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REVIEW

Periodontal surgery in furcation-involved maxillary molars revisited—an introduction of guidelines for comprehensive treatment

Clemens Walter · Roland Weiger · Nicola Ursula Zitzmann

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Abstract Maxillary molars with interradicular loss of periodontal tissue have an increased risk of additional attachment loss with an impaired long-term prognosis. Since accurate clinical analysis of furcation involvement is not feasible due to limited access, morphological variations and measurement errors, additional diagnostics, e.g., with cone-beam computed tomography, may be required. Surgical treatment options have graduated from a less invasive approach, i.e., keeping as much periodontal attachment as possible, to a more invasive approach: (1) open flap debridement with/without gingivectomy or apically repositioned flap and/or tunnelling; (2) root separation; (3) amputation/trisection of a root (with/without root separation or tunnel preparation); (4) amputation/trisection of two roots; and (5) extraction of the entire tooth. Tunnelling is indicated when the degree of root separation allows for opening of the interradicular region. Alternatively, root separation is performed particularly in root-canal treated teeth with reduced coronal tooth substance requiring crown restorations. As soon as the attachment of one or two roots in maxillary molars is severely reduced, root removal is indicated and performed either as amputation or trisection including the corresponding part of the clinical crown. While the indication for regenerative measures in maxillary molars with furcation involvement is very limited, extraction and replacement with implants is restricted, particularly in sites requiring complex alveolar ridge augmentation and sinus elevation. A systematic approach for decision making in furcation-involved maxillary molars is described in this overview, including what constitutes accurate diagnosis and what indications there are for the different surgical periodontal treatment options.

Keywords Furcation involvement · Furcation surgery · Diagnosis · Decision making · 3D imaging

Abbreviations and acronyms

FI	Furcation involvement
PPD	Probing pocket depth
PAL	Probing attachment level
Sc&Rp	Scaling and root planning
RCT	Root canal treatment
SPT	Supportive periodontal treatment
FDP	Fixed dental prosthesis
RDP	Removable dental prosthesis
CBCT	Cone-beam computed tomography
GTR	Guided tissue regeneration
EMD	Enamel matrix derivative proteins
BoP	Bleeding on probing

Introduction

Are maxillary molars with loss of periodontal tissue in the furcation area hopeless teeth per se, making extraction inevitable as an immediate or delayed consequence [1–3]? Treatment of the periodontally involved maxillary molars presents a set of challenges unique to the posterior dentition, given the presence of furcations, root proximities, and the maxillary sinus [4]. Additional problematic anatomical features exist in molar teeth such as enamel projections, concavities of the root, development grooves on root trunks, interradicular ridges, and the fact that the furcation entrance is smaller than most conventionally used

C. Walter · R. Weiger · N. U. Zitzmann (✉)
Department of Periodontology, Endodontology and Cariology, University of Basel,
Hebelstrasse 3,
4056 Basel, Switzerland
e-mail: n.zitzmann@unibas.ch

scaling instruments [5, 6]. Consequently, a basis for the clinical management of furcation-involved teeth is eliminating any plaque-retentive morphology in order to provide access for plaque removal for the patient and for professional maintenance. Various treatment options that aim to retain teeth in the molar region, including regenerative or resective surgical procedures, have been introduced in recent decades. Professional interest in these measures has decreased this century due to complications and failures and to a recent preference for the implant alternative. The reported high prevalence of peri-implant diseases [7] and recent advances in periodontal diagnostics, including three-dimensional imaging, may lead to renewed interest in traditional periodontal surgery.

It is the aim of this overview to describe a systematic approach to making decisions about furcation-involved maxillary molars, including accurate diagnosis and indications for the different surgical periodontal treatment options.

Materials and methods

A MEDLINE search (PubMed) until September 2009 (30th) was conducted using the keywords “furcation defects” and “decision making” or “treatment planning”. Any relevant work published in the English language and presenting pertinent information about the described issue was considered for inclusion in the review. The combinations of the search terms resulted in a list of 53 titles (18 plus 41, of which 6 were listed twice). Abstracts were first screened to identify possibly relevant publications. Full text analysis was performed on 26 of these, out of which 10 were finally included in the review. Other manual searches included examining the bibliographies of the retrieved publications and of other previous reviews, thereby including 40 additional references. Articles were excluded if they were not in English, if they related only to dental implants or mandibular molars, or if they were case reports. In addition to this structured review process, a narrative approach was conducted on the relevant aspects related to furcation diagnosis and treatment outcome. The literature implemented in this part of the review was thoroughly discussed among the authors until a consensus was achieved.

Prevalence of furcation involvement in maxillary molars, prognosis, and risk factors

A study of patients with periodontal disease of varying severity revealed that about 50% of maxillary molars had at least one furcation site with deep involvement [8]. In patients diagnosed for generalized advanced periodontitis, the prevalence of furcation-involved maxillary molars was as high as 90% [9]. In a retrospective study of patients with chronic or aggressive periodontal disease, maxillary molars were more frequently diagnosed with furcation lesions than mandibular molars (72% versus 50%) [10].

Maxillary molars with interradicular loss of periodontal tissue have an increased risk of additional attachment loss with an impaired long-term prognosis. Among periodontally compromised teeth, maxillary molars are the teeth most likely to be lost [1, 11].

Multiple factors influence the prognosis of furcation-involved teeth, including: (1) tooth-related factors such as furcation involvement (FI) degree III and bone loss at the initiation of periodontal therapy; (2) factors related to the dentition such as the number of molars left [10]; and (3) patient-related factors such as difficulties with daily oral hygiene measures or smoking habits [10, 12]; and (4) the applied treatment modality [1]. Kalkwarf et al. [13] tested several different non-surgical and surgical therapies in molars with furcation involvement. Irrespective of the treatment option applied, a further deterioration was observed in furcation sites of maxillary molars during the 2-year follow-up period. However, molars treated with osseous resectional surgery including alterations of the tooth morphology did not, unlike more conventional treatments, exhibit such extensive periodontal breakdown that extraction was required.

Diagnosis of FI in maxillary molars

Accurate diagnosis of the FI is essential for adequate decision making and treatment planning, particularly when resective measures are deemed necessary. FI diagnosis includes the estimation of the degree of horizontal and vertical furcation involvement, the assessment of the residual inter- and periradicular bone, and the evaluation of the root morphology with the root trunk length and the degree of root separation. Without this information, periodontal surgery may reveal unexpected findings, which may mean that the treatment plan will have to be subsequently intraoperatively altered. Diagnosis is generally based on clinical and two-dimensional radiographic measures and includes probing pocket depth (PPD) with bleeding on probing (BoP), probing attachment level (PAL), probing the furcation entrance and periapical radiographs [13].

FI is clinically measured at three sites (buccal, mesiopalatal, and distopalatal) of maxillary molars using a curved scaled probe, e.g., Nabers (PQ2N, HU-Friedy), which is marked at 2 or 3 mm intervals [14, 15]. The mesial furcation is more easily probed from the palatal aspect due to the larger buccolingual width of the mesiobuccal root. The distal FI is usually located in the middle of the distal tooth surface and is probed either from the buccal or the palatal [16]. Most classifications used to describe the severity of FI are related to the amount of horizontal attachment loss. A useful modification has been recently introduced [17], based on Hamp et al. [14], with a sub-classification of FI degree II. The additional FI II–III allows for a discrimination of horizontal loss of periodontal tissue exceeding 6 mm without a detectable "through and through" destruction.

Degree 0: furcation not accessible with a periodontal probe
Degree I: horizontal loss of periodontal tissue support up to 3 mm
Degree II: horizontal loss of support exceeding 3 mm, but no more than 6 mm
Degree II–III: horizontal loss of support exceeding 6 mm, but no detectable "through and through" destruction
Degree III: horizontal "through and through" destruction of the periodontal tissue in the furcation

A calculation of the FI degrees at two opposing furcation entrances of a maxillary molar may be helpful in estimating the "true" degree of FI (personal communications reviewer 3). Since a maxillary molar has, in most instances, a width smaller than 12 mm at the furcation fornix, two opposite FI degree II–III meet within the furcation below the crown, and the FI degree is most likely a true degree III. In many instances, however, an accurate clinical analysis of furcation involvement is not feasible due to limited access, morphological variations, and/or measurement errors. Controversy exists in the literature about the accuracy of estimating the furcation involvement of maxillary molar teeth from clinical measurements. While Eickolz [18] and Eickholz and Kim [19] reported only small differences between clinical and intrasurgical assessments of furcation degrees using a Nabers probe, Mealey et al. [20] documented a clear underestimation of the clinical vertical and horizontal furcation depth measurements. Bone sounding after administration of anesthesia, however, improved the diagnostic accuracy of furcation invasions relative to surgical determinations [20]. Using intrasurgical horizontal probing and silicone impressions, Zappa et al. [21] found that 27% of true degree III furcations had been clinically underestimated, while overestimation was found in 18–21% of the degree I and 21% of the degree II furcations. The differences between the clinical and surgical assessments were up to 9 mm, which indicates that the clinical measures are of limited value [21].

Diagnosing furcation involvement from radiographs entail the problem that radiographically, only mineralized bone structure and its density is depicted, and radiographic translucency can also result from low bone density. Clinical FI measurements, however, also assess attachment and do not necessarily produce "false negative" results when horizontal probing resists in the connective tissue. When assessing periapical radiographs in maxillary molars, a small triangular radiographic translucency across the mesial or distal roots of these teeth, the so-called "furcation arrow", may indicate a more advanced furcation involvement [22]. Although the association of the furcation arrow with degree II or III FI was significant compared with uninvolved furcations, this image was not seen in approximately half of these sites with degree II or III FI [23]. Thus, it appears that radiographs alone do not detect FI with any predictable accuracy and that probing the furcation areas is necessary to confirm the presence and severity of FI [16].

Comparing the sensitivity of diagnoses based on either clinical examination or radiographic evaluations (conventional periapical radiographs) showed that FI was detected more frequently by conventional periapical radiographs than by clinical examination [9]. While in 65% of FI teeth, the clinical and radiographic findings about the degree of furcation involvement were similar, 22% were found by radiographic examination only, and in 3% of cases, furcation involvement was detected by clinical examination alone [9]. In contrast to these findings, Topoll et al. [24] demonstrated that the clinical identification and classification of furcation involvements was more precise than panoramic or periapical radiographs when compared to the intrasurgical measurements. These limitations of diagnosing FI from two-dimensional radiographic images has been ascribed to variations in the shape of the roots, superimposition of the palatal root, thickness of the alveolar bone, and other morphological variables [22, 25].

FI diagnosis with three-dimensional tomography

Limited information about the molars' periodontal tissue support and about the interradicular bone from clinical investigations and two-dimensional radiographs may lead to inappropriate treatment decisions, e.g., about which root or roots should be removed. Intrasurgical alteration of the treatment plan after surgical visualization of the furcations is an unpleasant consequence of this insufficiency. Three-dimensional diagnostic approaches with high-resolution computed tomography have been used in periodontology for more than 10 years, and it has been demonstrated that CT-based identification and classifications of FI are equivalent to the macroscopic evaluation [26]. The drawback of this CT technique is the high exposure to radiation of high-risk organs in the skull, such as eye lens and thyroid gland, as well as the technical difficulties and costs involved. More recently, a good imaging quality has been obtained with dental cone-beam computed tomography (CBCT), which requires markedly less radiation exposure than conventional CT devices [27, 28]. When periapical radiographs, panoramics, CT and CBCT measurements of furcation defects were compared with their corresponding histologic specimens, it was found that intraoral radiography was limited by visibility in the buccolingual direction, while image quality (contrast, brightness, distortion, clarity of bone structures, and focus) was superior using CBCT [29]. In addition, CBCT appears to be better for assessing furcation involvements and crater defects, while periapical radiographs scored higher for contrast, bone quality, and delineation of the lamina dura [30]. Data available from in-vitro studies revealed a good accuracy of cone-beam CT concerning linear and volumetric measurements of osseous defects [31, 32].

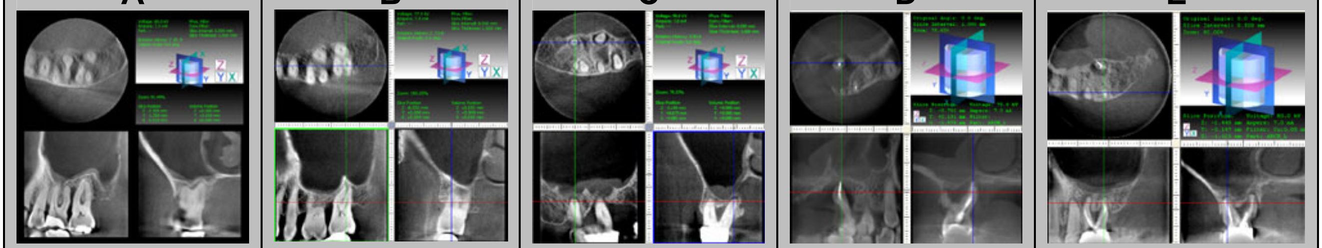
The potential of CBCT has been evaluated clinically for decision making in the periodontal treatment of furcation-involved maxillary molars [17]. The estimated degree of FI based on clinical measurements and periapical radiographs was confirmed in the CBCT in 27% of the sites, while 29% were overestimated and 44% revealed a clinical underestimation, according to the CBCT analyses. Almost two thirds of the clinical degree II furcations and the majority of the sites with clinical degree II–III were indeed degree III furcations. Obviously, all clinically assessed degree III furcations were verified in the CBCT as a through-and-through lesion. The CBCT analyses indicated that several additional radiographic findings related to morphological variations and pathologic observations are also relevant for the decision-making process (Fig. 1). In a recent study, it was demonstrated that estimates from a three-dimensional cone-beam computed tomography of the furcation involvement of maxillary molars have a high degree of agreement with those from intrasurgical assessments. Overall, 84% of the CBCT data were confirmed by the intrasurgical findings. While 14.7% were underestimated (CBCT<intrasurgical value), the CBCT data lead to an overestimation in only 1.3% compared to the intrasurgical analysis [33].

Therapeutical considerations prior to periodontal surgery

Any type of surgical periodontal intervention is planned only after the initial periodontal treatment has been completed. This initial active treatment should be performed after a thorough clinical and radiographic examination, diagnosis, treatment planning, and case presentation. The initial treatment phase consists of oral hygiene instructions, extraction of teeth irrational to treat, removal of plaque, and calculus by non-surgical scaling and root planning (Sc&Rp), and the preservation of their recurrence by good patient oral hygiene. If required, initial therapy also includes odontoplasty to remove enamel pearls in the furcation area and provisional restorations, splinting of teeth, endodontic treatment in combined lesions, and help with tobacco use cessation (Fig. 2). Splinting becomes necessary only if tooth mobility interferes with patient's satisfaction or the masticatory function, if an increase is anticipated following planned surgical interventions or if regenerative periodontal therapies are planned. There is no scientific basis for routinely splinting hypermobile roots to adjacent, less mobile teeth in order to preserve periodontal health [34].

When initial therapy is completed, a re-evaluation is conducted after 8–12 weeks at the earliest [35], which includes repetition of all clinical measures (i.e., PPD with BoP, PAL, and FI, see “Diagnosis of FI in maxillary molars” section). This consecutive approach allows for healing of inflamed periodontal tissues, reduction of PPD and BoP, potentially establishing a new attachment or even initiating the regeneration of the periodontal tissues. As long as the periodontal conditions during the re-evaluation reveal “closed periodontal pockets” with probing pocket depths (PPD) of ≤4 mm, FI degree 0 or I, and no bleeding on probing (BoP^-), just minimal invasive supra- and subgingival biofilm-management is provided, and patients are included in a supportive periodontal treatment program with 3–4-month intervals (Fig. 2) [36]. Sites revealing residual PPD of 5 mm should have non-surgical retreatment. Sites with residual PPD of ≥6 mm require additional therapy in order to prevent further attachment loss or even tooth loss during supportive periodontal care [37]. Molars, in particular, respond less favorably to non-surgical periodontal treatment than single-rooted teeth [38, 39]. Hence, molars with residual furcation involvements of degree II and/or III that are not accessible to patients' personal oral hygiene and bleed on probing require additional surgical therapy. Particularly, if extended restorations are planned, additional factors should be considered before initiating periodontal surgery to determine whether diseased or damaged molars could be restored with a favorable prognosis [40]. These factors include:

- manageable periodontal conditions, patient's ability and willingness to maintain oral hygiene and tobacco use cessation, the general health and periodontal status of the patient enables surgical intervention;
- root morphology permits the planned surgical therapy;
- caries lesion is accessible for removal;
- favorable pulpal prognosis or endodontic outcome;
- adequate restorability with sufficient remaining tooth structure for retention of a crown, the patient's restorative needs, strategic value of the tooth, alveolar bone conditions, and ability to place implants in case of tooth extraction;



A	B	C	D	E
Fusion of the whole or part of two adjacent roots	**Root proximity**	**Periapical lesion**	**Combined periodontal endodontic lesion**	**Other findings**
A1) fusion of mesiobuccal and distobuccal root	**B1)** root proximity of buccal roots	**C1)** periapical lesion at the mesiobuccal root	**C1)** periodontal-endodontic lesion at the mesiobuccal root	root perforation
A2) fusion of mesiobuccal and palatal root	**B2)** root proximity of mesiobuccal and palatal root	**C2)** periapical lesion at the distobuccal root	**C2)** periodontal-endodontic lesion at the distobuccal root	fenestration defects
A3) fusion of distobuccal and palatal root	**B3)** root proximity of distobuccal and palatal root	**C3)** periapical lesion at the palatal root	**C3)** periodontal-endodontic lesion at the palatal root	overfill of the root canal
				missing palatal or buccal bone plate

Fig. 1 Morphological variations and pathologic findings in maxillary molars using CBCT

– the patient's desires and financial resources (information about costs and treatment alternatives), adequate long-term prognosis

From a reconstructive perspective, a crown-to-root ratio of 1:1 is assumed to be the minimum, provided that the residual attachment can be maintained by ensuring adequate access for plaque control [41]. Instead of the crown-to-root ratio, the residual attachment with the ratio supported-to-unsupported tooth length has been considered to be even more decisive [17]. Recently, an analysis of data from a 10-year retrospective study confirmed that >50% bone support of the remaining roots is needed for tooth retention in the long term [42].

It must be noted that some contraindications for surgery exist for medical or psychological reasons or in non-compliant patients [16]. In such cases, either changing the treatment plan or non-surgical Sc&Rp is still the treatment of choice, although it is less effective in calculus removal than an open approach [43].

Surgical treatment options

Surgical treatment aims to: (1) improve Sc&Rp in areas not accessible during the initial therapy with a non-surgical approach [44]; (2) eliminate residual inflammation and arrest the progression of periodontal disease; (3) establish an environment that is conducive to adequate plaque control in the long term; and ideally, (4) regenerate the periodontal tissues, i.e., establish a periodontal attachment including alveolar bone, periodontal ligament, and cementum.

In the literature reviewed, treatment recommendations were given that related to clinical diagnoses or, alternatively, therapeutic options were elaborated according to their degree of invasiveness and the amount of periodontal attachment that could be maintained (Fig. 3) [17]. In a maxillary molar, the number and degree of furcations involved will determine the required therapy; whereby the invasiveness of the treatment increases with the severity of the furcation involvement (degree II and III). The practicability of the surgical intervention, however, depends significantly on anatomic and morphological factors, such as root proximities and root fusion (Fig. 1).

Resective and non-resective treatment options: indications and practical considerations

Based on “primum nihil nocere”, any periodontal treatment should aim to keep as much tooth structure and periodontal attachment as possible. While degree I furcation involvement can be successfully treated by non-surgical mechanical debridement, surgical therapy is indicated for molars with persisting increased PPD (≥6 mm) after initial treatment and/or advanced furcation involvement (degree II or III, Fig. 3).

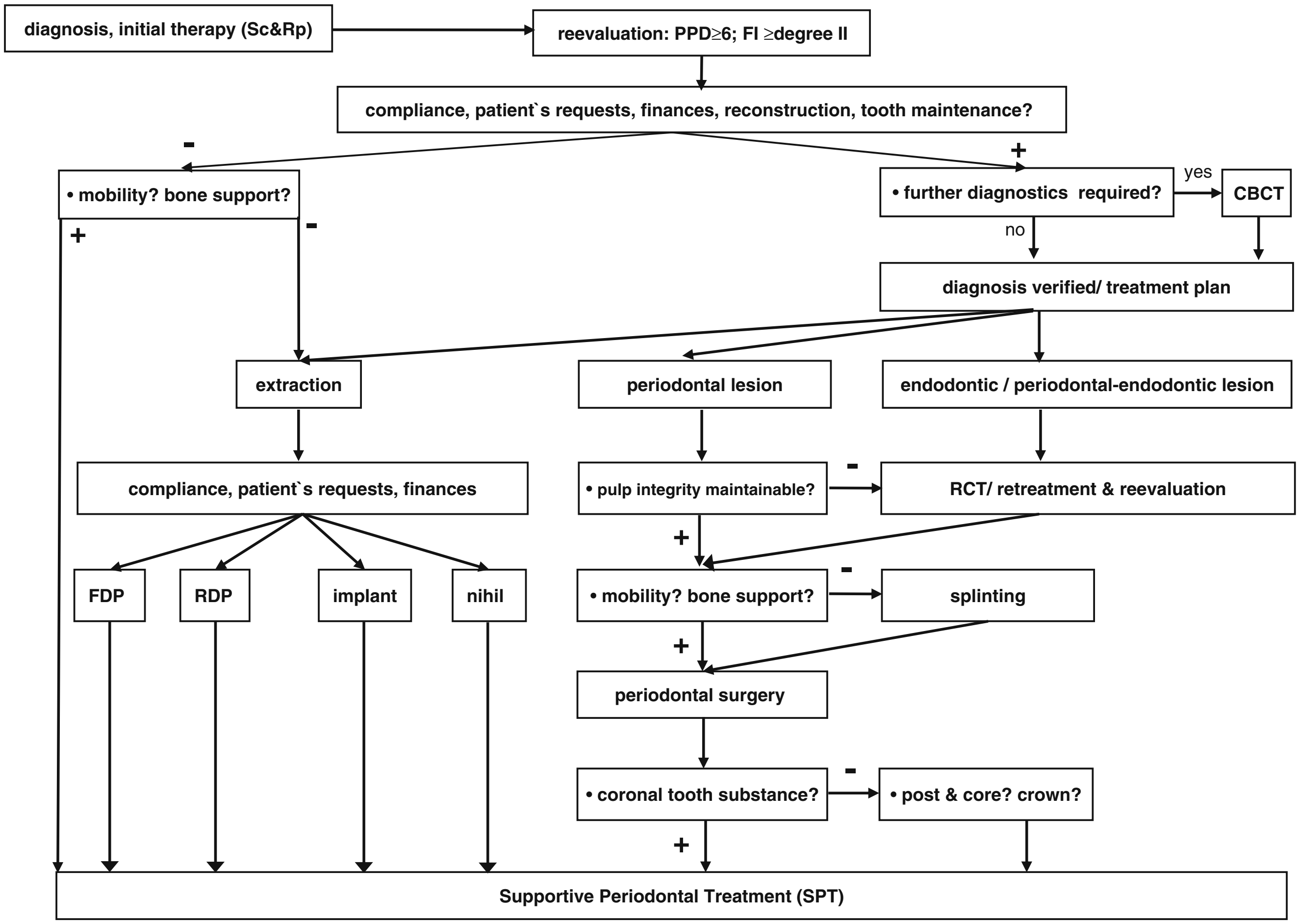
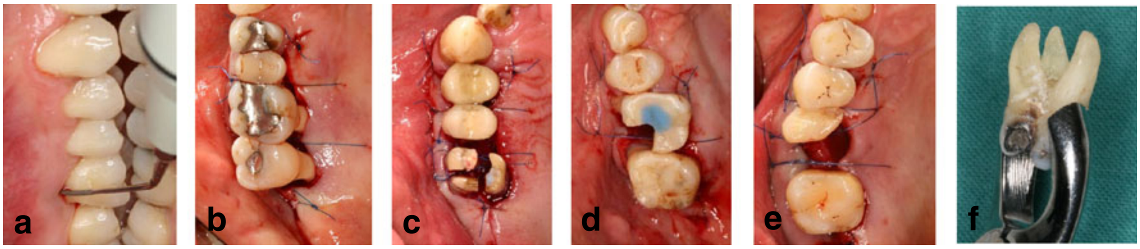


Fig. 2 Decision making in maxillary molars with furcation involvement

1) An open flap debridement (OFD) improves the professional cleaning and is best combined with a gingivectomy or an apical repositioning flap (ARF). The respective flap management depends on the width of the keratinized gingiva. The aim is to reduce or eliminate the pocket, and thus maintain at least 3 mm keratinized gingiva [9, 16]. Further, some supporting bone may need to be removed by ostectomy to change irregular bone defects into slightly scalloped, normal contours for a positive osseous architecture and to reduce the post-treatment accumulation of plaque [16, 44]. In addition, widening and shallowing the furcation by odontoplasty creates better access for plaque control and maintenance. However, excessive tooth removal by odontoplasty often results in hypersensitivity and pulpal damage and may increase the risk of root caries.
2) If maxillary molar furcations demonstrate advanced involvement (degree II or III), tunnelling into all three roots can be performed without interfering with the pulp integrity or the coronal tooth structure. The tunnelling procedure has, however, some limitations in maxillary molars because several prerequisites have to be fulfilled [16, 45]. There must be:

– clear two-way access for all entrances;
– good root spread with a wide furcal entrance [46];
– a short root trunk with a high furcation entrance and long roots. However, to allow for possible odontoplasty of the entrance, the floor of the chamber should not be close to the roof of the furcation. Moreover, the patient must have a low caries index and be able to control plaque using pipe cleaners.

In most tunnel procedures, interfurcal bone has to be sacrificed vertically, opening the furcation sufficiently to allow soft tissue to cover the bone with enough residual space to accommodate cleaning instruments and to avoid a gingival rebound [16]. Tunnelling is always combined with an ARF to ensure pocket elimination. Since one of the greatest concerns with the tunnel procedure is the increased risk of root caries, the daily use of fluoride and chlorhexidine gels in the area of exposed root dentin is recommended [47].



0	1	2	3	4	5
SPT (supportive periodontal therapy with Sc&Rp)	OFD (open flap debridement)[1] with/without ARF (apically repositioned flap)	Root separation	Amputation/ Trisection of a root	Amputation/ Trisection of two roots	Extraction of the tooth
			+/- root separation +/- tunnel preparation		
	1a) without tunnel preparation		3a) distobuccal root	4a) distobuccal + palatal root	
	1b) with tunnel preparation		3b) palatal root	4b) distobuccal + mesiobuccal root	
			3c) mesiobuccal root	4c) mesiobuccal + palatal root	

[1]: OFD can be combined with regenerative measures such as GTR or enamel matrix proteins (indicated in buccal degree II FI with limited success)

Fig. 3 Therapy options for maxillary molars with FI according to treatment invasiveness

3) Instead of tunnelling, root separation is indicated in molars with endodontic treatment, with the floor of the pulp chamber in close proximity to the furcation, and/or with reduced coronal tooth substance requiring subsequent crown restorations [44, 48, 49].
4) More often, the periodontal attachment of one or two of the three roots in maxillary molars is severely reduced and the removal of the affected roots is indicated. Depending on the degree of tooth destruction and the resulting form and contour of the molar tooth, an amputation of a root or a trisection is indicated (Fig. 3). During root amputation, the clinical crown is maintained and only the affected root is removed. For the trisection procedure, the affected roots are removed, together with the corresponding part of the clinical crown. The mesiobuccal root with an average root surface area of 118 mm^2 is considered to be a more valuable root than the palatal (115 mm^2) or the distobuccal root (91 mm^2) [5, 50, 51]. The reason why the distobuccal root of the first maxillary molars is amputated most frequently is most likely related to an advanced attachment loss with involvement of the associated distal furca. This is generally the result of the difficult access interfering with oral hygiene measures. Further reasons are the proximity to the mesiobuccal root of the second maxillary molar with a thin, vulnerable interdental bony septum, which is more easily compromised [52].

As soon as root separation or resection is indicated, endodontic therapy of the remaining root canals becomes necessary and should be completed prior to the resection in order to avoid infection of the endodontic system and to provide the therapist with information about the successful obturation in advance (Fig. 4a, b) [48]. The coronal part of the roots to be resected is obturated with colored composite resin, which is easily identified following root amputation or trisection. Delaying the obturation of the remaining root canals has been recommended in those cases in which the indication for root amputation or hemisection has not been conclusively established [48]. The additional diagnostic measures that CBCTs allow, facilitate more detailed surgical treatment planning, with a clear decision about the resective interventions needed and specification of which roots should be kept. Since the accurate detection of furcation involvement and the assessment of root morphology clearly affects the diagnosis, it is essential for the choice of treatment and the preoperative endodontic therapy, and may even lead to the decision not to do the planned surgical procedure (Fig. 2) [17]. Thus, unnecessary treatment

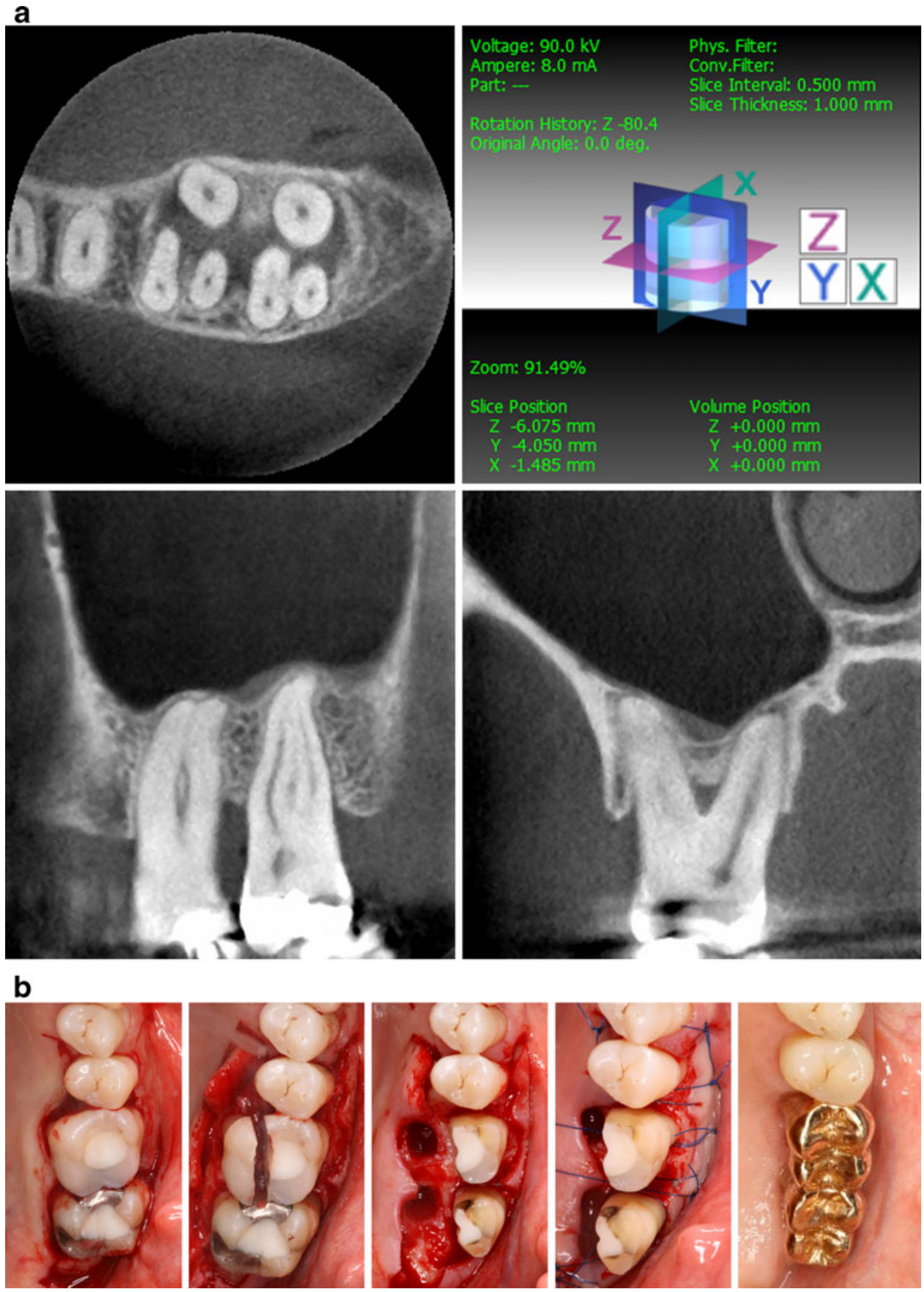


Fig. 4 Patient with furcation involvement in first and second left maxillary molars. **a** CBCT-based decision making for the first and second left maxillary molar in a 42-year-old male diagnosed with advanced periodontitis. Both teeth exhibited FI degree III and root proximity of the buccal roots. It was decided to remove the palatal root as the additional loss in periodontal attachment was less than with a removal of both fused buccal roots. **b** Mucoperiostal flaps were raised on the buccal and the palatal site. After thorough debridement using hand and ultrasonic instruments, the palatal roots of both teeth were trisected. In the first maxillary molar, a tunnel was prepared between the buccal roots. The flaps were apically repositioned and the wound was sutured with monofil synthetic material (5×0). Splinted gold crowns were inserted after a 6-month healing with provisional restorations

interventions may be avoided, patient discomfort, treatment time and costs reduced, and treatment effectiveness enhanced. Long-term data on CBCT "guided" maxillary molar surgery or data from a cost–benefit analysis for this new application are, however, not yet available.

Provided that sufficient coronal tooth substance is maintained after the amputation or trisection procedure, any exposed dentin areas are preferably restored with composite resin. While a single root amputation does not necessarily affect the crown morphology, most trisections with removal of the accompanying crown portion and root separations require restoration with a crown. Depending on the amount of coronal tooth substance left, placement of a fiber-reinforced composite post, preferably one that is narrow and tapered, is indicated to support the core build-up (Fig. 2) [16, 53].

Periodontal surgery with adjunctive regenerative measures

Regeneration of periodontal tissues may be achieved by Guided Tissue Regeneration (GTR), using resorbable or non-resorbable membranes. In furcation-involved maxillary molars, however, the use of GTR provides very limited improvements in clinical conditions and is restricted to buccal lesions. While GTR procedures applied in maxillary molars are unable to resolve the characteristics of degree III FI defects [54], the chances of success in single degree II FI are greater due to the larger osteogenic surface, better support and vascular supply to grafts, and better accessibility to treatment techniques, particularly on the buccal side [55]. Stable horizontal attachment gains were demonstrated over a 10-year follow-up period in degree II furcations of maxillary and mandibular molars treated with GTR, while the initial vertical attachment gains diminished over time [56]. According to a systematic review, the outcome of completely closing FI degree II following the placement of barrier membranes remains unpredictable [57].

More recently enamel matrix derivative proteins (EMD) were introduced to periodontal regenerative surgery, aiming at the induction of regenerative processes in the periodontal tissues similar to human embryogenic development. An early animal study indicated that EMDs have the potential to induce the regeneration of acellular cementum and the new formation of periodontium with inserting fibers [58]. Until today, however, the induced mechanisms in the presence of EMD are not completely understood. According to a current systematic review on biological effects of EMD on various cell types, a positive impact on wound healing and new periodontal tissue formation was evident [59]. Clinically, a higher rate of conversion of degree II to degree I furcations was obtained on applying EMD in proximal furcation defects than with OFD alone [60]. Long-term data are, however, lacking, and the clinical relevance of this minor improvement remains questionable.

Molar extraction and therapeutic alternatives

Extraction of the furcation-involved maxillary molar is the final option and is most likely indicated if the molar is:

- unopposed and the terminal tooth in the arch;
- first molar with adjacent second premolar and second molar, each with enough bone (attachment) to support a fixed dental prosthesis (or implant placement);
- a solitary distal abutment tooth that presents with increasing mobility.

Moreover, molars with FI and significant loss of proximal bone shared with adjacent teeth should be extracted to preserve the periodontal health of these teeth [61], especially if the neighboring teeth would make good prosthetic abutments. These indications are generalizations and do not always apply to specific situations. Many factors must be taken into consideration, including the strategic importance of the tooth or teeth in question [16, 62]. While the replacement of a second molar is questionable, several patients want to have an extracted first molar replaced and/or do not accept the concept of the shortened dental arch with a premolar occlusion and missing first and second molars. With periodontally healthy abutment teeth in the second premolar and second molar position, an FDP is a reasonable alternative, particularly when crown restorations are already planned in these teeth. Otherwise, dental implants are indicated to replace missing molars, particularly in the first molar position, provided that the bone quantity and quality is sufficient. Increased implant failure rate in the posterior maxilla, particularly with smooth implant surfaces, has been related to the very spongious bone quality (type IV) frequently found in this area [63, 64]. Further, the alveolar bone height in the maxillary region is often reduced due to vertical ridge resorption and the increased pneumatization of the maxillary sinus. As a result, bone augmentation procedures with a lateral antrostomy are frequently required during implant placement or as a staged approach. The risk of this surgical intervention is increased in smokers and periodontally compromised patients [65, 66].

Long-term results of the different surgical procedures

According to a recent systematic review, the success rates after resective periodontal surgery vary between 62% and 100% after an observation period of 5 to 13 years [45]. The most frequent complications after tunnelling procedures or root-resective therapy seem to be root fractures and caries in the furcation area. The studies included, which were mainly retrospective in nature, covered a time period from 1972 to 2006, during which there were obviously many changes in treatment concepts [10, 67]. In a prospective clinical intervention study, it was demonstrated that tooth maintenance of furcation-involved teeth is feasible in the long term, provided that the periodontal treatment is adequate, and subsequent reconstructive measures with supportive periodontal care are carried out [68]. Fugazzotto [69] investigated resected molars and single tooth implants in two groups of patients over at least 5 years and found similar success rates (defined as healthy implants and intact resected teeth) of 96% after 11–13 years. In the maxilla, the success rate after amputation of one root (mesiobuccal, distobuccal, and palatal) or both buccal roots varied between 95.5% and 100%. Implant failures dominated in the second molar position of the mandible, with an 84% success rate as compared to 98–99% in the maxilla and in the first molar position in the mandible [69].

Root resection can be a valuable procedure when the tooth in question has a high strategic value or when specific problems exist associated with treatment alternatives such as dental implants. Root resection may be the treatment of choice when the proximity to anatomical landmarks (e.g., maxillary sinus, mandibular canal) limits the amount of bone available for dental implants. In addition, the presence of the remaining healthy root complexes will maintain the alveolar bone associated with them, which prevents the resorptive process. Finally, medically compromised patients may benefit from the maintenance of existing roots, avoiding multiple reconstructive surgical procedures [70].

Conclusion

Preventing the loss of periodontal tissues, particularly in the furcation area, is clearly the best periodontal therapy for long-term tooth retention. However, maxillary molars with furcation involvement are not inevitably assessed as having a hopeless prognosis. Distinct indication criteria have to be applied for the various surgical interventions in the periodontal treatment of furcation-involved maxillary molars. These surgical procedures are still valuable treatment options and enable the elimination of residual inflammation while providing sufficient access for oral hygiene measures to ensure a good long-term prognosis. If the clinical examination and the conventional two-dimensional radiographs cannot provide sufficient information about the furcation involvement and the morphological variations, a detailed assessment is feasible with dental cone-beam computed tomography. Adequate application of this method facilitates a precise diagnosis, the selection of an appropriate treatment option, and thus avoids unnecessary surgical or endodontic interventions. The use of CBCT needs to be carefully justified by weighing up the diagnostic benefits and risks [30]. However, the technical and financial efforts involved and the additional radiation risk of the radiographic examination is justified, as long as the outcome of the treatment provided can be improved and the fundamental principle for diagnostic radiology abbreviated ALARA (As Low As Reasonably Achievable) is respected [71].

While the indication for GTR or the application of EMD in maxillary molars with FI is very limited, their extraction and replacement with a dental implant is restricted, particularly in sites requiring complex alveolar ridge augmentation and sinus elevation. Depending on patients' wishes and expectations, the surgical periodontal treatment options described above enable tooth maintenance with a good long-term prognosis.

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Conflict of interest The authors declare that they have no conflict of interest.

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