused on the development of open-source software (also for telemedical applications, e.g., teleplanning) and medical robotics: Navigation-software can be made globally available for all researchers synchronously via internet and is therefore this approach is likely to speed up progress in this field. Medical robotics to assist the surgeon in realization of the computer-based preoperative plan are likely to gain in significance in the near future[9].

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Address:
Kurt Schicho
University Hospital of Cranio-Maxillofacial and Oral Surgery
Medical School
University of Vienna
Waehringer Guertel 18-20
1090 Vienna
Austria.
Tel: +43 1 40 400 4252
Fax: +43 1 40 400 4252
E-mail: kurt.schicho@utanet.at