General Discussion
The last century, dentistry has developed from an artisan trade that could relieve pain-stricken visitors from their agony and pain by just extraction of the affected teeth to a science that involves prevention of tissue damage, planned movement of teeth, planned changes in function, planned changes in facial appearance to increase the aesthetic appearance of the requestor and still, occasionally of course, relieve patients from pain. Over the years the educational profile of the dentist had to be modified too to accommodate for developments that had taken place in existing fields of technology or simply because a whole new technology was introduced that expanded the existing armamentarium of the dentist. Such modifications can be expected in every academic field that involves the application of technology.

The “modern” dentist has a highly specialized profile, with expert scientific knowledge and insights in anatomical, biochemical and mechanical interactions of the complex of tissues that make up the orofacial system meanwhile also concerning the complex biochemical and microbial processes occurring in the mouth and the changes that occur during the progress of caries, periodontitis, peri-implantitis, infections of an endodontic origin, osseointegration of dental implants etc.. Apart from this, the modern dentist needs good visual and tactile senses, and highly trained manual skills. The aforementioned skill set enables the modern dentist to determine whether, e.g., a change in the orofacial system needs additional investigation, supervision of change or immediate treatment. These skills are based on pattern recognition in combination with a thorough knowledge of healthy and diseased tissues. This knowledge grows with the years of experience making the dentist a “better” dentist in that he or she is better at both recognizing disease and the challenges that are faced during treatment.

With the advent of digital technology and the introduction of 3D digital workflows, the question rises what changes will occur in current and future workflows, and what is the impact of these changes with regard to the profile of the dentist. The modern dentist should be able to up to date apply the technology in the dental field and to keep up with the changes occurring in that field: modern dentistry has become highly dependent on technology and its dependency will increase over time. As will be for many other fields, also dental technology will follow Moore’s law to some extent\(^1\) (figure 1).
Evolution in diagnostic technology

The patient has always been dependent on the clinical skills of the dentist to assess the condition of the orofacial tissues and to distinguish between healthy and diseased tissues. For example, the clinical environment (temperature, humidity, lighting, etc.) will have an impact how tissues are presented. The dentist has to heavily rely on pattern recognition fed by clinical examples and experience in differentiating between subtle differences in the condition of tissues and the patient’s physical condition. This rather subjective skill set is dependent on, e.g., the condition of the dentist on a particular day or even at a particular moment that day. This phenomenon was nicely illustrated by Goldman et al.3,4 who showed that the result of X-ray diagnostics vary between clinicians at the same moment of the day and even in the same clinician over time. When dental technology is able to reduce the subjective component, this will be a great asset for the patient. In this respect the term “Computer Aided Diagnosis” is used for solutions where a computer will analyse a 3D (or 2D) radiographic datasets to facilitate or improve the human aided diagnosis.5
Apart from X-ray information other 3D datasets can also be incorporated in the diagnostic process. Consecutive intra-oral 3D scans of the dentition provide a multiplicity of information concerning, e.g., wear and can enable us to differentiate between pathological and physiological wear of the dentition. It has been shown that the intra-oral scanners are very accurate at a local level (Chapter 2), but are not yet as accurate as conventional impression materials for general applications. But for the assessment of wear the local accuracy of the intra-oral scanners can be used in conjunction with software that can assess the severity of pathological wear. These scanners can also be used for monitoring changes in the position of teeth to assess phenomena like crowding of the teeth.

Other Computer Aided Diagnosis applications will involve the monitoring of external changes in tissues with 2D (changes in colour) and 3D (changes in texture of the surface) in combination with pattern recognition algorithms. External changes that involve swelling of the tissues can already be assessed with 3D camera systems, but the accuracy of these measurement is in need of refinement. The camera system tested (Chapter 3) could accurately detect changes >5.9 ml. Important limitations of the tested system were related to the resolution of the system and the applied software algorithms. This was nicely illustrated by the applied software: for the same data set older software algorithms performed worse than newer algorithms showing that optimized software algorithms play a pivotal role in the accuracy of a 3D measurement system. However, the improvement that can be obtained by just applying sophisticated software is limited. Greater improvements are expected from hardware improvements. For example, the resolution of digital photo cameras has increased exponentially over the years (figure 2). However, beyond a certain resolution the difference in image quality that can be perceived by the human eye is reached, therefore it is expected that this curve will level off for consumer cameras, but may continue to follow Moore’s law for technical applications such as optical 3D scanning systems.

For the hard tissues underlying the soft tissues, we need imaging systems that “see” through tissues. Yet, radiographic techniques are most applied for this purpose. These can provide information in 2D or in 3D but at the cost of exposure to radiation and with a limited resolution. Other imaging technologies can also be applied in the diagnostic process. Ultrasound imaging is one of these that even though it is yet limited in resolution as the wavelength of the ultrasound signal is still rather large compared to the level of detail we like to depict. Ultrasound has been tested for caries detection and encouraging findings have been reported. High frequency ultrasonic scanners have been tested to solve the aforementioned resolution problem. Even though some of these scanners were primarily designed as an alternative for traditional impression materials, they show
promising results resolution-wise\textsuperscript{8,9} and may be incorporated at some level in Computer Aided Diagnostics. Another technology that has great promise is optical coherence technology (OCT).\textsuperscript{10} Unfortunately, the equipment is yet suitable for research purposes only and currently, there are no OCT scanners for intra-oral use available for the dental practice. The availability of new technologies and the increase of diagnostic resolutions will go hand in hand with further software improvements and it can be presumed that many, if not most, diagnostics will be done with automated systems within the next decades.

Evolution in treatment planning technology
Though some available technology may have limited value from a diagnostic perspective (see previous session), others have already shown their value in the treatment planning process. For some treatment modalities, e.g., implant treatment planning, there is already software available that enables the clinician and dental technician to plan suprastructure and implants position. Even though in some software X-ray data can be combined with digital models of the dentition, it is still not a full functional simulation. Nevertheless, this combination can be used to plan implant treatment and to produce surgical guides to facil-
imate implant placement, particularly for difficult anatomical areas like the floor of the nose (Chapter 4) or the mastoid region (Chapter 5).

To enable a complete simulation of the patient, data collected with different imaging technologies has to be combined in one 3D model which ideally results in a photorealistic model of the patient allowing for a simulation of different treatment modalities. Even though this approach is already feasible\textsuperscript{12}, there is yet no complete and fully developed solution for a full simulation of the functional and aesthetic aspects of a treatment. When considering the current state of technology and what is needed to achieve a technical solution, it is expected that a full simulation will become available in the next decade.

Most of the current treatment planning technology also deals with the actual production process. The objective of technology in a production process is to establish a high and constant quality while reducing the costs of the end-product. Reducing the costs is usually achieved by minimizing or eliminating the human factor in a production chain. In Chapter 7 a practical way of using technology as an aid for the technician to digitally plan and produce a cranial implant is shown. In Chapter 8 the next step is illustrated by showing that a digital workflow for producing multicomponent dental appliances without resorting to a physical model of the dentition is already feasible. The implications of this proof of concept are profound. Align Technology, Inc. for example, produces about 40,000 parts a day resulting in a total of 8–10 million aligners each year.\textsuperscript{13} Such a production process still involves the production of multiple models of the dentition of the patient, however. A digital workflow for the production of full acrylic appliances without having to resort to a physical model of the dentition will significantly reduce the production costs of these aligners and will reduce the production time meanwhile reducing the amount of waste material by not needing physical models anymore.

Another example is the traditional fabrication of multicomponent dental appliances. This production was previously restricted to dental technicians with proper hand-eye coordination and fine motor skills to bend steel dental spring on a plaster model. The introduced digital workflow (Chapter 8) enables everyone with experience with computers to design such appliances. The production of the appliances occurs by machines. The proposed workflow can easily be streamlined further as most 3D software can be scripted, thereby automating certain tasks. A simple script can lead the end-user through the whole process. The treatment planning will therefore shift from a traditional, labour intensive process that requires the input of multiple specialists to a highly automated, computer aided process that can be executed by a single person with both a dental and a technical background.
Evolution of treatment technology

In Chapter 4 a study is described going beyond the planning and production process of technology pointing to more profound aspects of technology. With regard to tasks that require human involvement, the objective of technology is to make difficult tasks easier and to make impossible tasks possible for human. Examples of the latter are the development of technology that can compensate for inexperience or human flaws and/or is able to expand the human abilities with extra competencies. The study described in Chapter 4 provides the dentist with a solution to treat calcific metamorphosis of the root canals that normally left the dentist with the tantalising technical prospect of reaching the root canal space through spatial and drilling skills without the complications of excessive and uncontrolled dentine destruction or worse: root perforation. Access to such calcified teeth traditionally relied on the ability to drill precisely in the direction of the anticipated canal opening based on knowledge of anatomy, 3D mental visualisation and a steady hand able to hold bur orientation. The proposed method provides a coupling of the CBCT dataset and the actual physical root canal and makes endodontic treatment of such complex cases less challenging meanwhile bringing it within reach of general practitioners. The principle of using a 3D printed device to guide the operator was used to perform the endodontic treatment, but other treatments like apical surgery can be simplified using similar technology and a similar workflow. In these cases the surgeon is left with a similar challenge: mental visualization of the anatomy and the location of the apical anomaly that needs to be treated. By removing the need for visualization the operation will become easier and the end result more predictable. This principle has already been applied successfully in a clinical case. Over time more technology will evolve that compensates for the lack of visualization or fine motor skills and for clinical experience. This implies that the dentist of the future will get better results without having to rely on experience and highly trained fine motor skills as this can be compensated by applying technology, which will have a profound effect on the education and training of the dental professionals.

Evolution of the disruptive nature of 3D technology

“Disruptive technology” or “disruptive innovation” are terms coined by Clayton M. Christensen. Currently, disruptive innovation is defined as a technology that brings a much more affordable product or service that is much simpler to use into a market which allows a whole new population of consumers to afford, to own and have the skill to use a product or service, whereas historically, the ability to access was limited to people who have a lot of money or a lot of skills.
While sustaining innovations build further on known technology, refining and improving technology mainly is based on demands and wishes of current users, disruptive innovations are based on new technologies and have the ability to change the complete market. To become truly disruptive, such technologies must at some point become better and cheaper than the “old” sustaining technologies. When considering the introduction of digital technology as a sustaining innovation then the changes will be minor and can easily be predicted. When digital technology is regarded disruptive, the resulting changes for the dental profession will be huge.

With regard to the current 2D and 3D digital technologies for dental applications, they do not meet that standard yet, but have the potential to become disruptive. Their disruptive potential is driven by two phenomena, viz. the rapid development in technology expanding the possibilities for diagnosis / treatment planning / treatment execution and the influence of the innovations on the cost of healthcare. When digital technology evolves to being disruptive, the disruption will most likely come in two stages. In the first stage, digital technology will make things easier and will make things possible for dentists that have been impossible up till then. At this stage a shift will take place in the tasks that traditionally exclusively belonged to the profile of the dentist as a number of these tasks now can be delegated to differentiated staff as lower level training and education is needed. In the second stage, technology will replace the human factor, leaving the dentist more and more in a supervising position and no longer in an operator position.

Even though the aforementioned will be difficult to accept for everyone, this disbelief relies on the false presumption that there are human competencies that are so unique that they cannot be replaced with technology. When considering key competencies of the dentist for instance, the diagnostic abilities and the fine motor skills are among the most important ones. When we strip down the process of diagnostics, the diagnostic competencies of the dentist consists of diagnostic data being combined and using a decision tree to come to a single diagnosis or simplified set of diagnostic options. However, before reaching such an algorithm, the first issue has to be solved that the diagnostic process often relies on the ability of a dentist to correlate a vast store of diagnostic knowledge with direct and indirect clues given by the patient combined with data from laboratory tests and imaging (X-ray, etc.). Yet, this still seems a task that is too difficult to handle for any computer program. But with the aforementioned definition, it’s not any more of a challenge than winning a game of “Jeopardy!”, and this task will become within reach with time. Actually, for Jeopardy this has already been accomplished in 2011 by the “Watson” technology from IBM. One might argue that the gathering the data by interviewing the patient cannot be performed
by a computer, but Cortana, Siri and GoogleNow are assistant services for mobile devices that are already able to break down human speech to search terms and the “Watson” technology is able through machine learning to distil other levels of meaning that would normally only be discernible to humans. When we will have an electronic assistant with the ability to respond to diagnostic or therapeutic questions combined with IBM’s “Watson” artificial intelligence technology, we already are at the frontier of practicing evidence-based, cost-effective, personalized medicine.

So, are the thoughts mentioned above still a future goal or already within reach? When considering the amount of data that needed for diagnosis in dentistry and even for a multiplicity of medical ailments, we can state that this amount of data is limited. Solving a game of checkers\(^{18}\) where the computer needs to solve \(5 \times 10^{20}\) board positions or a poker game\(^{19}\), where the computer needs to handle \(3.19 \times 10^{14}\) information sets can already be performed by a computer at or beyond the level of the most skilled chess and poker players. Regarding that for dentistry we only need a limited amount of information sets, we may expect diagnosis technology like “Watson” to take over most of the diagnostics within 10 years.

Apart from the in-office application of this kind of technology, there will be another level of disruption, viz. home-diagnostics. In its advanced form, the development of diagnostic technology will eventually lead to probes or sensors that can be connected to a communication device like a smartphone, enabling a layperson to assess the oral health of themselves. The ‘home-made diagnosis’ should also result in a preventive and curative advice and, if necessary, this may be combined with the address of the nearest dental professional. For the medical and dental professional this will mean that the patient of the future won’t come as frequently and will come with a demand for specific care and no longer with a demand for a general solution for his or her problem.

What will be harder for patients to accept than replacing humans for the diagnostic process, is replacement of humans at an actual treatment level. However, as described in Chapter 8, some of fine motor skills, like wire bending, can already be replaced by technology while also other competencies like the preparation of a crown can also be performed by a robot using laser technology.\(^{20}\)

Key competencies of dental specialists also will change with the advent of new technology. For orthodontists, two main competencies are insight in growth and development and insight in the biomechanics of tooth movement. A complete human simulation model already be made by combining 3D data from the dentition, a scan of the face and cone beam CT data. With such a simulation model a computer will become able to determine the anomaly and propose an orthodontic treatment plan, and design and fabricate the
appurtenant orthodontic appliances (see Chapter 8).
Also the oral and maxillofacial surgeon will ‘lose’ competencies with time as it is very likely that with the advent of new technologies as augmented reality the projection of anatomy and operation planning (simple) operations can be done by robots. Moreover, when imaging technologies and robotics further develop, a surgical robot will become able to take over move complicated operations that may be hindered by the human factor.

**Conclusion and future directions**
Currently, 3D technology is already commonly applied in decision making, fabricating surgical guides, and dental restorations etc. Complete 3D workflows are yet scarce and the added costs of such workflows are still rather high. But it will just be a matter of time before complementing technology will take over many diagnostic and manual skill of the dental profession. As a result, the dental profession will change with time making the dentist to a monitor and supervisor of the dental health as part of the general health while the dental technician will evolve into a planner and engineer for the actual dental treatment.
Literature


