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3

Three dimensional virtual surgical planning in the oncologic treatment of the mandible

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Abstract

Objectives: In case of surgical removal of oral squamous cell carcinomas, a resection of mandibular bone is frequently part of the treatment. Nowadays, such resections frequently include the application of 3D virtual surgical planning (VSP) and guided surgery techniques. In this paper, current methods for 3D VSP leads for optimisation of the workflow, and patient-specific application of guides and implants are reviewed. Recent findings: Current methods for 3D VSP enable multi-modality fusion of images. This fusion of images is not restricted to a specific software package or workflow. New strategies for 3D VSP in Oral and Maxillofacial Surgery include finite element analysis, deep learning and advanced augmented reality techniques. These strategies aim to improve the treatment in terms of accuracy, predictability and safety.

Conclusions: Application of the discussed novel technologies and strategies will improve the accuracy and safety of mandibular resection and reconstruction planning. Accurate, easy-to-use, safe and efficient three-dimensional VSP can be applied for every patient with malignancies needing resection of the mandible.

Keywords: CAD/CAM, data fusion, head and neck cancer, mandible, optimisation, virtual surgical planning

Introduction

In case of surgical removal of oral squamous cell carcinomas, a resection of mandibular bone is often part of the treatment. A resection of the mandible with a microscopic free margin of at least 5 mm on both ends of the resected specimen is required according to current clinical guidelines (Dutch online guideline database, 2015). The oncological–surgical challenge is to plan and perform an adequate resection with sufficient margins, based on preoperative clinical and imaging information.

Nowadays, mandibular malignancy resections frequently include the application of 3D virtual surgical planning (VSP) and guided surgery techniques. Currently, VSP is mostly based on computed tomography (CT) data. Both intra-operative navigation and 3D printed surgical guides have been shown to provide an accurate translation of the 3D VSP to the surgical procedure (Bittermann et al., 2013; Schepers et al., 2016; Wilde et al., 2015; Yu et al., 2013).

For reconstruction of the mandible after a continuity resection and with extra-intraoral communicating wounds, a free vascularised fibular flap is reported as the gold standard (Cordeiro, Disa, Hidalgo, & Hu, 1999). Several studies have reported an accurate and safe workflow for 3D VSP-based fibula reconstruction of mandibular defects, occasionally in combination with a patient-specific reconstruction plate (Essig et al., 2011; Roser et al., 2010; Schepers et al., 2015; Weijs et al., 2016; Weitz, Wolff, Kesting, & Nobis, 2018; Yang et al., 2019; Zhang et al., 2016). This paper critically reviews current methods for 3D VSP, leads for optimisation of the 3D VSP workflow and patient-specific application of guides and implants.

Optimisation of virtual planning – CT and MRI fusion

The aim of a bony resection of the mandible is to radically remove the tumour from the mandible or realise sufficient margin in relation to the soft tissue tumour. In general, three methods for image- based planning of such tumour removal are described. The first of which is a basic screen-to-screen interpretation of the extend of the tumour as the surgeon studies both the CT and magnetic resonance imaging (MRI), and occasionally PET scan results before the surgical procedure (Kraeima et al., 2015). Secondly, when, additionally a 3D VSP method is applied, the extend of the tumour can be included in the preoperative plan. This inclusion is usually performed by means of digital delineation on CT data (Schepers et al., 2016; Wilde et al., 2015). In this 3D VSP process, it is not always clear where to virtually plan the resection margins of the mandible. When the surgical margins are not well included in the preoperative plan, an intra-operative exploration or deviation from the 3D VSP may be needed. In addition, intra-operative deviation from planning can result in an inability to use the prepared patient specific guides and reconstruction plate, which leads to suboptimal reconstructions (Ramella et al., 2017). Thus, planning for adequate tumour removal should include detailed bone information as well as tumour characteristics such as localisation, size, shape and extension (Dai et al., 2012). In this respect, as the third alternative, it is a great progress when this information is extracted from multi-modality imaging: CT and MRI together (Dong, Dong, Hu, & Xu, 2011).

It is reported that a fusion of CT and MRI 2D slices combines the sensitivities of both modalities. This fusion provides the surgeon with more accurate information regarding the tumour in relation to the surrounding structures (Abd El-Hafez et al., 2011; Blatt, Ziebart, Krüger, & Pabst, 2016; Dai et al., 2012; Farrow et al., 2016; Nemec et al., 2007). The combination of information with regard to localisation, extent, size and shape of the tumour, as provided by CTs and MRIs, is crucial for adequate resection planning (Blatt et al., 2016; Dai et al., 2012; Rana et al., 2012, 2015). Application of this combined CT and MRI workflow has been shown to result in an accurate resection of mandibular tumours with tumour-free bone margins and no per-operative deviation from planning (Kraeima, Dorgelo, et al., 2018; Kraeima, Glas, Witjes, & Schepman, 2018; Kraeima, Glas, Steenbakkers, Spijkervet, Roodenburg, & Witjes, 2018). Figure 1 provides a schematic overview of this method, including the postoperative evaluation. An alternative strategy, the "triple-cut" method, was introduced by Ramella et al., 2017 (Ramella et al., 2017). In this strategy, multiple virtual scenarios for resection and reconstruction are combined in a single set of 3D printed guides. In this study, the bone margin status after resection was not reported, so this outcome cannot be compared with the study by Kraeima et al (Kraeima, Dorgelo, et al., 2018; Kraeima, Glas, et al., 2018; Kraeima, Steenbakkers, et al., 2018).

One could argue that tumour-free bone resections of the mandible with the afore mentioned methods could reflect an overestimation of the required and performed resection. It has been reported for breast cancer that MRI estimates tumour size more accurately compared to CT only, but overestimates the size (Pop et al., 2018). For oral head and neck cancer, it was reported that MRI decreases underestimation of the tumour in comparison with CT (Sarrión Pérez, Bagán, Jiménez, Margaix, & Marzal, 2015). Especially when the MRI shows marrow oedema or suspects peri-neural extension, the exact tumour border delineation is challenging, however still the best preoperative indicator in the 3D VSP workflow (Kolk et al., 2014; Van Cann et al., 2008). Histopathological confirmation of the exact tumour extension in suspected areas of bone is in need of the bony specimen to postoperatively be cut into thin lamellae. These lamellae should be superimposed on to the 3D virtual model of the 3D resection planning including the tumour and the bone. This superimpositioning is still under development and not part of current routine, no reports were found with regard to such analysis.

The described 3D VSP workflow requires the availability of hard- and software as well as corresponding technical expertise. This is facilitated by a technical physician as part of the multidisciplinary team. It can be seen as a disadvantage that this expertise and additional hard- and software are not yet widely available in every hospital.

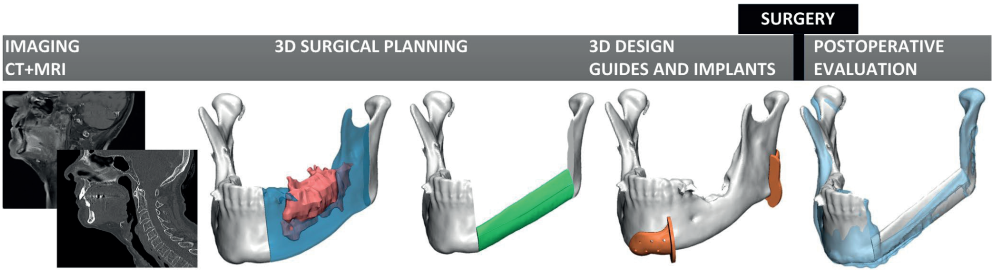

Figure 1 Overview of the workflow for 3D VSP in mandibular resection surgery. First the CT and MRI data is fused in order to combine bone and tumour information. After delineation of the tumour the resection is planned, as presented in blue in the second image. The mandible is reconstructed by planning a free vascularised fibular flap (green). In order to translate the procedure towards the actual surgery, patient specific cutting guides (orange) are designed and fabricated. After completion of the surgical procedure again a (CB) CT scan is made for detailed 3D evaluation, as presented in the last image

Radiation dose visualisation in case of ORN

The use of multi-modality image fusion in 3D-VSP is not only applicable for mandibular resection planning, but also for surgical treatment of osteoradionecrosis (ORN). When a patient develops severe ORN (Marx, 1983; Rice, Polyzois, Ekanayake, Omer, & Stassen, 2015; Spijkervet, Brennan, Peterson, Witjes, & Vissink, 2019), a surgical intervention may be indicated, including removal of affected bone. ORN is defined as bone death following radiotherapy (RT) and is characterised by a non-healing area of exposed bone (Lambade, Lambade, & Goel, 2013; Marx & Johnson, 1987). There is a reported pathophysiological relationship between the occurrence of ORN in the jaw and the cumulative radiation dose to the bone as the radiation dose is reported to be a risk factor for the development of ORN. The risk of developing ORN of mandibular bone is considered to be medium when the bone was exposed to a cumulative dose of 40-60Gy and high when the bone was exposed to a cumulative dose >60Gy (Costa et al., 2016; Lyons & Ghazali, 2008; Reuther, Schuster, Mende, & Kübler, 2003; Wong, Wood, & McLean, 1997). When the original radiation dose is added as a visual volume into 3D-VSP, this information can support the decision with regard to resection planning (Kraeima, Dorgelo, et al., 2018; Kraeima, Glas, et al., 2018; Kraeima, Steenbakkers, et al., 2018). Yet, there is no consensus in literature with regard to the exact cut-off for received radiation dose in case of planning a mandibular resection (Marx, 1983; Rice et al., 2015).

Optimisation of image processing - deep learning

Each of the aforementioned 3D VSP applications require a segmented model of the anatomical structures and occurred pathology, of which the 3D models in Figure 1 are an example. In other words, a conversion step in which 2D slices of DICOM data (e.g., CT data) are segmented into a 3D virtual model. This segmentation can be time-consuming and user-dependent. Improvement of the 3D virtual model is achieved by optimisation of segmentation techniques (Minnema et al., 2018; Qiu et al., 2019). The use of a Deep learning image processing strategy could reduce the time and user dependency. Deep learning is a method of machine learning that enables a computer program to learn in a progressive way from its own experience, in order to continuously improve its ability to perform the (3D segmentation) task (Kwang Gi Kim, 2016). Artificial neural networks, which are a type of deep learning architecture, are computing systems that can learn and progressively improve their ability to learn (Schmidhuber, 2015). When applying artificial neural networks to segmentation of anatomical structures in medical image data (e.g., CT or MRI), the segmentation workflow is optimised by automation, decrease of the inter-observer variability and improvement of the accuracy (Neslisah Torosdagli et al., 2017; Zhou, Takayama, Wang, Hara, & Fujita, 2017). As is reported by Minnema et al. (Minnema et al., 2018, 2019), this method is applicable to both CT and ConeBeam CT (CBCT) data sets. Potentially, neural network application would enable accurate and fast segmentation of the required anatomical structures from each modality that the neural network is trained to process (Qiu et al., 2019). Currently, the application in daily practice is depending on the hospitals own engineering facilities and not implemented in widely available commercial software packages. It is expected that within a few years these functionalities are validated and implemented in easy-accessible 3D VSP software applications. This will lead to time saving, less user-dependent 3D VSP workflows.

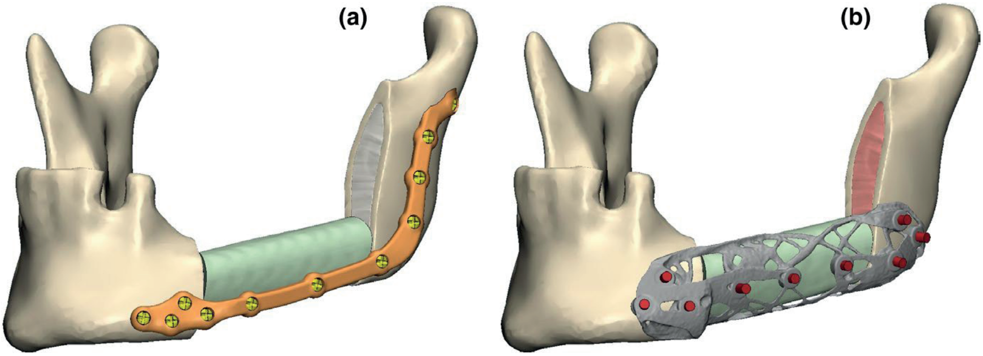

Figure 2 (a) An example of a 'conventional' patient specific reconstruction plate, fixating a fibula flap and the remaining segments of the mandible after resection. (b) A minimalistic, topology optimised design of a patient specific reconstruction plate based on finite element analysis. The input requirements in the analysis relate to bone characteristics (e.g., spongeous bone in red, cortical bone in yellow), location of the screws and expected load.

Optimisation of the 3D implant design—finite element analysis

Once a 3D-VSP is completed and approved by the surgeon, the VSP can be translated towards the patient using patient-specific surgical cutting and drilling guides and osteosynthesis materials, of which examples are presented in Figures 1 and 2a. The shape and fitting of these patient specific attributes is usually tailored to the contour of the bone of the individual case. In addition, the screw location and trajectories are planned, based on the thickness of the (cortical) bone and allowed surgical access. Tailoring of these products is performed in a 3D VSP design software application, based on experiences of the involved surgeons and engineers and starting from conventional off-shelf plate designs. This design process usually lacks a systematic application of biomechanical analysis on an individual patient basis. It is reported that these osteosyntheses can be subject to failure in terms of plate fracture or screw loosening, due to inadequate design adaptations of inhomogeneous loads (van Gemert et al., 2012; Kimura et al., 2006).

The application of biomechanical models to design osteosynthesis materials and implants, using the finite element (FE) method, was reported as a potential solution for failure of the materials (Deshmukh, Kuthe, Chaware, Bagaria, & Ingole, 2012; Kimura et al., 2006; Rodrigues et al., 2018). Finite element models, however, are not uniform and have a variation in required input factors such as constraints, load, mechanical properties of the bone, muscle forces and vectors. The application of a FE model can predict the behaviour, such as load distribution, stress or failure, of, for example osteosynthesis plates or implants. In search of further optimisation of the design of 3D VSP-based osteosynthesis and implants, the output of a FE model should be incorporated in the design process and function as input to a topology optimisation study. Topology optimisation is a mathematical method that, given certain boundary conditions, can optimise the design or layout of an object that match the input requirements. Application of topology optimisation has to be explored in future studies, using a FE model, applied to the design of osteosynthesis and implants and optimal locations for screws in oral and maxillofacial surgery. Figure 2 presents an example of a topology optimised design of a reconstruction plate in the mandible. Not only will this topology optimisation enable the evaluation of different designs, also the use of different materials with different characteristics (e.g., wear rate or stiffness) can be evaluated and adequate load transfer via the implants can be assured based on the FE analysis (Sutradhar, Park, Carrau, & Miller, 2014; Sutradhar et al., 2016).

Optimisation of 3D VSP translation during surgery — augmented reality

Once the 3D-VSP is completed and the implant and surgical guides have been designed and produced, the plan must be translated to the actual surgical procedure. This translation is commonly performed with 3D printed surgical guides, which is time consuming. The use of intra-operative navigation can be used as an alternative to 3D printed guides for translating the 3D VSP into a surgical procedure (Nemec et al., 2007; Yu et al., 2013, 2016; Zinser et al., 2013). Using intra-operative navigation has some drawbacks, however, mainly that the surgeon has to look away from the surgical field to receive feedback from the system (Berger et al., 2017) and the absence of haptic feedback to be received by the surgeon during the cutting or drilling. In case 3D information can be projected onto the surgical field, with good stability and accuracy, such an approach will probably optimise the translation from 3D VSP to the actual surgical procedure. The use of augmented reality via head mounted devices has been reported as a potential technique for translating 3D VSP to the actual surgical procedure (Bosc, Fitoussi, Hersant, Dao, & Meningaud, 2018). The first reports of augmented reality-supported navigation have shown that both speed and accuracy of performing the navigational tasks were significantly improved (Ahn, Choi, Hong, & Hong, 2019; Meulstee et al., 2018).

Analysis of postoperative accuracy

A widely reported advantage of using 3D VSP is improvement in accuracy of the mandibular resection and reconstruction. As described, several methods for further optimisation of the 3D VSP workflow are in place or development, mainly to improve the speed and accuracy. To objectify this (improved), accuracy multiple methods are in use. Usually, a postoperative CT or CBCT is made which is aligned with the preoperative 3D VSP (Baan et al., 2016; van Baar, Liberton, Forouzanfar, Winters, & Leusink, 2019; van Eijnatten et al., 2018; Kraeima, Dorgelo, et al., 2018; Kraeima, Glas, et al., 2018; Kraeima, Steenbakkers, et al., 2018; Schepers et al., 2015). As reported by van Baar et al. (van Baar et al., 2019), heterogeneity in evaluation methods limits comparison of postoperative outcomes between studies. Furthermore, the aim for postoperative evaluation differs between studies. For example, outcome measures of evaluation can be the accuracy of the performed resection with regard to oncologic safety, the accuracy of the reconstruction in relation to a fibula graft or osteosynthesis materials, and the postoperative position of the inserted implants with respect to dental rehabilitation. It is important to define the primary outcome measure before defining a method for postoperative evaluation. Although it is not within the scope of this review to provide a guideline for measurement of postoperative accuracy for the different outcome measures, it is important to mention that pre- and postoperative CT or CBCT data are obtained conform a scanning protocol. Subsequently, validated software should be used for the image processing and alignment of the planning with the postoperative result. The definition of accuracy should be defined using anatomical landmarks or regions of interest that are easily recognisable and reproducible for clinicians. In addition, inter-observer variability is advised to be included in the analysis in order to present the user independency of the chosen method. Finally, development of improved software applications (Baan et al., 2016) is expected to reduce the manual steps in current methods for 3D VSP and postoperative analysis, leading to improved objective and reproducible data describing the accuracy.

Conclusion

Current methods for 3D VSP enable multi-modality image fusion and are not restricted to a specific software package or workflow. Image fusion will improve the accuracy and safety in case of mandibular resection and reconstruction planning. New strategies for 3D VSP in oral and maxillofacial surgery include using finite element analysis, deep learning and advanced augmented reality techniques. When applying such strategies, treatment will be improved in terms of accuracy, predictability and safety. The ultimate outcome will be that 3D VSP is applied for every patient in an optimised tailored way.

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