Three-dimensional virtual surgical planning in head and neck oncology surgery

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Summary

Nowadays head and neck oncology surgery relies on the use of three-dimensional virtual surgical planning (3D VSP), mainly when it concerns surgery on bony structures. 3D VSP is used to improve the treatment in terms of accuracy, predictability and safety. 3D VSP enables, among other things, very precise single-stage resection and reconstruction surgery. The general aim of this thesis is to develop and optimize the 3D VSP workflows used for resection and reconstruction surgery in head and neck oncology surgery.

In **Chapter 2 and 3** an overview is given of the latest developments of 3D VSP and computer-aided-design (CAD) for reconstruction of mandibular and maxillary defects. **Chapter 2** provides insight in the latest developments in 3D VSP and CAD for prosthetic rehabilitation of maxillary defects in head and neck cancer patients. 3D VSP allows for preoperative planning of resection margins and osteotomies, and recent advancements in multimodal imaging and personalized implant development using CAD have improved the translation of 3D VSP to surgery. Additionally, techniques like intraoperative imaging and augmented reality have enhanced the accuracy and precision of the procedure. With the use of 3D VSP and CAD, ablation surgery, reconstructive surgery and prosthetic rehabilitation can be planned preoperatively. Many reconstruction possibilities exist and the choice depends on patient characteristics, tumour location and experience of the surgeon. The ultimate goal of maxillary defect reconstruction is to restore facial form and oral function in accordance with the individual needs of the patient.

Chapter 3 describes the current methods for 3D virtual surgical planning and guided surgery techniques in cases where mandibular bone resection is required as part of the treatment for oral squamous cell carcinomas. Recent advancements in 3D VSP methods have enabled multi-modality fusion of images, which is not limited to a specific software package or workflow. New strategies such as finite element analysis, deep learning, and advanced augmented reality techniques have been developed to improve the accuracy, predictability, and safety of the treatment. The implementation of these novel technologies and strategies is expected to enhance the accuracy and safety of mandibular resection and reconstruction planning. The use of three-dimensional VSP can be applied for every patient with malignancies requiring resection of the mandible, providing an accurate, easy-to-use, safe, and efficient planning tool.

Pre-operative margin planning for the segmental resection of affected bone in mandibular osteoradionecrosis (ORN) is difficult. In **Chapter 4** a possible relation between received radiotherapy dose, exposed bone volume and the progression of ORN after segmental mandibular resection is studied. It is hypothesized that 3D visualisation may aid in determining the location of the resection planes, especially when immediate bone reconstruction is considered. The study included patients diagnosed with grade 3-4 ORN who underwent segmental resection. Postoperative imaging was fused with three-dimensional reconstructions of RT isodose volumes. The primary outcome was recurrence of ORN after segmental resection. Subsequently the RT-exposed mandibular bone volumes were calculated and the location of the bone cuts relative to the isodose volumes were assessed. Out of thirty-three patients, five developed recurrent ORN after segmental mandibular resection. All patients with recurrent ORN were resected inside an isodose volume of ≥ 56Gy. The absolute mandibular volume radiated with 56Gy was significantly smaller in the recurrent group (10.9 mL vs. 30.7 mL, $p = 0.006$), as was the proportion of the mandible radiated with 56Gy (23% vs. 45%, $p = 0.013$). The volume of radiated bone did not predict the risk of progression. The finding that recurrent ORN occurred with bone resection margins within the 56Gy isodose volume suggests that this could serve as a starting point for pre-operative planning to reduce the risk of ORN recurrence.

Zygomatic implants can help patients with maxillary defects by improving the retention and stability of obturator prostheses, leading to better oral function. However, achieving accurate prosthetic-driven placement of these implants can be difficult, and free-hand approaches can result in deviations from the preplanned implant positions, making immediate implant-retained obturation challenging. In **Chapter 5** a complete 3D workflow for immediate implant retained prosthetic rehabilitation following maxillectomy is introduced. The workflow consists of a 3D VSP for tumour resection, zygomatic implant placement, and an implant-retained prosthetic-obturator. It is hypothesized that when specially designed guides are used, implants can be placed with such precision that they are suitable for immediate loading of the prosthetic-obturator. To test the feasibility of the workflow, 3D virtual surgical planning was performed on five fresh frozen human cadavers for the resection of the maxilla and guided placement of ten zygomatic implants using custom cutting and drill/placement-guides. A preoperatively designed and printed obturator prosthesis was placed and connected to the zygomatic implants. Accuracy of implant positioning was assessed by merging pre- and post-operative CT scans and conducting 3D deviation analysis. Results showed that the preoperatively designed obturator prostheses matched the per-operative implant positions accurately, allowing for immediate loading. The mean prosthetic point deviation on the cadavers was 1.03 ± 0.85 mm; the mean entry point deviation was 1.20 ± 0.62 mm; and the 3D angle deviation was 2.97 ± 1.44°. **Chapter 5** demonstrates the feasibility of 3D virtual surgical planning for accurate execution of ablative surgery, zygomatic implant placement, and immediate implant-retained obturator prosthesis placement. The next step is to apply this workflow in the operating room for patients undergoing maxillectomy.

In **Chapter 6** the surgical workflow of guided placement of zygomatic implants introduced in chapter 5 is evaluated. Zygomatic implants have been placed in 10 patients using 3D printed drill guides after maxillectomy was performed. The study aimed to assess the accuracy of implant positioning and prosthetic fit of the obturator prosthesis in this one-stage procedure. The results showed that the zygomatic implants (n = 28) were placed with good accuracy (mean deviation of 1.73 ± 0.57 mm and 2.97 ± 1.38° 3D angle deviation). The accuracy of the abutment positions was 1.58 ± 1.66 mm, with the accuracy of the abutment position in the occlusal plane being 2.21 ± 1.33 mm and an accuracy of 1.32 ± 1.57 mm in implant height. Additionally, in all cases the obturator prosthesis fitted as pre-operatively planned. This feasibility study shows that this novel application of 3D-printed surgical guides results in predictable zygomatic implant placement and provides the possibility of immediate prosthetic rehabilitation in head and neck oncology patients after maxillectomy.

The current practice in oral and maxillofacial surgery involves virtual surgical planning using CT and MRI scans to predict the outcome of complex procedures. The translation of the virtual surgical plan to the operating room involves the use of 3D-printed guides or real-time navigation systems. The study in **chapter 7** aims to improve the accuracy and speed of this translation process using an augmented reality visualization technique for image-guided surgery. Surgeons can interact with the virtual surgical plan and navigation data in real-time while in the operating room. A user study was conducted to compare the augmented reality technique to the gold standard perioperative navigation system (Brainlab) in terms of user-friendliness, usability, and accuracy of typical navigation tasks. The results showed that the completion time of navigation tasks was 1.71 times faster using augmented reality (P = .034), and accuracy improved significantly (P < .001). The proposed workflow can be used as an addition to existing verified image guidance systems in a wide range of image-guided surgery procedures. The user study demonstrated that our technique enables typical navigation tasks to be performed faster and more accurately compared to the current gold standard, and qualitative feedback was more positive compared to the standard setup. Despite participants' relative unfamiliarity with VR/AR and gesture-based interaction, they reported that navigation tasks become easier to perform using augmented reality.

In **chapter 6** zygomatic implants are used to enhance the retention and stability of obturator prostheses in patients with maxillary defects after maxillectomy. Placement of zygomatic implants in the optimal prosthetic position can be challenging due to various factors such as limited bone mass of the zygoma, limited visibility, length of the drill path, and proximity to anatomical structures such as the orbital cavity. To address this issue, in a study was conducted on human cadavers using an augmented reality (AR) navigation approach for zygomatic implant placement after total maxillectomy (**Chapter 8**). This approach aims to eliminate some of the challenges of using surgical guides and conventional surgical navigation, while potentially improving accuracy. In this study, an AR navigation interface with a connection between a commercially available navigation system and the Microsoft HoloLens was used. AR navigated surgery was performed to place 20 zygomatic implants in 5 human cadaver skulls after total maxillectomy. The implant positions on Post-operative CT scans were then compared with the preoperative 3D VSP to assess accuracy by calculating distances in mm of entry-exit points and angle deviation as outcome measures. Results were compared with the accuracy of 3D printed surgical guides as presented in **chapter 5** of this thesis.

The study found that the mean entry point deviation was 2.43 mm ± 1.33 mm, the 3D angle deviation was 5.80° ± 4.12° (range 1.39° - 19.16°), and the mean exit point deviation was 3.28 mm (± 2.17 mm). The abutment height deviation was on average 2.20 mm ± 1.35 mm, and the accuracy of the abutment in the occlusal plane was 4.13 mm ± 2.53 mm. While surgical guides performed significantly better for the entry-point (P = 0.012) and 3D angle (P = 0.05), there was no significant difference in accuracy for the exit-point (P = 0.143) when using 3D printed drill guides or AR navigated surgery. This study shows a novel AR dynamic navigation system for placement of zygomatic implants. Despite the fact that guides lead to a more accurate placement compared to AR navigation, the accuracy of AR navigation is acceptable as well and authors are convinced that it will continue to improve and that future research will identify specific applications where AR navigation is beneficial.

In the general discussion (**Chapter 9**) the results of the studies described in **Chapters 2-8** were discussed in a broader perspective and some perspectives for future studies are given.