Summary
Even though the first digital workflow for a dental application was described in the early 1970’s and was materialized in the early 1980’s, it did not inundate general dental practice at that time. Those days, burdened by lavish prices, challenging procedures, arduous handling and restricted applications, digital technology was only embraced by early adopters and 3D aficionados. Due to the exponential gain in processing power, the decrease in costs of hardware and the development of user-friendly software, nowadays a shift is presumed to take place. Yet, technology and end-users seem to have reached a level that facilitates the rapid flourishing of new appliances and services that deliver (parts of) a 3D digital workflow. Currently, many technology providers seem to emphasize on an increased remuneration as an inspiring impetus to convince less procedurally inclined practitioners to employ their technological solution. Fortunately, 3D technology seems to offer much more than just financial compensation. Technology will help care providers by making difficult procedures easier and will offer solutions allowing for a treatment and/or treatment outcome that cannot be achieved with traditional procedures. Technology will also aid in eliminating human errors and may eventually lead to humans becoming superfluous in certain procedures. Finally, technology will enable dental practitioners to deliver high quality products with a constant level of quality at a lower price, bringing a better and more affordable care within reach to a broader group of patients.

Therefore, the aim of the PhD research described in this thesis was to extrapolate available technology for optimizing 3D workflows to the dental, maxillofacial and orthodontic practice, specifically its applications in diagnostics (intra-oral dental scanners, 3D stereography), treatment planning (3D computer aided planning, digitally designed templates for placement of dental and craniofacial implants) and appliance manufacturing (single component and multicomponent appliances, complex devices for maxillofacial rehabilitation).

In chapter 2 the first steps in developing a full digital workflow for dental applications were taken: 3D scanning of a full arch with the intention to assess the accuracy of three intra-oral scanners. A master model made of stone was fitted with three high precision manufactured PEEK cylinders in the regions 36, 41, 46 and scanned with three intra-oral scanners (Lava Cos, iTero, CEREC). The digital files were imported in Geomagic software. Next, the distance between the centres of the cylinders and the angulation between the cylinders were assessed. These values were compared to the measurements made on a high accuracy 3D scan of the master model. The distance errors were the smallest and most consistent for the Lava COS. The distance errors for the CEREC were the largest and least consistent. Angulation errors were all small. The Lava COS in combination with a high
accuracy scanning protocol resulted in the smallest and most consistent errors of all three scanners tested when considering mean distance errors in full arch impressions, both in absolute values and in consistency for both measured distances. For the mean angulation errors, the Lava COS had the smallest errors between cylinders 1-2 (region 46 to 41) and the largest errors between cylinders 1-3 (region 36 to 46), although the absolute difference with the smallest mean value (iTero) was very small (0.0529°). An expected increase in distance and/or angular errors over the length of the arch due to an accumulation of registration errors of the patched 3D surfaces was observed, but the effects were statistically not significant. This study showed that for making impressions of implant cases for digital workflows, the most accurate scanner with the scanning protocol that will ensure the most accurate digital impression should be used. In our study model that was the Lava COS with the high accuracy scanning protocol.

In the study described in chapter 3, the possibilities of facial 3D scanner were assessed. Volume changes in facial morphology were assessed using the 3dMD DSP400 stereo-optical 3-dimensional scanner, which uses visible light and has a short scanning time. Twenty-four healthy volunteers with and without an artificial swelling of the cheek were scanned, twice in the morning and twice in the afternoon (in vivo measurements). A mannequin head was scanned 4 times with and without various externally applied artificial swellings (in vitro measurements). The changes in facial contour caused by the artificial swelling were measured as the change in volume of the cheek (with and without artificial swelling in place) using 3dMD Vultus® software. The in vivo and in vitro reliability expressed in intraclass correlations were 0.89 and 0.99, respectively. In vivo and in vitro repeatability coefficients were 5.9 and 1.3 ml, respectively. The 3dMD stereophotogrammetry scanner is a valid and reliable tool to measure volumetric changes in facial contour of more than 5.9 ml and for assessments of facial swelling.

In the study described in chapter 4 it was shown that current technology can help to cope with difficult treatment challenges in a predictable manner. 3D digital mapping technology was employed for predictable navigation of obliterated canal systems during root canal treatment to avoid iatrogenic damage of the root. With the aid of computer software, digital endodontic treatment planning for anterior teeth with severely obliterated root canal systems was accomplished, based on cone beam computed tomography (CBCT) scans and intra-oral scans of the dentition. On the basis of these scans, endodontic guides were fabricated for the planned treatment through digital designing and rapid prototyping.
The custom-made guides allowed for an uncomplicated and predictable canal location and management. The developed method of digital designing and rapid prototyping of endodontic guides allowed for reliable and predictable location of root canals of teeth with calcifically metamorphosed root canal systems.

In chapter 5 a systematic literature review is described of the current status of 3D technology in the prosthetic rehabilitation of maxillofacial defects (ear, nose, orbital). MEDLINE, COCHRANE and EMBASE databases were systematically searched for articles pertinent to the use of 3D technology in maxillofacial prosthodontics up to December 31, 2015. Eligible papers described the use of 3D technology in the workflow of maxillofacial prostheses. A total of 82 out of 1900 identified papers was considered eligible. Although 3D technology is increasingly used in maxillofacial prosthetics, almost all eligible papers were technical notes and case reports describing how certain steps in the traditional workflow of making maxillofacial prosthesis could be replaced by 3D technology. No clinical trials comparing different techniques are yet published neither papers assessing time efficiency or costs. Moreover, none of the included papers described a 100% 3D workflow due to lack of appropriate software and limited options for rapid prototyping, e.g., printing silicone prostheses with matching coloring and or details. It is assumed that in the near future techniques needed for 3D technology in facial prostheses will become easier to apply and cheaper with time as well as that a 100% 3D workflow for facial prostheses will become available as shown in the various chapters in this thesis. This assumption implicates that 3D technology in maxillofacial prosthodontics is evolving and will replace certain steps, if not all, in the traditional workflow of designing and fabricating facial prostheses. No full 3D workflow is yet available, however.

Applying technology to facilitate the placement of implants in challenging cases, like in the floor of the nose, is discussed in chapter 6. In dentate cases, the surgeon needs to avoid the tips of the roots of the teeth below the floor of the nose, while placing the implants in a prosthodontically preferred position in the floor of the nose. With the aid of 3ds Max software, digital planning of implants in the nasal floor based on CBCT data was performed in three patients. Surgical guides for implant placement were digitally designed and fabricated using rapid prototyping. In all three patients, implants could be placed and nasal prostheses could be manufactured as planned. All anterior teeth remained vital. Analysis of planning and post–implant placement CBCT scans revealed high accuracy of implant placement. Thus, the applied method allows for reliable implant placement in close proximity to the preoperatively planned implant position.
In chapter 7, technology to facilitate the placement of implants in challenging situations, like the mastoid region, was discussed. In this chapter a method is described that enables digital planning of extra-oral implants in the mastoid region utilizing commercially available 3ds Max software and rapid-prototyping techniques to manufacture a corresponding surgical guide. The appropriateness of the digitally designed surgical guides for placing extra-oral implants was tested on six human cadaver heads with simulated bilateral ear defects. With the aid of CAD software designed for reverse engineering and 3D animation, digital implant planning based on CBCT data was performed. On the basis of this planning, surgical guides were digitally designed and fabricated using rapid prototyping. After implant placement, a second CBCT scan was made to compare the preoperative planning with the actual postoperative implant positions. Twenty-four implants were placed in total. Comparison of the pre- and postoperative CBCT scans revealed that adequate accuracy of implant placement was achieved, both for deviation of the neck (1.56 ± 0.56 mm) and the tip (1.40 ± 0.53 mm) of the implant as well as for deviation of the angulation of the implant (0.97 ± 2.33°). The developed method for digitally planning of extra-oral implants in the mastoid area and designing surgical guides allows for placement of implants in the mastoid area in close proximity to the preoperatively planned implant position.

Apart from placement of dental implants in difficult clinical situations, other challenges exist. In chapter 8 computer-aided techniques that can be used in the reconstruction of defects in the skull are discussed. A novel technique for digital designing of an implant for cranioplasty using an easy-to-use piece of generic industrial software (Geomagic Studio) that uses a curvature-based, hole-filling algorithm was described. The advantage of this approach is that it is suitable for all kinds of defects, including those that extend across the midline of the skull. The workflow gives the user full control over the design, production and material used for the cranial implant. To show its applicability, a CBCT image was made of a patient with a cranial defect as well as of two cadaver heads. The resulting datasets were converted to a surface model. The defect was reconstructed using the curvature based reconstruction algorithm. The cranial implants were designed in software. The fit of the implants was assessed independently by two maxillofacial surgeons and by comparing the planned CAD file with CAD files of the original skull before the defect was created and the skull with the implant in place. The implants that were inserted according to the planning, showed excellent fit and adaptation to the skull. The developed digital workflow for designing custom-made cranial implants is an easy-to-use, fast method to insert well-fitting cranial implants if an autologous bone flap is not available or less appropriate.
In the study described in Chapter 9, 3D digital technology was applied to produce a multicomponent dental appliance without the need of a physical model of the dentition. The dentition of a volunteer was scanned with an intraoral scanner (Lava Chairside Oral scanner C.O.S., 3M). The resulting digital impression was used to design two multicomponent orthodontic appliances. On basis of this design, biocompatible acrylic baseplates were produced with the aid of a 3D printer. The metal springs and clasps were produced by a bending robot. The fit of both appliances in the mouth of the volunteer was assessed by two experienced orthodontists. The fit of both the orthodontic appliances was rated as excellent. Thus multicomponent dental appliances consisting of an acrylic baseplate and other parts, such as clasps, springs, or screws can be made with the aid of a digital workflow. When using this approach, there is no need for a physical model of the patient’s dentition.

In the general discussion (chapter 10) different aspects of digital workflows are discussed and placed in a broader perspective thereby attempting to go both broader and deeper into the implications of the introduction of 3D digital technology in dentistry. Complete 3D workflows are yet scarce and added costs for these workflows are still rather high. It is predicted that, related to the exponential increase in the hardware possibilities and the equally rapid decrease in costs, a disruptive change can be prognosticated in near future. Complementing technology will than take over many diagnostic and manual skills of the dental profession. As a result, the focus of the dental profession will shift by positioning the dentist as a monitor and supervisor of dental health while the dental technician will evolve into a planner and engineer for the actual dental treatment.