

Computer-assisted abdominal surgery: new technologies

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Abstract

Background Computer-assisted surgery is a wide field of technologies with the potential to enable the surgeon to improve efficiency and efficacy of diagnosis, treatment, and clinical management.

Purpose This review provides an overview of the most important new technologies and their applications.

Methods A MEDLINE database search was performed revealing a total of 1702 references. All references were considered for information on six main topics, namely image guidance and navigation, robot-assisted surgery, human-machine interface, surgical processes and clinical pathways, computer-assisted surgical training, and clinical decision support. Further references were obtained through cross-referencing the bibliography cited in each work. Based on their respective field of expertise, the authors chose 64 publications relevant for the purpose of this review.

Conclusion Computer-assisted systems are increasingly used not only in experimental studies but also in clinical studies. Although computer-assisted abdominal surgery is still in its infancy, the number of studies is constantly increasing, and clinical studies start showing the benefits of computers used not only as tools of documentation and accounting but also for directly assisting surgeons during diagnosis and treatment of patients. Further developments in the field of clinical decision support even have the potential of causing a paradigm shift in how patients are diagnosed and treated.

Keywords Computer-assisted surgery · Cognition-guided surgery · Big data · Human-machine interface · Surgical process models · Machine learning · Computer-assisted surgical training

Introduction

Computer-assisted surgery (CAS) is a wide field of technologies with the potential to enable healthcare providers to improve efficiency and efficacy of diagnosis, treatment, and clinical management. Also, in abdominal surgery, CAS is widely adopted and increasingly used for different kinds of surgical assistance. This review will provide an overview of CAS especially in the field of laparoscopic minimally invasive surgery (MIS). It will present latest key technologies and exemplify whether and to what extent computer-assisted technologies impact present and future surgical therapy.

Literature search

A MEDLINE search based on the MeSH term in Table 1 was performed. Retrieved citations ($n=1702$) were screened for inclusion. To limit retrieved publications, the search term was conducted for laparoscopic surgery assuming that a representative subset of publications would be retrieved. Further references were obtained through cross-referencing. Titles and abstracts of full papers were manually assessed for relevance by two authors (HK and FW) and presented to the other authors according to the topics image guidance and navigation in abdominal surgery, robot-assisted surgery, human-machine interface, surgical processes and clinical pathways, computer-assisted surgical training, surgical processes and clinical pathways, and clinical decision support. The authors then made

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Table 1 Search algorithm

(guidance [All Fields] OR (navigation [All Fields] AND “system*” [All Fields] OR (“computers” [MeSH Terms] OR “computer*” [All Fields]) AND (“helping behavior” [MeSH Terms] OR (“helping” [All Fields] AND “behavior” [All Fields]) OR “helping behavior” [All Fields] OR “assistance” [All Fields]))) OR “surgery, computer-assisted” [MeSH Terms] OR (“surgery” [All Fields] AND “computer-assisted” [All Fields]) OR “computer-assisted surgery” [All Fields] OR (“computer” [All Fields] AND “aided” [All Fields] AND “surgery” [All Fields]) OR “computer aided surgery” [All Fields] NOT (orthopedic surgery OR neurosurgery OR ophthalmologic surgery OR orthognathic surgery OR otolaryngology OR surgery, plastic OR thoracic surgery OR traumatology OR obstetrics OR anaesthesia management OR musculoskeletal system)

decisions on presented publications upon their field of expertise based on abstract screening and full-text analysis. Based on this judgment, 64 articles were finally considered eligible to be included for the purposes of this review. To present an overview of the total number of publications on the topic, a statistical analysis on (the) annual and cumulative publication count with the term “computer-assisted surgery” was performed (see Fig. 1).

Definition of computer-assisted surgery

There is no single definition of CAS, and definitions vary widely since many different applications for computer assistance in surgery exist. Whereas CAS is often thought of as

mere image guidance and navigation, the online encyclopedia Wikipedia refers to it more comprehensively as “computer-assisted [...] to the use of a computer as an indispensable tool in a certain field, usually derived from more traditional fields of science and engineering” [1]. Thus, generally speaking, CAS entails a set of applications used at the surgical workplace preoperatively, intraoperatively, as well as postoperatively to improve surgical efficiency and efficacy.

Image guidance and navigation in abdominal surgery

Image guidance and navigation describe systems that assist the surgeon by means of radiologic imaging. They help exploring the patient’s anatomy in order to find targets faster and spare structures at risk.

Preoperative or intraoperative imaging is combined with a tracking system for the surgical instruments. Then, both are aligned in a registration step to the coordinate system of the patient. The system visualizes the points of interest in relation to the surgeon’s instruments and the patient’s anatomy in real time allowing insights and orientation for hidden anatomical features (see Fig. 2).

In neurosurgery, this technology has found its way into clinical routine and is also used in orthopedics and ear-nose-throat surgery [2]. However, navigation is of limited use in abdominal surgery, because tissue shift and organ deformation compromise the validity of the underlying preoperative imaging.

Fig. 1 Annual search term analysis “computer-assisted surgery” in the MEDLINE database

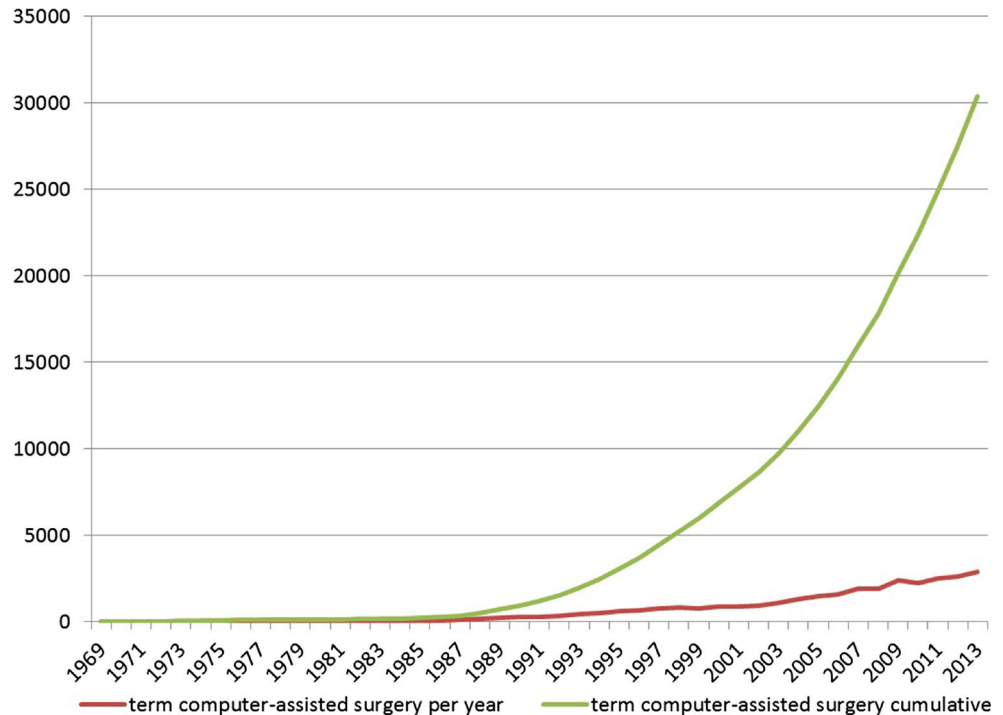




Fig. 2 Navigation system for laparoscopic rectal surgery in a porcine model. A *primary screen* shows the laparoscopic video and a *secondary screen* visualizes the aorta and the ureter in relation to the instruments

Possible clinical applications include various different procedures such as adrenalectomy [3], pediatricsplenectomy [4], pancreaticoduodenectomy [5], esophagectomy [6], and hepatectomy [7]. But, all of them remained limited to feasibility studies with case reports or small series, because they required a lot of effort in the setup, provided comparatively small advantages for the surgeon, and did not solve the problem of tissue shift. Only few navigation systems in these cases especially designed for liver surgery managed to bridge the translational gap and have been approved as a medical product [8, 9].

Recent developments are using novel intraoperative imaging modalities such as computed tomography (CT) to update preoperative imaging [10, 11] or combine preoperative MRI of the liver with intraoperative CT [12]. Although even with the use of intraoperative imaging, the tissue shift caused by respiration and intraoperative manipulation negatively affects accuracy of navigation systems considerably. Furthermore, intraoperative CT imaging generally results in increased radiation exposure for the patient and possibly even the surgical team. Intraoperative MRI could be a solution, and Tsutsumi et al. proved its feasibility visualizing the common bile duct in three patients undergoing laparoscopic cholecystectomy and the urinary bladder in two patients undergoing laparoscopic ventral hernia repair [13].

Despite navigation for abdominal surgery being “just around the corner” for more than a decade, limited progress has been made to overcome the well-known tissue-shift problems and complex setup [14, 15]. However, very promising commercial systems as the CAS-ONE Liver Surgery system (Cascination AG, Bern, Switzerland) have recently been

developed [16], although it still remains to be proven whether benefits can be demonstrated in randomized controlled trials and if these outweigh the increased investments in the systems, the training, and the logistics.

Robot-assisted surgery

Robot-assisted surgery has been a fast growing field of surgery for nearly 15 years and is one of the most common technologies in CAS [17]. Today, the da Vinci® (da Vinci Surgical System®, Intuitive Surgical, Sunnyvale, CA, USA) is mostly used. The da Vinci® is entirely controlled by the surgeon, who uses hand controls and foot pedals to manipulate a camera arm and at least two instrument arms [18, 19]. It has mostly been used for laparoscopic prostatectomy easing troublesome conventional laparoscopy. Thus, compared to open surgery, robotic prostatectomy allowed to provide the well-known advantages of laparoscopic surgery such as less use of analgesics and shorter hospitalization for a cohort formerly treated with an open approach and improving the learning curve [20]. In two recent meta-analyses, there is evidence suggesting improved urinary function, lower intraoperative organ injuries, and improvements in positive surgical margins comparing robotic-assisted with laparoscopic radical prostatectomy; however, both authors state that these results should be interpreted with caution due to limited and heterogeneous evidence [21, 22]. Nonetheless, robot-assisted surgery in prostatectomy is even discussed as becoming gold standard in the near future [23]. Another field with similar characteristics is robotic hysterectomy which even surpasses case numbers of robotic prostatectomy [20]. In recent years, considerable effort has been put into robot-assisted colorectal surgery. A recent systematic review by Kim et al. for robot-assisted colorectal surgery analyzed 39 case series, 29 comparative studies, and one randomized controlled trial, 69 studies in total. They concluded that robot-assisted colorectal surgery is safe and feasible and shows at least comparable results to conventional laparoscopic or open surgery [24]. Nonetheless, this technology is encountering serious challenges in colorectal surgery. The system is currently incapable of performing multi-quadrant surgery without readjusting the position of the system cart holding the instrument arms which results in time-consuming readjustments of the system during an operation causing longer operation times. Several surgeons solved this problem by a hybrid approach. They used the robot only for pelvic dissection and performing adhesiolysis and colonic mobilization by conventional laparoscopy [24]. Since the robot demands complex servicing and operation times tend to be longer, significantly higher costs have been reported in randomized control trials for robotic colorectal surgeries [25]. In addition, results from randomized controlled trials showed no significant differences in hospital stay, surgical complications,

postoperative pain score, resection margin clearance, and number of lymph nodes harvested compared to conventional laparoscopic surgery [26]. For laparoscopic fundoplication, Müller-Stich et al. reported a lower operation time, but in a recent meta-analysis, total operating time was significantly higher, while perioperative complication rates and length of hospital stay were comparable between laparoscopic and robot-assisted fundoplication [27, 28].

Apart from complex telemanipulation systems for all instruments, there is increasing interest in stand-alone robotic camera holders. These systems aim to replace humans as a camera operator. Particularly in solo surgery or small medical centers with fewer personnel, this tool might be helpful. These systems have been reported to be much cheaper than the da Vinci® by a factor of 10–20 [25, 29]. Gumbs et al. proved safety and feasibility in a case series of 200 laparoscopic pancreatic procedures using a robotically controlled laparoscope holder (Viky EP®, EndoControl, Grenoble, France) [29]. Gillen et al. evaluated 123 patients using a similar system (Soloassist®; Actormed GmbH, Barbing, Germany) in a case-control study for laparoscopic cholecystectomy. They found a significantly increased total operating time (104 vs. 90 min; $p=0.001$) but a lower overall surgical staff operation time (number of surgeons multiplied by operating time) (104 vs. 180 min; $p=0.001$) [30]. However, it has to be mentioned that these robotic camera holders are lacking real autonomy as well as learning behavior and have to be constantly controlled by surgeons by voice or manual interaction during surgery which costs time and effort. A new generation of cognitive robots that are context-aware and help the surgeon based on individual view preferences may lead to a future with autonomous robots operating the camera mainly on their own [18].

Human-machine interface

The term human-machine interface (HMI) describes the junction between a human and a machine. It involves both human senses and actions on one side and input as well as output devices on the other side. The user interacts with the HMI to control the hardware or software and to receive helpful feedback.

In minimally invasive CAS, the interaction with the computer is a key factor for the success of an operation. The classical HMI combination of a personal computer, consisting of a monitor, keyboard, and mouse, needs direct human interaction and is thus very impractical intraoperatively requiring a nurse to operate the system [31]. In contrast, modern devices tend to be mobile and available at the point of care. Tablet- or smartphone-based products to access healthcare information systems or view radiological images are commercially available and in clinical use even in the sterile operation area [32–34]. Tablet-based augmented reality (see Fig. 3) and 3D



Fig. 3 Tablet-based augmented reality

visualization have been reported for hepatectomy and pulmonary segmentectomy [35, 36], neurosurgery [37], and percutaneous access to the renal pelvis for, i.e., nephrolithotomy by Rassweiler et al. [38, 39]. Recently, optical see-through head-mounted displays like google glass™ (Google Inc., Mountain View, USA) were used for intraoperative augmented reality and medical training [40]. More intuitive input methods like voice or gesture control are now in focus of research. Examples are electromyographic armbands like the Myo™ armband (Thalmic Labs Inc, Kitchener, Canada) or the Microsoft Kinect™ gesture detector (Microsoft Corp, Redmond, USA) for touchless interaction in a sterile environment [41, 42]. Another way is to use voice control and voice recognition for intraoperative control of computers [43].

Experimental and clinical research to validate these new methods demand time, effort, and thoroughly planned studies. Unresolved issues remain data privacy, patient safety, and compatibility in the current clinical environment [44]. New HMI are fascinating at first sight, but for a successful clinical implementation, abovementioned challenges have to be addressed.

Surgical processes and clinical pathways

Clinical pathways (CP) are defined descriptions of diagnostics and therapies to solve a specific problem of a patient and aim for standardization of patient care and optimization of the

clinical outcome. There is strong evidence for CP decreasing length of stay and postoperative complications as well as to improving comprehensive documentation and decreasing inpatient costs [45]. In order to develop, discuss, and implement CP, there is need for an intuitive and clear depiction. For this purpose, the Business Process Model and Notation (BPMN) was developed in the organizational and business science to establish a standardized taxonomy of organizational processes and can also be used in CP modeling [46–48].

To establish the link between CP and CAS, the modeling and the implementing processes have to be considered. As most CP are comprehensive and complex, thorough implementation as well as optimization will need mathematical and computational support. Doebbeling et al. used the *VirtECS Scheduling* engine to run simulations in the perioperative management workflows of the operating room. These simulations balanced the workload which resulted in less overtime, fewer cancelled shifts, less resource strain, and increased staff satisfaction [49].

In conclusion, modeling CP reveals organizational responsibilities of patient care within the multidisciplinary network of modern medicine. It governs specific diagnostic and therapeutic tasks, which makes it liable to mathematical optimization. In the case of jurisdictional and insurance-related arguments, it is also able to document and report the whole process of patient care conclusively and automatically. In the future, simulators for CP optimization may help to develop and improve integrated CP.

Computer-assisted surgical training

Competent skill levels and procedural knowledge are vital for successful patient outcome in surgery. With the increasing public demand for patient safety and the rising complexity of modern operations, the necessity of operative training outside the operating room is not doubted anymore. Modern computer- and media-based training modalities enable surgeons to acquire the psychomotor skills and surgical knowledge necessary before operating on real patients [50–54]. Due to additional technical challenges and psychomotor demands, training is especially relevant for MIS [55–58].

The psychomotor aspects of minimally invasive surgery can be trained with virtual reality (VR) trainers that use computer simulation with haptic feedback to train psychomotor skills and procedural aspects of operations (see Fig. 4). The trainees receive automated instructions and feedback. Their performance can be continuously recorded, and training progress can be monitored [59, 60]. VR trainers have proven advantages for patient safety. In a study by Zendejas et al., a group of surgical residents with an extensive simulator training program had faster operative times and improved patient outcome with significantly less complications in endoscopic



Fig. 4 Computer-assisted virtual training with a surgical virtual reality simulator

hernia repair compared to the group with the shorter VR training program [61].

Online learning platforms provide videos of operations, explanations and teaching of surgical techniques, the relevant anatomy, and perioperative management [62, 63]. The efficacy of online learning modules has been studied with positive results for online learning both alone and combined with other training modalities [64].

As liver anatomy is very complex, 3D visualization techniques have been developed to improve learning performance of medical students. In a cohort of 156 medical students, it has been shown that students exposed to 3D liver anatomy visualization performed significantly better to a set of anatomical and evaluative questions [65].

Surgical training courses have been established worldwide to ensure adequate skill learning before performing operations on patients. Different training modalities and their combinations have been compared regarding training effects. Multimodality training combines the available training modalities for optimal training outcome [66–68]. Future developments of training modalities for surgical interventions include the use of automated detection of the movements of the surgeon and the instrument to collect their movement patterns reflecting experience and creating continuous individualized feedback for trainees to enhance their learning curves. The emerging technologies open up new possibilities of accumulating experience and surgical knowledge to assist surgeons in their learning curves and decision-making processes in multi-dimensional ways.

Clinical decision support and cognition-guided surgery

Nowadays, surgeons often face a large and complex amount of information, i.e., increasing amounts of individual patient data and prognostic factors, rising number of diagnostic guidelines, and treatment concepts. Because of this information overload, clinical decision support (CDS) systems have gained interest in the field of medicine over the past few years

[69]. The general definition of CDS by Musen et al. is “a computer which is able to solve clinical problems together with a clinician” [70]. They defined three types of these decision-making support systems: systems which store information or patient data, systems which analyze information, and systems which assist in a patient-specific problem. Eberhardt et al. defined CDS as follows: a computer which provides intelligent information for a problem. To solve a problem intelligently, the computer requires information that pertain to the current problem. Furthermore, the computer needs a database containing relevant information on a certain topic (domain knowledge) as well as an interacting algorithm which integrates the current information of the specific situation with the general information of the database. Finally, a CDS needs an HMI which allows interaction between the users and the computer [69].

There is a variety of technical approaches which can be applied to CDS, the easiest of which is the rule-based approach which solves problems by applying determined rules in the “if-then” manner. The first clinical decision support called MYCIN used a rule-based approach (“if-then”) to diagnose infectious diseases and was named after the antibiotics it was designed to recommend [71]. As this approach is rigid and only able to solve problems, which were previously defined in the database, machine-learning algorithms have gained importance over the past few years. The advantage is based on the ability to learn from previous cases and hence to continuously extend knowledge of the medical problem. Machine-learning algorithms used for these systems are artificial neural networks, random forest models, and Bayesian belief network models.

Stojadinovic et al. developed a CDS to predict the individual survival rate of patients diagnosed with colon cancer [72]. This CDS was built with a database containing knowledge about colonic cancer (e.g., clinical or pathological findings), a machine-learned Bayesian belief network algorithm, and a user interface to insert the necessary data and to depict the results respectively. To construct the database and validate the CDS, a total of 146,248 records from the Surveillance Epidemiology and End Results Database (SEER) were used. Among these records, the overall survival was analyzed, and a subgroup analysis was made for the use of the CDS. They found a positive predictive for their CDS value for mortality rates at 1, 2, 3, and 5 years at 74, 80, 82, and 84 %, respectively. Moreover, key variables and their importance for the patient’s outcome that changed over the years have been discovered. They can be applied to an individualized CDS. Although this program was tested on retrospective data, the potential of CDS is shown.

Currently, further CDS models have been constructed to facilitate a surgeon’s work, for example, prediction of the survival rates of patients after liver transplantation and treatment for acute appendicitis [73–75]. Recently, the Transregional

Collaborative Research Centre “Cognition-Guided Surgery” has been funded at the University of Heidelberg, the Karlsruhe Institute of Technology, and German Cancer Research Center by the German Research Foundation (DFG). The aim is to create a technical, knowledge-based cognitive system to support the surgeon. It will act in a similar way to a human assistant while permanently retaining vital knowledge to be transferred, accumulated, and reused for future operations. One of the main objectives includes knowledge-based intraoperative surgical assistance.

However, CDS is not yet ready to be implemented in daily practice, and a paradigm shift is on the rise, in which computers develop from mere data capturing and storing systems to teachable, context-aware assistants.

Discussion

CAS is a heterogeneous field of advanced computer sciences. A steadily increasing yearly number of publications on this topic can be observed suggesting an exponential growth interest on the field (Table 1). The use-cases presented in this review do not represent the entirety of CAS but serve as examples of present and future directions in surgery. Based on the judgment of the authors, a technology rating table was drawn and can be seen in Table 2. Especially, further developments in the field of clinical decision support have the potential of causing a paradigm shift in how patients are diagnosed and treated on a broader scale. Medical device manufacturers are keen on these new techniques. Unfortunately, recent legislative medical device acts and regulations signify high regulatory and thus financial challenges for academic researchers as they often render it impossible to evaluate self-developed technologies in the clinical setting. On the other hand, financially potent companies such as Karl Storz (endoscopy equipment and integrated operating rooms), Intuitive Surgical (da Vinci®), SAP (Medical Research Insights), IBM (Watson Oncology), and Apple (Healthkit) are either already global medical device manufacturers or are investing in

Table 2 Technology rating table for abdominal surgery

	Technical maturity	Available products	Disruptive potential
Image guidance, navigation	+++	++	+
Robot-assisted surgery	+++	++	++
Human machine interface	++	+	++
Surgical processes and clinical pathways	++	++	+++
Computer-assisted surgical training	++	++	+++
Clinical decision support	+	+	+++

+ to a minor extent, +++ to a major extent

healthcare applications to a great degree. These financially potent companies will be adopting promising technologies fast and at the same time they will provide approved, integrated, and workflow-oriented tools. Clinical reality may thus change faster than expected due to company-driven innovation before academic researchers will be able to evaluate the changes in time. However, thoroughly planned clinical studies that evaluate these new products are a bare necessity and will be the foundation of broad acceptance in the surgical community. As a consequence, research-oriented surgeons should thus partner with potent manufacturers and implement evaluation processes early in the development to finally perform well-designed clinical studies alongside new products entering the market.

Conclusion

As presented, CAS is increasingly used not only in experimental but also in clinical studies. Although CAS is at an early stage of development, clinical studies start showing the benefits of computers not only as tools of documentation and accounting but also for diagnosis and treatment. In the upcoming years, those tools and technologies will be increasingly used by early adopters and innovators on the verge to cross the chasm of the technology adoption lifecycle onto wide-spread use.

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Compliance with Ethical Standards This study has been conducted in compliance with ethical standards as set in the declaration of Helsinki. The figures supplied were conducted within our working group; detailed results are yet to be published. Informed consent was obtained for the tablet-based augmented reality experiment (Fig. 3). An animal trial (Fig. 2) has been approved by the local authorities.

Conflicts of interest None.

Author’s contributions Kenngott HG: study conception and design, acquisition of data, analysis and interpretation of data, and drafting of manuscript.

Wagner M: acquisition of data, analysis and interpretation of data, and drafting of manuscript.

Nickel F: acquisition of data, analysis and interpretation of data, and drafting of manuscript.

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