Surgery in the year 2030: Surgery 4.0?

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Introduction

Future developments in surgery are not only interesting for surgeons but also an issue for biomedical engineers and computer scientists in order to focus their own work and energy to areas which most probably become relevant. Surgery of the next decade may be described best by the keyword “surgery 4.0”.

The term and its meaning are as yet even unfamiliar to most surgeons and most probably even less known by engineers. We coined it in 2016 [Feußner 2016] to describe a vital development in surgery, which could conceivably become as disruptive in interventional medicine as the current trend toward economic and industrial digitalization. To make the parallels and contrasts more evident, a reflection on the Fourth Industrial Revolution is helpful.

The global economy is assumed to move forward to the Fourth Industrial Revolution. Commonly, the mechanization of production using water and steam power is considered to have driven the First Industrial Revolution. The next “revolutionary” impact on industrial productivity came from mass production facilitated by the availability of electrical energy and improved workflow organization (assembly line, etc.). This was followed by the Third Industrial Revolution, which is characterized by the use of information technology (IT) and robots to automate production.

Today, a systematic transformation of industrial production is under way, which can be grossly defined as the comprehensive computerization of manufacturing.

The vision is some type of self-organizing or autonomous production: the factory with its production lines “understands” what has to be produced and autonomously carries out all necessary steps and adjustments. This strategy, originally propagated by the German Government as the Industry 4.0 initiative, is evidenced in the customization of products under the condition of highly flexibilized production. This highly automated technology is enabled by the introduction of methods of self-optimization, self-configuration, self-diagnosis, cognition and intelligent support of the few human beings who are still required to master this complex process. The main pillars are as follows:

1. Interoperability: The ability of machines, devices, sensors, and people to connect and communicate with each other via the Internet of Things (IoT) or the Internet of People (IoP).
2. Information transparency: The ability of information systems to create a virtual copy of a physical world by digital models with sensor data. The very dense net of information is available for all stakeholders. A huge amount of raw data have to be collected and interpreted in a higher context.
3. Technical assistance: Decision-making has to be facilitated by preparing all necessary information. Humans have to decide all necessary preconditions (information) that have already been provided.
4. Decentralized decisions: The ability of lower-level systems to make decisions on their own and to perform their tasks as autonomously as possible. Only in the case of exceptions and/or conflicting goals are tasks to be escalated to a higher level.

Autonomous decision-making by mechatronic support devices is the real disruptive element of Industry 4.0. Humans will need to be confident that machines are able to act and react reasonably, reliably, and as fast and as safely as a human worker.

There are, however, some necessary preconditions for this vision to become reality.

1. The IoT must support direct communication or dialogue with the technical equipment. If one device alters its functionality, the whole technical environment is informed.
2. Data/information must be provided wherever it is needed in real-time and by a high-quality, reliable service (5G telecommunication).

Surgery and the 4.0 development

What then has all this to do with surgery? Some context in the form of a brief review of modern surgical history may be helpful.

The beginning of scientific surgery dates back about 150 years. Retrospectively, this comparatively short period of time can be subdivided into three different eras. In the beginning, surgeons learned to master the specific challenges of the different anatomical regions – beginning with the abdomen and ending with the brain. In the next phase, surgery was not any longer confined to resection/amputation, but the focus was now laid on substituting deficits. Destroyed joints were replaced by artificial implants, and functional reservoirs were developed to accommodate for the roles of the stomach or rectum, for example, after their resection. The ultimate highlight of the era was the transplantation of whole organs (the heart, liver, kidneys, etc.).

The trend today is to further minimize the surgical trauma – collateral damage to other organs, functional impairment, and pain due to the operative intervention. This third era of surgery started with the introduction of laparoscopic surgery. Laparoscopy was, however, only the beginning of a broad development in many medical disciplines toward minimally invasive therapy.

We are now arguably on the threshold of a new era. This does not mean that further advances in reconstruction (phase II) or trauma reduction (phase III) should no longer be pursued, but the innovative impact comes now from another discipline: information/digitalization.

Although surgery is often considered a manual or technical discipline, it will not remain unaffected by the general trend toward the information age development.

On the contrary, surgery in the information age is more or less a synonym of "surgery 4.0". Surgery will soon adapt new technologies and methodologies, such as the IoT, process modeling, cooperative learning machines, and new approaches to the generation of knowledge that will affect surgery – all with the aim to improve the quality, efficiency, and outcomes of surgical care. Surgery 4.0 might be the chance to master the difficult situation surgery is currently in.

Surgery is forced to maximize quality and value of surgical in a highly competitive environment. Surgery 4.0 or "information-based surgery" might be the best chance to respond to these needs. Some practical aspects of "surgery 4.0" are delineated.

The fully integrated, "cognitive" OR workplace

Today, the surgical OR is a workplace comprehending the OR table, the surgical lamps and a plethora or peripheral devices working completely independent of each other. The OR of the future will be a highly integrated environment of smart intraoperative assistance systems collaborating with each other via the IoT.

Model-based surgery

A fully integrated OR, however, is only conceivable if the surgical activities – the workflow – is known and can be "understood" by the system. The precondition is a modelling of the surgical workflow.

A "surgical model" is an evidence-based, detailed plan of a particular surgical intervention with a clear description of the workflow from skin incision to closure. It not only includes the normal course of an operation but considers potential modifications and deviations as well. To create "surgical models" either bottom-up or top-down approaches may be considered [Neumuth 2017]. Modern IT methodologies such as machine learning will become extremely helpful to establish "model-based surgery". However, even the most advanced computer technology cannot substitute for surgical expertise – an urgent challenge for the surgical community to engage and scientifically collaborate in the development of Surgery 4.0.

Knowledge extraction

Since the preoperative diagnostic workup and the whole treatment as well as the postoperative care will be meticously documented in each individual case, these easily accessible data will become very valuable for gaining new insights retro- or prospectively (data mining). For surgical decision making, hundreds or thousands of similar cases can easily be identified as a fundament of evidence-based treatment.

The key: Surgical Data Science

As shown above, the future transformation in surgical care will be driven by data/information. The key elements on the path toward evidence-based surgery are new tools to measure, model, and quantify surgical processes including intraoperative decision-making and knowledge extraction. An intelligent collaboration between care providers and devices/technologies will be enabled. A new scientific domain is, thus, gradually emerging: Surgical Data Science. It is defined as follows: "Surgical Data Science is an emerging scientific field with the objective of improving the quality of interventional healthcare and its value through capturing, organization, analysis, and modeling of data. It encompasses all clinical disciplines in which patient care requires intervention to manipulate anatomical structures with a diagnostic, prognostic, or therapeutic goal, such as surgery, interventional radiology, radiotherapy, and interventional gastroenterology. Data may pertain to any part of the patient care process (from initial presentation to long-term outcomes), may concern the patient, caregivers, and/or technology used to deliver care, and is analyzed in the context of generic domain-specific knowledge derived from existing evidence, clinical guidelines, current practice patterns, caregiver experience, and patient preferences. Data may be obtained through medical records, imaging, medical devices or sensors that may either be positioned on patients or caregivers or integrated into the instruments and technology used to deliver care. Improvement may result from understanding processes and strategies, predicting events and clinical outcome, assisting physicians in decision-making and planning execution, optimizing ergonomics of systems, controlling devices before, during and after treatment as well as from advances in prevention, training, simulation and assessment. Surgical Data Science builds on principles and methods from other data-intensive disciplines such as computer science, engineering, information theory, statistics, mathematics, and epidemiology, and complements other information-enabled technologies such as surgical robotics, smart operating rooms, and electronic patient records." [Maier-Hein 2017] It also includes a significant impact on surgical education and training. Surgical Data Science (SDS) not only enables objective computer-aided skill evaluation but also automated coaching.

Discussion

Surgery of the next decades will certainly gain a new profile due to the vast use of information. Self-evidently surgery 4.0 is not only confined to a more or less abstract utilization of information but will also have a massive impact upon the use of a new hardware: Intelligent, cognitive surgical assistance systems (“robots”) will reduce the surgical workload by (semi-) autonomous manipulations like camera navigation or suturing. Integrated, precisely navigated percutaneous or endoscopic puncture probes could replace conventional surgical cancer resection by local ablation. Based upon an “intelligent” OR environment even completely new surgical approaches like combined laparoscopic/endovascular interventions are becoming conceivable. From the surgical viewpoint, these options would be highly attractive, but this also means that technology will play an increasing role in modern surgery. Simply accepting this fact is not enough what surgeons can do. They are even summoned up to contribute actively to technical progress by identifying currently existing deficits, by careful evaluation and improvement of prototypes and generally by providing their domain knowledge. Hopefully, this will lead to a new “culture of cooperation” between basic scientists, computer scientists, engineers and clinically active surgeons.

Conclusions

Surgery 4.0 does not mean that robots will perform surgery on their own in the future. This can neither be the vision of surgeons nor would it be accepted by the majority of patients in societies with a highly developed healthcare system, as one very recent study [Arnold 2017] has shown. However, artificial intelligence, robotics, model-based surgery, and many additional principles of Surgery 4.0 will certainly help to make surgery more evidence-based, safer, and easier, all with the goal of a better outcome and experience for the patient.

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