IN VIVO AND IN VITRO EXAMINATION OF THE EFFICACY OF TARGETED ENDODONTIC MICROSURGERY

Ph.D. Thesis

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1 Publications

I. Nagy E, Fráter M, Antal M. Gyökércsúcs rezekciója navigált endodontiai mikrosebészeti technikával [Guided modern endodontic microsurgery by use of a trephine bur]. Orv Hetil. 2020 Jul;161(30):1260-1265. Hungarian. doi: 10.1556/650.2020.31778. PMID: 32653869. **IF: 0.540**

II. Antal M, **Nagy E**, Braunitzer G, Fráter M, Piffkó J. Accuracy and clinical safety of guided root end resection with a trephine: a case series. Head Face Med. 2019 Dec 21;15(1):30. doi: 10.1186/s13005-019-0214-8. PMID: 31861995; PMCID: PMC6925511. **IF:1.882**

III. Antal M, **Nagy E**, Sanyó L, Braunitzer G. Digitally planned root end surgery with static guide and custom trephine burs: A case report. Int J Med Robot. 2020 Aug;16(4):e2115. doi: 10.1002/rcs.2115. Epub 2020 Jun 3. PMID: 32304137. **IF: 2.547**

IV. Nagy E, Braunitzer G, Gryschka DG, Barrak I, Antal MA. Accuracy of digitally planned, guided apicoectomy with a conventional trephine and a custom-made endodontic trephine: An in vitro comparative study. J Stomatol Oral Maxillofac Surg. 2021 Sep 30:S2468-7855(21)00200-7. doi: 10.1016/j.jormas.2021.09.014. Epub ahead of print. PMID: 34601166. **IF: 1.569**

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2 Abbreviations

2D: 2 dimensional

3D: 3 dimensional

3DSGs: 3-dimensional–printed surgical guides

AD: angular deviation*

ANG: angular deviation*

ARE: apex removal error

CBCT: Cone Beam Computed Tomography

CI: Confidence Interval

C-silicone: condensation silicone

DD: distal deviation

DICOM: Digital Imaging and Communication in Medicine

CI: Confidence Interval

FOV: field of view

GD: global deviation

IRM: Intermediate Restorative Material

MTA: mineral trioxide aggregate

NSAID: Non-Steroidal Anti-Inflammatory Drug

ODE: osteotomy depth error

OGYÉI: Országos Gyógyszerészeti Intézet

PD: proximal deviation

RKEB: Regonális Intézményi Tudományos és Kutatásetikai Bizottsága

RMGIC: Resin modified glass ionomer cement

* In different publications, due to the implemented nomenclature, different abbreviations have been used for the same term.

RPM: Revolutions Per Minute

SD: standard deviation

SNC: Supernumerary canal

Super-EBA cement: Super- ethoxy benzoic acid cement

SZTE: Szegedi Tudományegyetem

3 Introduction

A new era has begun as instead of doing great number of implant surgeries, both dentists and patients have realised the importance of tooth preservation. All the available instruments from different disciplines are given for this purpose. With their help, microsurgical apical resection has become a valid alternative to dental implants.

Apicoectomy is a routine surgical method in which the apical 3 mm of the root tip is removed. This surgical intervention is only indicated in case of root canal treated teeth when the tooth has an endodontic lesion that cannot be resolved by retreatment. First endeavour to save the tooth with apical surgery was described in 1884 by John Farrar [1]. Ever since then, a long journey has begun. Conventional apicoectomies were aimed to remove the apex and the periapical granulomatous tissues with one simple surgery. Due to the lack of knowledge and adequate instruments these interventions could not provide stable success rate in the long term [2]. With the improvement of science and diagnostic instruments (digital periapical x-Ray - providing better resolution, CBCT [3], microscope [4], piezo instruments) there is a chance to improve the precisional steps of the surgical procedure itself [2]. Better understanding of root canal system complexity involving the apical third of the root could explain many unsuccessful apex removals. Beside the root canal ramifications, opened dentinal tubules can also harbour persistent bacterial increment[5]. Applying retrograde root canal filling during apicoectomies was the first step towards a proper treatment. The early obturation materials (e.g.: amalgam) were not able to seal the canal or the tubules hermetically. Orientation of the tubules is anatomically determined, and the classical resection line with 45 degrees to the root axis opens a big surface that cannot be properly sealed. Therefore, the open, enlarged surface is ideal for bacterial colonisation or persistent bacterial infection[6, 7], however, still there is no existing antibacterial treatment during the mentioned surgical interventions. Because of the microscopic size of bacteria and the lack of ideal material for retrograde filling with satisfying marginal sealing capacity before bioceramics, apical resection has always been a method with a very variable success rate (17-96%)[8-10]. This classical intervention may be quite invasive and carries the risk of damaging anatomical structures in the vicinity of the target area[11] as well.

3.1 Microsurgery and apicectomy

Severe modifications of the original technique were introduced by Kim et al[12]. Based on Gilheany et al.'s work, it has become obvious, that by cutting only 1mm from the apex, 40% of the lateral canals, by cutting 2 mm 86% and by a 3mm cut 93% of lateral canals can be removed during apicoectomy[5]. Thus, it is widely accepted that 3 mm of the root tip has to be removed in order to eliminate >90% of the ramifications and lateral canals[13]. According to Kim et al. this can be even 98% regarding deltae, ramifications and other accessory canals[12]. The use of high-power magnification can also elevate the success rate to as high as 94 %[8]. The optimal cut must be performed perpendicularly to the root axis. This alteration from the conventional technique facilitates postoperative healing by opening less dentinal tubules and decreasing microleakage. [5] As apical or coronal deviations can both lead to suboptimal results, the localisation of the 3 mm borderline is also very crucial, based on the previously mentioned publications [5]. The precise localisation, perpendicular cut and the retrograde preparation has certain requirements as well. In terms of localisation and 3D orientation during the surgical process, the use of CBCT prior to microsurgical apicoectomies is considered to be essential[14, 15]. For better visualisation, the use of high-power magnification is mandatory, accompanied by a whole branch of micro-instruments. Precision can be increased from flap elevation to resected tooth surface inspection with the help of minimally 8x-14x magnification. Using 14x-26x magnification it is possible to evaluate the retrograde obturation or the presence of crack lines, fractures at the site of the freshly cut apex[12]. For the perpendicular cutting-line it is essential, to apply a different retropreparation method with ultrasonic instruments. Ultrasonic retrograde preparation tips are available in a wide range of size and shape, aiding the minimal invasive, precise removal of previous root canal obturation material and shaping the optimal retrograde cavity. The standard rule of retrograde preparation is '3+3': by removing the apical 3 mm and possibly almost all the canal alterations presented there and preparing a 3mm deep "1st class" cavity into the root canal we can eliminate nearly all the factors [16] that would possibly hinder the healing process[17]. The ideal retropreparation cleans the dentin walls, provides some retention for the filling material, explores the isthmus, preserves as much sound dentin as possible and follows the directions of the root canal. As mentioned before, the proper sealing of the exposed root surface is also essential in terms of healing. Dentin-bonded resin composite filling materials (e.g. Retroplast; Retroplast Trading, Rorvig, Denmark) require less retention and can provide adequate sealing of the dentinal tubules as well[18]. However, due to their sensitivity to moisture, their application protocol is far not ideal in a surgical field and cannot provide as good healing statistics as the newly applied materials[19]. IRM, Super-EBA cements, MTA, Biodentine and maybe even RMGIC are current materials covering all the defined requirements towards modern retrograde filling materials[20]. All these inventions, materials and techniques are increasing the success of periapical surgery; however, the operator factor is still a problem that should be improved in the future.

3.2 Guided surgery

The idea of guided surgery derives from dental implantology. The widespread and confident usage of 3D planned surgical guides in implant dentistry was a great innovation that has been relocated into the field of endodontics also. The implementation itself had several stages. Depending on their usage in endodontics, they can be surgical and non-surgical endodontic guides[21, 22]. The type of support partly determines which field of endodontics can the guide be applied in. Bone- and tooth supported guides are suitable for endodontic treatment due to their firm fixation, opposite to the mucosa supported guides[22]. With their help, the risk of the operator factor can be standardised and the apicectomy, the root canal treatment or even fiber-post removal can be done with high precision and minimalised risk at any part of the oral cavity[23]. The progression of 3D planning, the use of different types of templates provides security in complicated cases, could not been solved before.

The recently formed two main directions of digitally guided endodontics have started to overcome their first limitations. The static guides are becoming more common, presenting trephine bur resected case studies continuously to the international literature[24], however the lack of follow-ups in the long run cannot validate this technique - only in few cases[25]. On the other hand, the presence of dynamic resection only is at its beginnings. The idea of dynamic apicectomy is published by Gambarini et al. and probably will never be as widely applicable as static guidance due to its special technical requirements, financial background, and reduced field of indication[26]. Concerning these, the precise examination of static guides and elaboration of trephine bur apicectomy is essential in digital dentistry.

After Pinsky et al. reported on the computer-assisted design and manufacturing of surgical templates for endodontic application in 2007, there was a set-back in the evolution of surgical endodontic guides[27]. However, they compared the guided approach to freehand surgery and found the former to be significantly superior. Results showed that distance from the apex was 0.79 mm (+/-0.33 SD) using guidance and 2.27 mm (+/-1.46 SD) using freehand drilling. The recent years have seen a renewed interest in surgical guides (templates) for endodontic surgery, possibly because stereolithographic manufacturing (i.e.: 3D printing) has become widely available and development in this direction has become a real possibility[21, 24, 28]. Patel et al., in a case report, described the use of a 3D printed custom retractor for endodontic surgery in 2016[29]. Realising that soft tissue retraction is a cornerstone of perfect visualisation and blood-free operation field, the invention itself was inevitable. On the other hand, with its incipient concept, we cannot mention it amongst the guided surgeries, forming a separated group of types of endodontic surgical guides. Strbac and colleagues published a case report, where a stereolithographically fabricated surgical template was used to help the osteotomy and the root resections[30]. In accordance with the guidelines of modern endodontic microsurgery, the appropriate osteotomy size, the bevel angle degree, and the recommended 3 mm apical resection level of the root ends for reducing the apical ramifications were virtually pre-planned. The precise localisation of this area is perfectly aided by the template. The use of digital impression and 3D planning reduced the discomfort of the patient and the risk factors during the operation. However, they admitted that the proximity of the maxillary sinus and related possible complications were still not controllable with this technique[30]. In these cases, the templates were not used to guide the osteotomy itself, as is usual in dental implantology. Meanwhile, Ahn et al. published a different approach of endodontic surgical guides in 2017[31]. This conception was based on the pilot guides of dental implantology. With the help of an anchor bur, they confirmed the position of the root tip and continued freehand osteotomy and apicectomy. The next innovation was introduced by Giacomino et al. in 2018 with a case series of 3 cases in anatomically challenging scenarios, without long term postoperative result[32]. His stereolithographically printed, tooth supported 3D planned guides allowed the application of trephine burs for apicectomy. The use of trephines in implantology and bone augmentation were well known[33-35]. There was scarce publication available of 3-dimensional–printed surgical guides (3DSGs) in endodontics that time. With the aid of the trephine bur, it has become possible to define the depth, the angulation, the osteotomy and apicectomy in one step. The previous parameters make the surgical intervention more feasible in complex cases. This publication is unique and the corner stone of other guided apicectomies, however, the lack of long-term results and pre-clinical examinations on the accuracy of the trephine bur application founded a new research field in endodontic surgery.

The rapid increase of publications in our topic encouraged us to publish our very first case report with 3 years follow-up in 2019 and to do some background research on this technique to validate the precision of trephine bur apicectomy and to improve the technique itself in terms of precision. Like other international publications, we started our data collection of this freshly invented technique mainly from case reports. Although the results were promising, starting in vitro examinations were necessary as well.

The pre-clinical phase is consisted of 2 main studies: comparing the trephine bur technique (semi-circular cut at 90 degrees) to the literature-based 90 degrees straight cut regarding the efficacy of the accessory canal removal from the apical 3 mm with the help of a microCT device. Later, measuring the precision of the conventional trephine burs and trephine burs with stopper (endo-trephines), by using 3D evaluation of the drilled holes in porcine mandibles.

Beside this, we continuously measured and analysed the clinical cases and published our results.

4 Aims of the study

Our research is composed of different layers to understand and to prove the validity of this new technique. Case presentations with short follow-ups and the lack of statistical data behind similar methods was an affirmation to set our goals.

1. To examine and evaluate the efficacy of apex removal with a trephine bur on the elimination of apical ramifications and accessory canals. Searching for significant alterations in statistics compared to the 90° straight resection line.

   Hypothesis: There is no significant difference between the 90 degrees cut and the semilunar resection line with trephine bur, regarding the elimination of apical accessory canals.
2. Measuring the precision of trephine-bur apicectomies, utilizing 3D planned, stereolithographically fabricated, tooth supported surgical templates and assess the effect of specially designed trephine (endo-trephine) on the osteotomy depth, angulation and size of the surgical window.

   Hypothesis:
   - Overpenetration would be a frequent finding with a conventional trephine, and less frequent or absent with the trephine equipped with a stop.
   - There would be no difference in the accuracy of the procedures performed with the two different trephines (conventional and endo-trephine).
3. To examine the in vivo application of the template-and-trephine method, analysing the advantages and disadvantages of the guided apical resection with trephine bur.

   Hypotheses:
   - There would be no difference in frequency and severity in the intra- and postoperative complications between the studied/tested method and the freehand technique (according to cases as reported by the literature).
   - The method would allow the resection of the root with the trephine in all cases, so no further manipulation to this end would be necessary
   - By utilizing this method, the vertical error of root-end resection and the error of osteotomy depth would not be greater than ±1 mm
   - The angular accuracy of the osteotomies would be close to that of template guided dental implantation

5 Materials and Methods

5.1 Efficacy measurements of semilunar apical resection

For measuring the precision and validity of the semi-circular resection line, in vitro comparison was necessary on extracted teeth. The study conformed to the Declaration of Helsinki „Ethical Principles for Medical Research Involving „Human Subjects”, adopted by the 18th Word Medical Assembly, Helsinki, Finland, June 1964, as amended by the 64th Word Medical Assembly, Fortaleza, Brazil, October 2013. The protocol was approved by the Regional and Institutional Committee of Science and Research Ethics, University of Szeged, Hungary (Approval No. RKEB 52/2018-SZTE).

To simplify the process, only upper front teeth were included. Initially 200 single rooted front teeth, extracted at the Faculty of Dentistry, University of Szeged (Szeged, Hungary), were selected. Teeth with root canal obturation, unfinished root canal treatment, double root, previous apicectomy or root resorption were excluded from the study. The remaining specimens underwent a progressive selection process as follows. Only 188 teeth were suitable for further investigation (some teeth had to be excluded due to uncertain root canal treatment or signs of injuries). The teeth were first visually examined with transillumination (DiaLux 2300L Kavo, Germany) under 12.5x magnification (Zeiss OPMI Pico, Carl Zeiss AG Germany). All specimens with no visible accessory canals (as judged by the presence or absence of foramens) or with accessory canals outside the apical third were excluded. The remaining teeth were radiologically tested with a multiscale X-ray microtomograph (Bruker Skyscan 2211, Bruker, Belgium) The initial step was to perform a pre-scan to exclude teeth with no ramifications or lateral canals in the apical third were radiologically identifiable. Specimens that passed this scan underwent full scan at 2.5 μm pixel resolution, using 1 mm Al filter, with the following source parameters: 110 kV tube voltage, 300 μA tube current and 600 ms exposition time. The final study sample consisted of teeth in which lateral canals and/or ramifications could be identified with this method in the most apical 3 mm of the apex. The removal of the apices was performed with a surgical motor at 800rpm (Implantmed W&H Dentalwerk, Austria) with copious water cooling (0.9% saline, 105ml/min) [36] and trephines with an outer diameter of 4,21mm (Hager&Meisinger, Germany). The axis of the resection was perpendicular to the root axis, exactly 3 mms, at the previously marked line. measured with a periodontal probe (CP-15) from the apex. The tooth was then laid on a metal plate on its palatal surface and stabilized with Krampon pliers above the 3 mm line so as not to interfere with the section. For the section, the trephine bur was placed perpendicularly to the axis of the root in a way that the uppermost point of its curvature touched the pre-marked 3 mm line (**Figure 1.).**

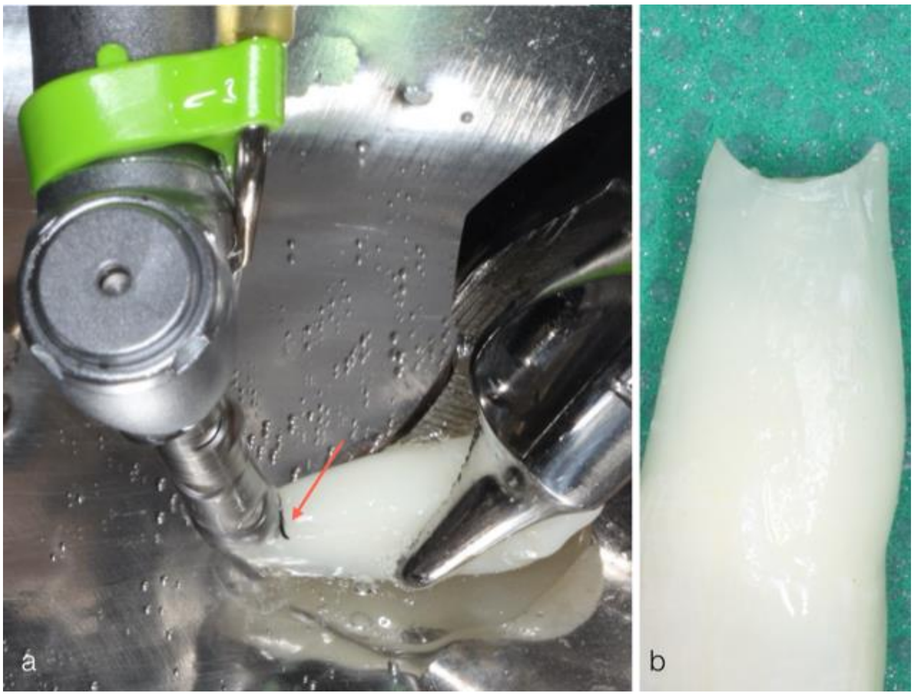


Figure 1. a) *removal of the apex tip at 3 mm,* ***b)*** *the characteristic concave outcome.*

After the removal of the apex detection, micro-CT scanning was performed again, with the same settings as before, in search for residual accessory canals or ramifications. (**Figure 2**.)

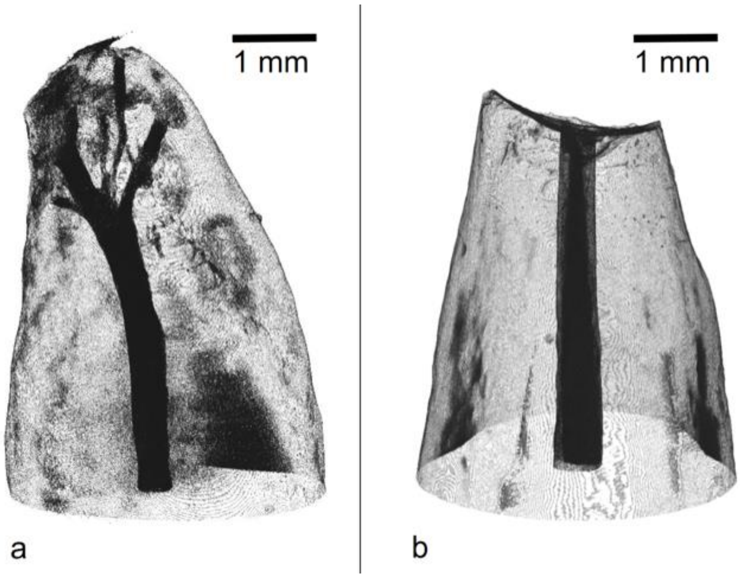


Figure 2. *MicroCT image before* ***(a)*** *and after* ***(b)*** *the semi-circular shaped apical resection line.*

The presence of residual accessory canals along the resection line, in the 2 lateral asymmetric area was examined on the post-op nano-CT image (**Figure 2.**). In cases where such accessory canals or ramifications were found, the semicircular section was transformed into a straight one along the original 3 mm section line by eliminating all the remaining tooth material below the line. This was done with a Lindemann bur (Hager&Meisinger, Germany). These specimens underwent one more CT-scan to verify that the second section eliminated the previously identified residual accessory canals or ramifications.

The data were analyzed descriptively, in line with the aims of the study. The number of teeth with only one identifiable canal (the main root canal) was recorded, but such teeth were not used further in the study. For the purposes of the study, a SNC was defined as any CT-identifiable additional canal besides the main root canal, regardless of being a lateral canal or a ramification. Only those specimens underwent the above sectioning procedures in which the presence of SNCs was verified with the full micro-CT scan. The number of teeth in which SNCs could be identified was determined with micro-CT. The number of SNCs (by counting them in the CT-images) was recorded. The percentage of the specimens when the semicircular section eliminated all SNCs completely and the percentage that required the straight section for complete elimination were also recorded. The latter calculations were done for the exact number of SNCs also. The number of SNCs was recorded by tooth type (central incisor, lateral incisor or canine) and the mean number of SNCs by tooth type was also calculated.

Efficiency was defined as the ability of the applied method (semicircular sectioning with a trephine bur) to eliminate SNCs expressed as a) the percentage of study specimens in which the method eliminated all SNCs and b) the percentage of the eliminated SNCs in the total number observed in all study specimens.

5.2 Guided modern endodontic microsurgery with a trephine bur. Introduction of the surgical technique

5.2.1 Manufacturing the surgical guide

In order to receive the personalised surgical templates, the impressions (Orthoprint, Zhermack Italy) previously taken from the upper- and lower jaw with orthodontic trays (Hager Werken, size 3) were articulated with the help of bite registration (O-Bite, DMG Germany). We adapted the light-curable methacrylate material to the surgical area (Elite LC, Zhermack Italy), especially to the periapical region of the tooth number 22 in full inter occlusion to stabilize the position of the future guide. Prior to the radiological examination, 6 gutta-percha pellets were placed into the pre-drilled holes of the acrylate template. With the help of a 3D implant planning software (SMART Guide, dicomLAB LTD., Hungary) we superimposed the data of the CBCT from the patient and the CBCT from the template and planned the surgical guide. The size of the osteotomy window was defined by the size of the trephine, the modern endosurgical principles, the size of and position of the apex and the surrounding anatomical structures. The angle, the depth and the diameter of the penetration was planned with the help of modern guided implantation planning software and options they could provide. **(Figure 3, 4).** The 3D planned template was stereolithographically printed.

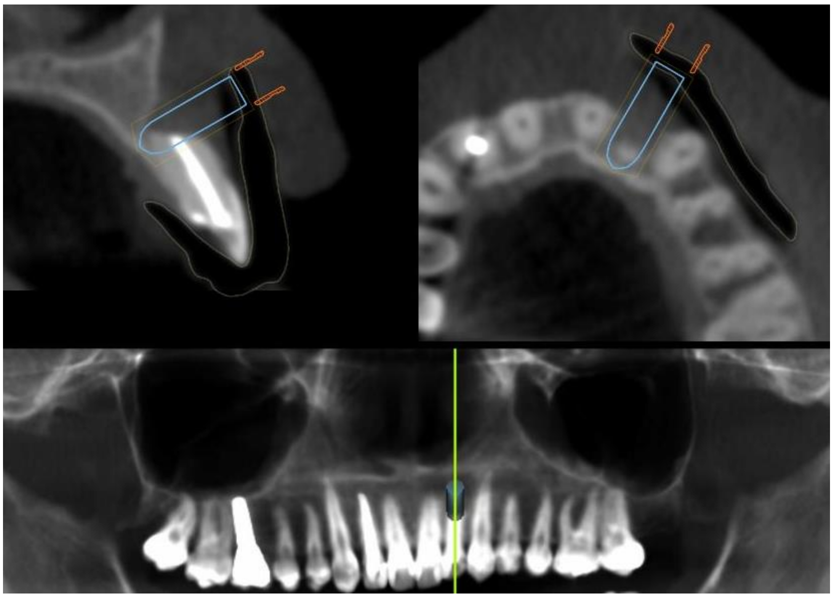


Figure 3: *Digital planning of the angle, depth of penetration and the diameter of the trephine bur in SMART guide planning software.*

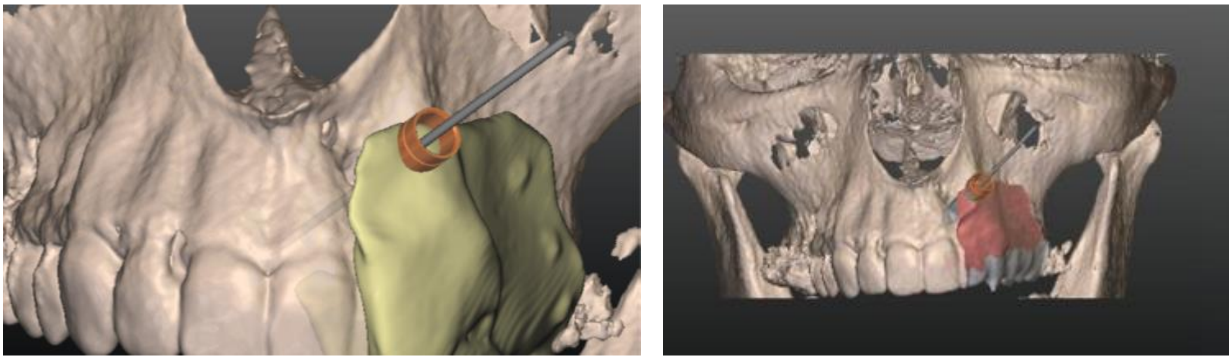


Figure 4: *Modelling the surgery with the help of the 3D sotfware.*

5.2.2 Surgical procedure

Following the modern endodontic microsurgical principles, operation microscope (Zeiss OpMi Pico2, Zeiss Germany), microsurgical instruments and materials were used during the surgery.

Terminal anaesthesia (Ultracain D-S Forte 1:100 000; Sanofi Aventis GmbH) was performed in the region of tooth number 22 and a full thickness, submarginal flap was elevated between teeth 21 and 23 in order to have a free access for the sleeve of the dentally supported guide. The diameter of the sleeve of the guide defining the position of the bony window was corrected according to the outer diameter of the trephine bur (4,5mm, Maisinger, Germany), while its height was defined by the planned penetration depth and the length of the trephine. The 3D planned template guided the osteotomy and the apicectomy in one step with copious amount of water cooling and precisely selected torque (Implantmed, W&H, Germany). (**Figure 5.)**

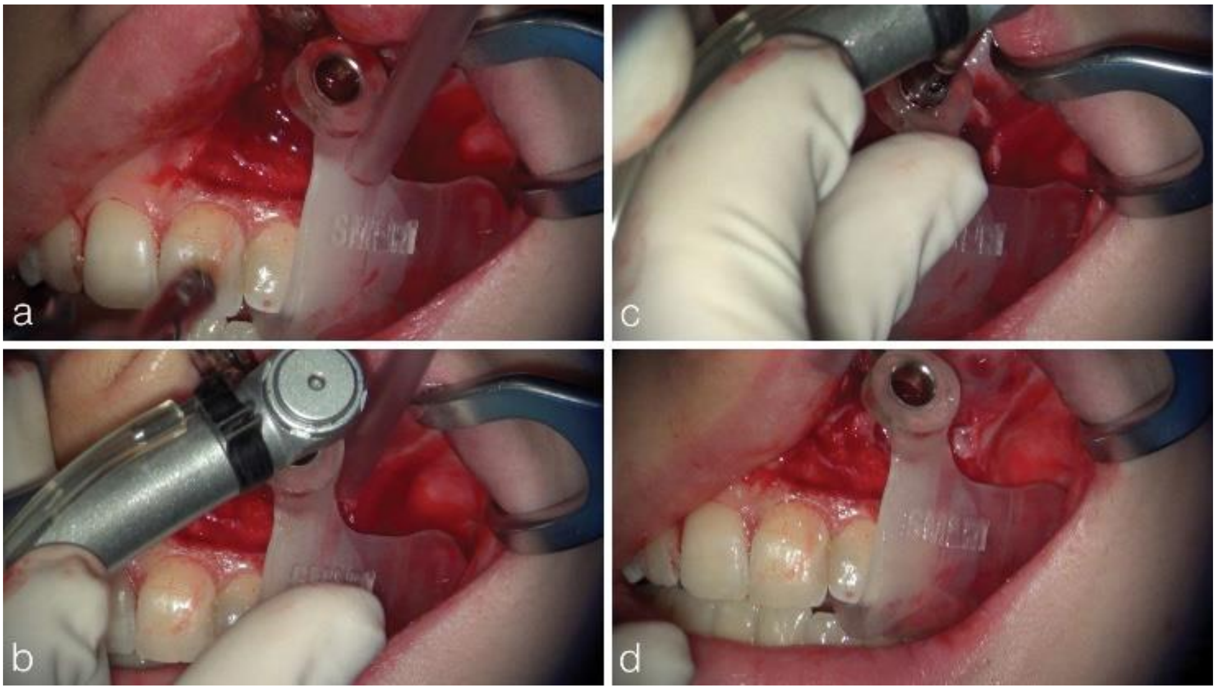


Figure 5*.: Surgical template in interocclusion* ***(a)****, microsurgical resection with trephine bur* ***(b, c, d)***

The freshly cut root surface was dyed with methylene-blue solution and went under examination with the help of 16 times magnification. The inflammatory tissues were removed from the periapical area with periodontal curettes. Ferric-sulphate solution was applied (Astringedent 15,5%, Ultradent Germany) with the help of cotton pellets to achieve proper haemostasis. For retrograde preparation Piezomed R1D and R2RD tips (W&H, Germany) and for the retrograde filling MTA (ProRoot MTA, Dentsply Maillefer, Switzerland)[37] was used. After removing the ferric-sulphate from the bone surface and inducing bleeding, non-resorbable (Silkam 4/0, B.Braun Germany) single interrupted sutures were applied for wound closure. Postoperative periapical x-Ray was taken to check the precision of the surgery and for documentation. (**Figure 6.)**

Figure 6.: *Trephine-shaped radiolucent area on the post-op x-Ray*

5.3 Accuracy and clinical safety of guided apicectomy

Eleven patients were enrolled (mean age: 48.9 ± 12.4 years). Seven of these patients were women (mean age: 45.4 ± 11.8 years), and four were men (mean age: 55.0 ± 11.0 years). The demographic and baseline clinical characteristics of the study population are given in **Table 1.** Lesion sizes - to give an approximation of the severity of the periapical process - were calculated as recommended by Kim et al [11]. All patients were referred for endodontic surgery by general dental practitioners to the Department of Operative and Aesthetic Dentistry, Faculty of Dentistry, University of Szeged (Szeged, Hungary). The inclusion criteria were persisting periapical lesion and pain with or without swelling, impossible or previously failed root canal filling revision, age between 18 and 75 years, and signed informed consent. Relative and absolute contraindications of endodontic surgery counted as exclusion criteria, as well as any other condition that would have put the patient at unacceptable risk during or after surgery. The study conformed to the Declaration of Helsinki “Ethical Principles for Medical Research Involving ‘Human Subjects”, adopted by the 18th World Medical Assembly, Helsinki, Finland, June 1964, as amended by the 64th World Medical Assembly, Fortaleza, Brazil, October 2013. Furthermore, the study observed the principles of Good Clinical Practice. The protocol was approved by the National Institute of Pharmacy and Nutrition of Hungary (Approval No. OGYÉI/43796-6/2018).

Case	Patient	Sex	Age	Tooth	Lesion size (mm) width x height x depth	Swelling	Fistula
1	1	F	29	22	3.42x2.74x3.13	-	+
2	2	F	32	12	3.06x3.58x2.94	-	-
3	3	F	48	11	3.02x2.83x5.24	+	-
4	3	F	48	21	6.37x6.46x5.47	+	-
5	4	M	40	11	16.33x12.48x10.08	-	+
6	5	M	49	11	5.13x4.46x4.18	-	-
7	6	F	47	12	3.30x4.66x3.23	-	+
8	7	F	52	22	4.51x3.23x4.18	-	-
9	8	M	64	44	4.91x7.61x5.88	+	-
10	9	M	67	34	2.40x4.30x2.42	+	-
11	10	F	43	14	3.60x3.90x4.51	+	-
12	11	F	67	11	4.37x2.43x5.54	-	-
13	11	F	67	22	3.69x4.59x3.18	-	-

Table 1. *Demographic and baseline clinical characteristics of the study population. Thirteen teeth were treated in 11 patients, resulting in altogether 14 root end removals. The lesion sizes were calculated utilizing CBCT scans, as proposed by Kim et al.: the maximum diameter of the lesions was measured in 3 directions parallel to the standardized axes: mesiodistal (L_x), apico-coronal (Ly) and buccolingual (Lz).*

5.3.1 Presurgical procedures

CBCTs were acquired (i-CAT Next Generation, Imaging Sciences-Kavo, Hatfield, PA, USA) with standard settings for all patients (120 kV, 5mA, 9 sec, voxel size: 250 µm, FOV: 110 mm; all scans in this study were done with these specifications). A bite block was used to ensure non-occlusion and a correct head position. A silicone impression (Zetaplus, Zhermack, Italy) was taken in a plastic tray (hi-tray, Zhermack, Italy), and it was scanned separately. The acquisition was always performed by an experienced radiologist according to the recommendations of the guide manufacturer (dicomLAB Ltd., Szeged, Hungary), with the minimum exposure necessary for adequate image quality [38].

The images were reconstructed as a volume (i-CAT Vision, Imaging Sciences International, Hatfield, PA, USA), and saved as DICOM files to provide input for surgical planning. The two scans were sent online to the template manufacturer, where they were registered, and sent back to the surgeon for planning. For 3D surgical planning, SMARTGuide 1.25 (dicomLAB Ltd., Szeged, Hungary) was used. For the planning of the surgeries, a virtual cylinder of the same dimensions as the actual trephine was used (**Figure7).**

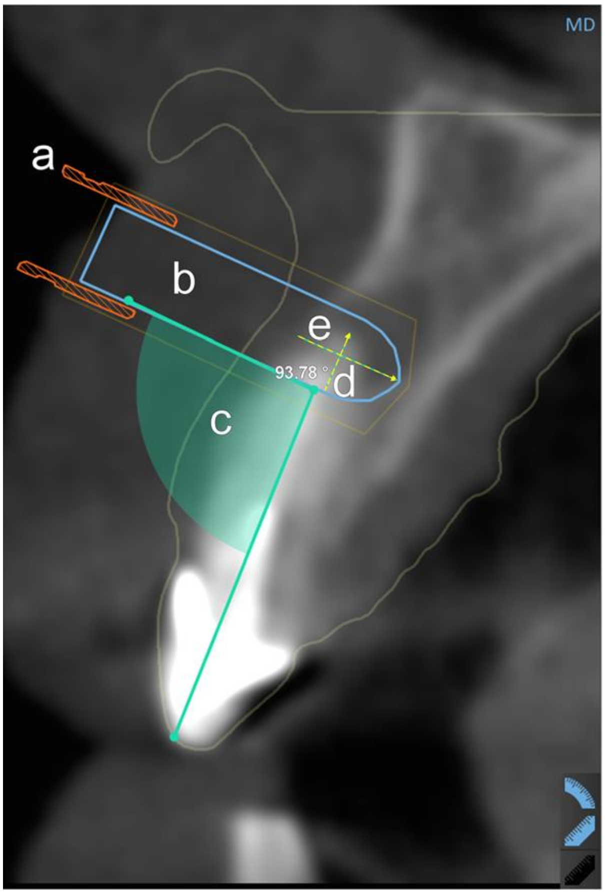


***Figure** 7. Surgical plan in the planning software (oro-vestibular view). **a** guiding sleeve; **b** virtual model to represent trephine; **c** the angulation of the planned osteotomy; **d** the planned depth of the osteotomy; **e** the planned length of the piece to be resected*

The only difference between the model and the trephine was that the model was rounded at the distal end, but this did not confound apical deviation calculations, as the axial lengths were the same, and for the calculations, two properly aligned models were compared (see below). This cylindrical model was positioned in a way that its axis was perpendicular to the tooth axis. The planned drilling length was 20 mm from the outer margin of the guiding sleeve in all cases. The surgical plans were prepared with the intention to resect 3 mm of the apical portion of the root. In cases with previous apicoectomy in history, only 1.3 mm was planned to be resected, always keeping in mind that enough root surface should be left to provide sufficient retention. All planning was performed by the same experienced surgeon, familiar with both implant and endodontic surgeries. The surgical templates were fabricated according to these plans, using a 3D printer (3D Systems ProJet MD 3510, USA). As a final step, to enhance the fit of the trephine in the guide, metal guiding sleeves of an inner diameter of 4.25 mm were inserted into the guiding tunnels of the templates. This diameter was wide enough to allow the rotation of the trephine of 4.21 mm outer diameter (**Figure 8**) but narrow enough to allow only negligible lateral deviation. After fabrication, the templates were tried on the patients' plaster casts to check correct and reproducible fitting. A final check was performed right before each surgery, on the patients' dentition. The insertion of the templates into the patients' oral cavity was always preceded by disinfection, as per the manufacturer's instructions.

Figure 8. *Left: the surgical setup demonstrated on a gypsum cast.* ***a)*** *surgical template* ***b)*** *guiding tunnel with metal sleeve;* ***c)*** *trephine. Right: intraoperative image*

5.3.2 Surgical procedure

The surgeries were performed under local anaesthesia (Ultracain D-S Forte 1:100 000; Sanofi-Aventis GmbH). Full-thickness flaps were raised, the size and shape were always determined individually by the anatomical properties and accessibility of the current case.

As the surgical guide was placed, it defined the exact osteotomy site and the angle at which the osteotomy would be performed. For the osteotomy, a bone trephine was used with an outer diameter of 4.21 mm (Hager&Meisinger, Neuss, Germany) under copious irrigation. The trephine was applied through the guiding sleeve of the template. (**Figure 8.)**

After the combined osteotomy and apicoectomy, periapical curettage was performed if necessary, and retrograde preparation was performed using a piezosurgery unit (Piezomed, W&H, Austria). For the retrograde filling, MTA was used (Cerkamed, Poland). Methylene blue was applied to visualize the ramifications. Before retrograde fillings, ferric-sulphate was used to ensure a bloodless working area. The retrograde preparation and filling were performed under high-power magnification (Opmi Pico, Zeiss, Germany). The flaps were closed and sutured with 5.0 monofilament sutures (Ethicon, USA). Within a month after the surgeries, a follow-up CBCT scan was made, with the same unit and settings as before the surgery. The sutures were removed 7±1 days following the surgery, and follow-ups were scheduled at 5 months and 12 months.

5.3.3 Analysis

The frequency and severity of intraoperative and postoperative complications were recorded, as well as the frequency of osteotomies when the root end was resected in the same step (i.e.: no further manipulation was necessary for this purpose). Frequencies and percentages were calculated. The angular deviation was analysed in Amira 5.4.0 (Thermo Fisher Scientific, USA) with dedicated algorithms. Pre- and postoperative CBCT scans of the given patient were transformed into the same coordinate system. For this registration, the region of interest was narrowed down to the analysed bone (i.e.: maxilla or mandible) to avoid inaccuracy stemming from differences in mouth opening. The bony tunnel formed by the trephine was manually segmented via a slice-by-slice method and transformed into a three-dimensional virtual model. As a next step, the cylindrical model used for planning was aligned with the model of the actual tunnel along their principal axes. The corresponding surgical plan was then extracted from the database of the planning and manufacturing system of the surgical guide and applied to a copy of the same cylindrical model. This way, it became possible to compare the result of the osteotomy with the plan in terms of the deviation of the principal axes (**Figure 9**).

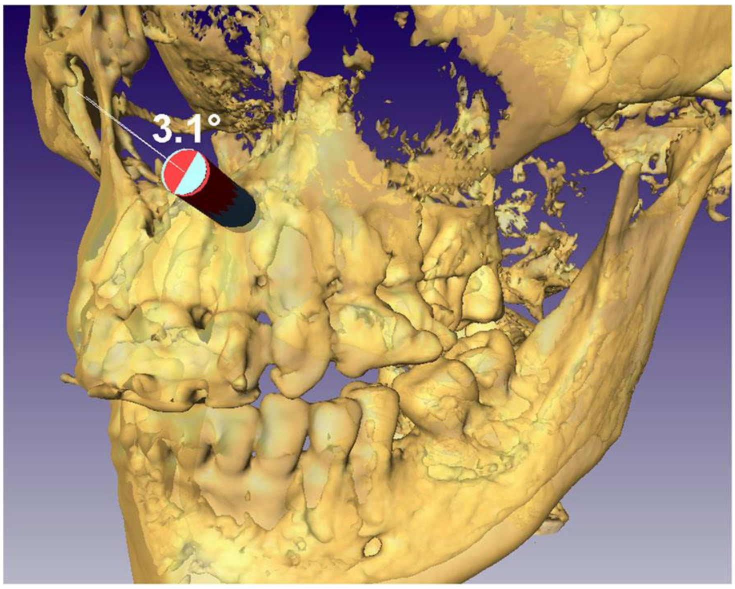


Figure 9. *Analysis of angular deviation in Amira (blue: planned, red: realized). This figure does not depict the analysis of any of the actual cases, it is for illustration purposes only*

The angular deviation was defined as the angle closed by the principal axes of the aligned models in degrees. The procedure was repeated three times for each case, and the mean of the three measurements was used for further analyses. The results were calculated as median (95% CI) as we found it more meaningful and informative in such a small sample than the usual mean (SD). The length of the given tooth was measured in both the preoperative and postoperative CBCT images (i-CAT Vision, i-CAT, USA). This allowed the calculation of the length of the resected piece, which was subtracted from the planned length to be resected. This way apex resection error (ARE) was calculated. Osteotomy depth error (ODE) was calculated similarly, by subtracting the actual depth from the planned depth (**Figure 10**).

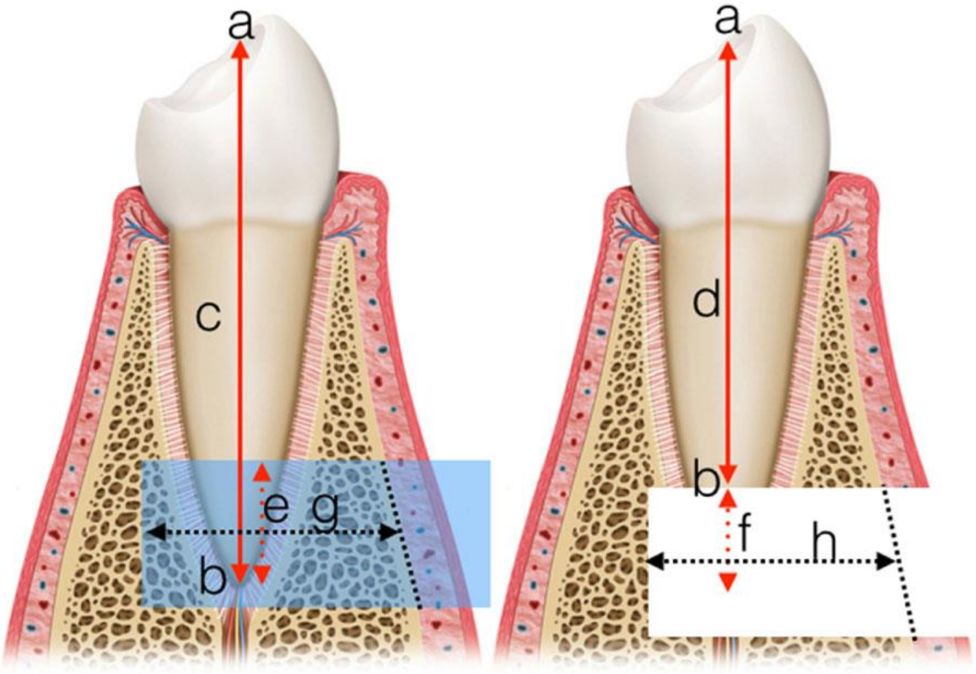


Figure10. *Explanation of the 2D measurements. Left: preoperative, Right: postoperative;* ***a****: coronal reference point;* ***b****: apical reference point (end points of the axis);* ***c****: axial length before surgery* ***d****: axial length after surgery;* ***e****: planned length of removal;* ***f****: actual resected length;* ***g****: planned depth of osteotomy;* ***h****: actual depth of osteotomy (for the measurements, the missing cortical was substituted by a straight line connecting the remaining cortical edges). Calculations: ARE = e-f; ODE = g-h*

The calculations were performed three times for each case, and the mean of the three measurements was used for further analyses. The results were calculated as median (95% CI), for the same reasons as given above. All statistical calculations were done in SPSS 23.0 (IBM, USA).

5.3.4 Introduction of the new technique with a custom-made trephine

The new procedure was explained to the patient, who presented with a persistent periapical lesion of the already root canal treated tooth 12 with a metal post, in both oral and written forms. He gave his informed consent to the surgery. The clinical testing of the method was approved by the Medical Devices Department of the Hungarian National Institute of Pharmacy and Nutrition (Approval No. OGYÉI/43796/2018). A vestibularly extended C-silicone impression (Zetaplus, Zhermack, Italy) was taken of the patient's upper dentition in a plastic tray (Hi-Tray, Zhermack, Italy), then two CBCT scans were taken: one of the patient and one of the impression (i-CAT Next Generation, i-CAT, USA; 120 kV, 5 mA, 9 seconds, voxel size: 250 µm, FOV: 110 mm, for both the patient and the impression. Both scans were sent to dicomLAB Dental for digital image registration. With the help of these images, dicomLAB Dental generated a model of the anatomy of the patient and sent this image back to the surgical team. For the planning, the unreleased upgrade of SMART Guide 1.26 was used, with the integrated model of the bone trephine as if selecting an implant or fixation pin to be used. (**Figure 11.**).

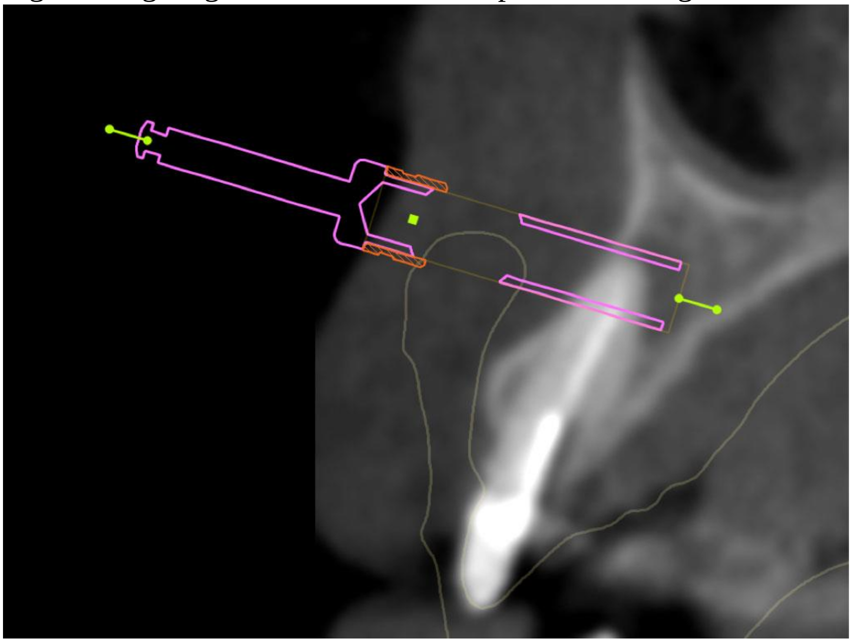


Figure 11. *Planning the surgery in the software with the model of the trephine. The position of the guiding sleeve is also displayed, which allows planning in such a manner that the operator will have to push the trephine exactly till stop to reach the optimal end result. Distances and lengths are measured with the built-in measurement tool of the software.*

Screenshots of the final plan are shown in **Figure 12**.

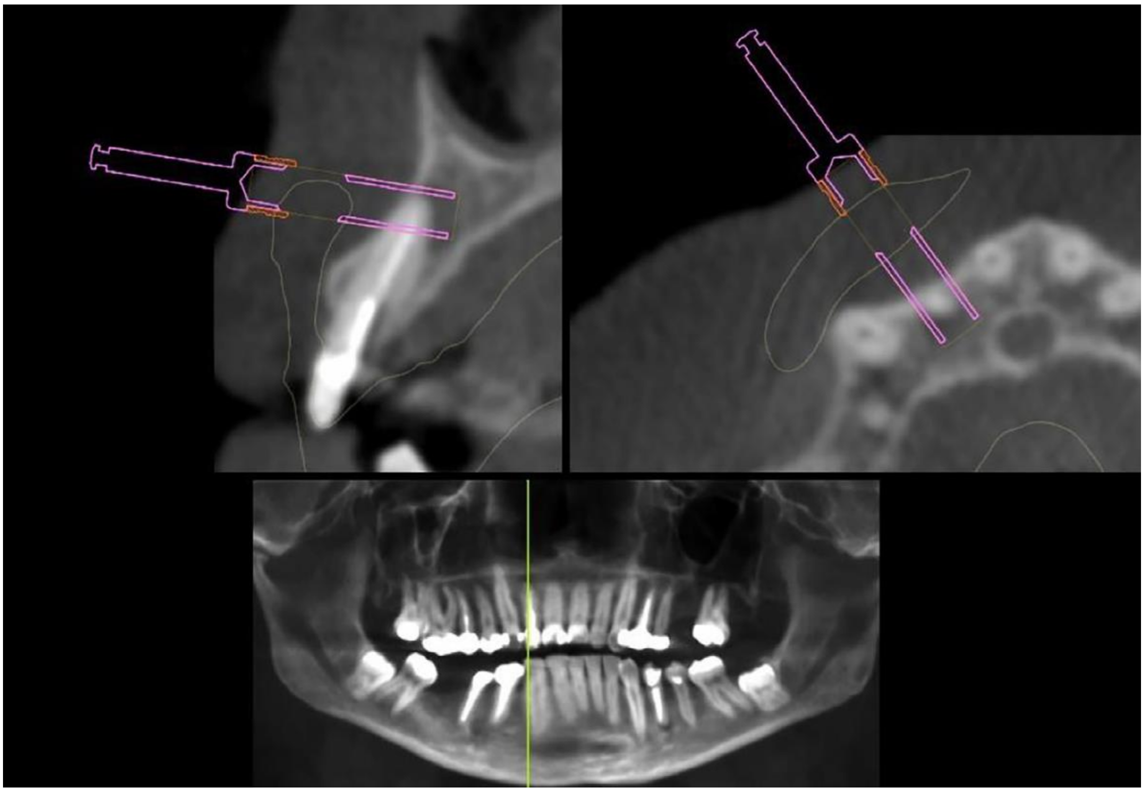
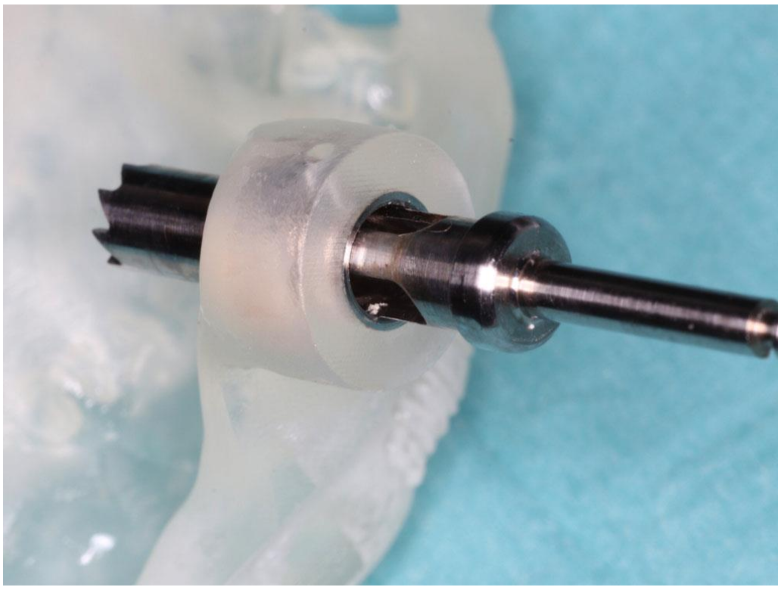


Figure 12. *Screenshots of the surgical plan exported from SMART Guide*



The plans were sent to dicomLAB Dental for 3D printing. When the final product (the tooth-supported surgical guide) had been delivered, the first step was to check the fit of the trephine in the guiding sleeve (**Figure 13.)**, and then a fit check was performed in the patient's mouth as well (**Figure 14.**).

Figure 13: *Trephine fit check outside the patient's mouth. Note the stop that mechanically prevents overpenetration*

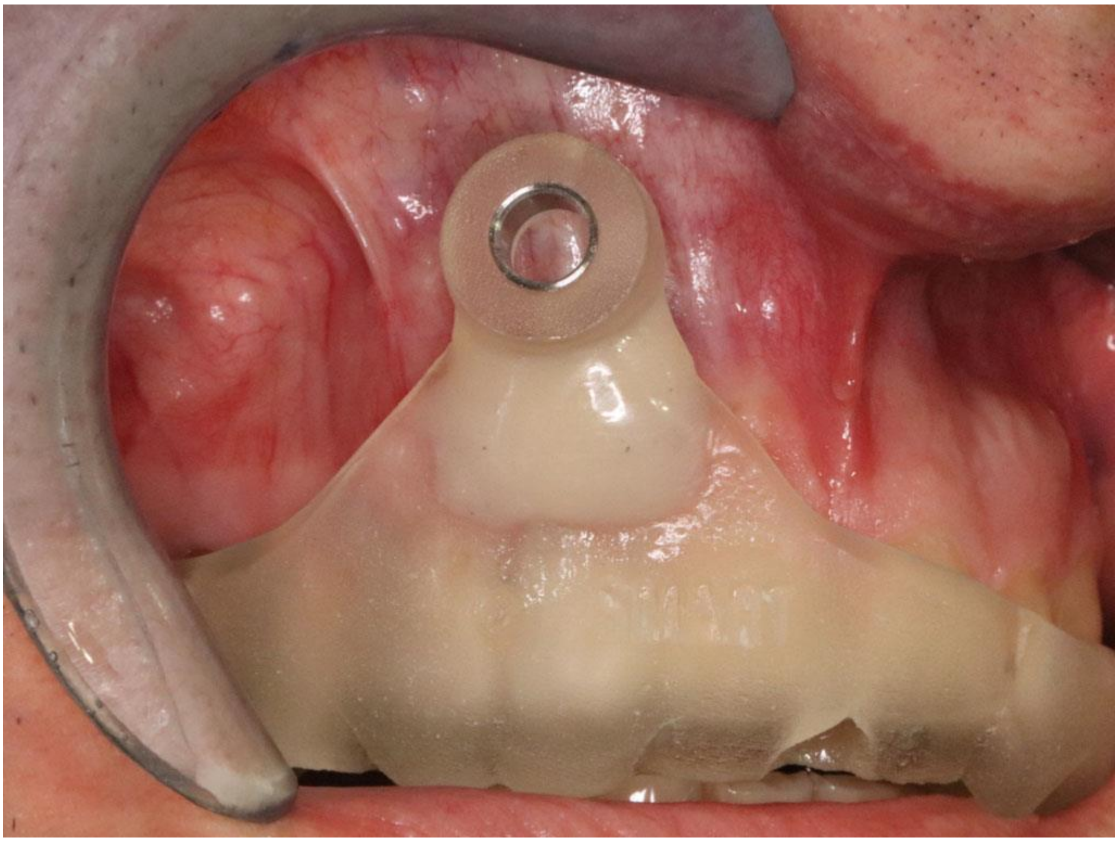


Figure 14: *Template fit check in the patient's mouth*

Once we had made sure that the fit of the trephine was suitable for the surgery and that the template sat firmly on the patient's dentition, the surgery began. To induce anaesthesia, subperiosteal infiltration with 3 × 2 mL Ubistein Forte (articaine-hydrochloride and epinephrine 1:100 000, 3M, Germany) was utilized. Anaesthetic was administered to the root of the treated tooth, and 2 cm both mesially and distally from the root, to ensure the block of sensation in the entire surgical site. Flap was prepared with a submarginal incision and with one vertical releasing incision. The guide was placed in a way that it also retracted the soft tissues, but a Freer elevator was also used to prevent the flap from sliding back underneath the guide. The trephine was inserted into the guiding sleeve and drilling was performed until the stop prevented the instrument from being inserted any further. Constant external irrigation was provided through a standard cannula (W&H, Austria) attached to the surgical unit and the hand piece. The irrigation fluid was saline at room temperature. The guide was stabilized manually at three points. The surgical access is shown in **Figure 15**.

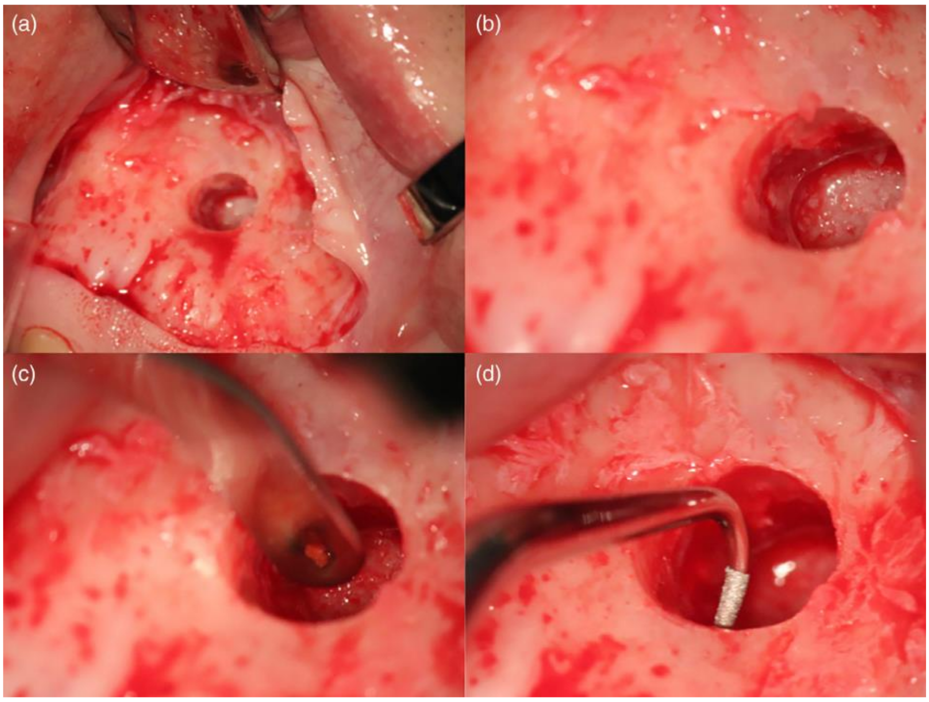


Figure 15. *After the osteotomy.* ***a)*** *Surgical access with the soft tissue flap retracted.* ***b)*** *A close-up of the access.* ***c)*** *Localization of the root with a micro-mirror.* ***d)*** *Insertion of the piezo instrument. Retrograde preparation and filling and wound closure were performed as recommended by Kim et al [11]*

When the trephine was removed, we noticed that it had not only resected the apex, but also removed it (**Figure 16**).

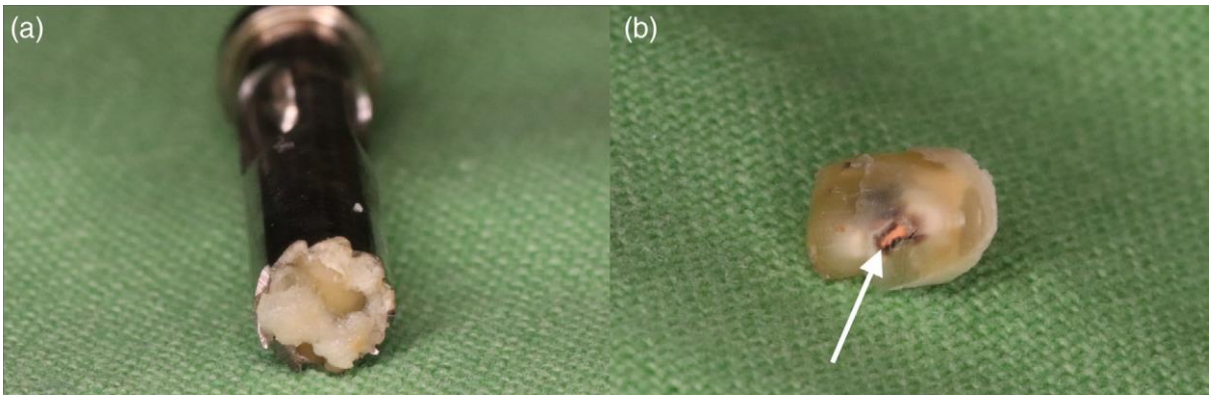


Figure 16. ***a)*** *Core specimen in the trephine.* ***b)*** *The removed piece of apex. The arrow points to the gutta-percha in the root canal*

The trephine prepared a symmetrical round access, through which retrograde preparation and filling could be performed. For a better view, epinephrine-containing solution (Tonogen, Richter Gedeon Nyrt.) was applied both inside and outside the bony housing. Inspection of the site and root canal location were done under surgical microscope (OPMI Pico, Zeiss, Germany). For the visualization of the root canal, methylene blue was used. Retrograde preparation was carried out with Piezomed (WH, Bürmoss Austria), with the R3D tip, to a depth of approximately 2.5 mm. The cavity was dried and bioceramic filling was applied (TotalFill Fast Set Putty, FKG, La Chaux-de-Fonds, Switzerland). The wound was closed with 5-0 Mopylen (Resorba, Nürnberg, Germany).

5.3.5 Analysis

To check positional three-dimensional analysis was performed in Amira 5.4.0 (ThermoFisher Scientific, Waltham, Massachusetts, USA), with dedicated algorithms. The planned position of the trephine bur was extracted from the digital surgical plan and compared with the actual position determined with the segmentation of the bur-hole (**Figure 9**). The following parameters were analysed: deviation of the distal endpoint (DD, mm), deviation of the proximal midpoint (PD, mm), and angular deviation (i.e.: the deviation of the principal axes, ANG, degrees). Proximal and distal refer to the ends of the trephine bur. PD and DD were broken down to x, y, z vectors, where x: horizontal, y: depth (mesio-distal) and z: vertical (cranio-caudal).

5.4 Accuracy of template guided resection with custom-made trephines

For the experiments porcine mandibles were used, an accepted model in the literature for dental implantology [39-41], because its density and mineral content is similar to that of the human mandible [42-45]. Fresh porcine mandibles with teeth were obtained from the local meat processing facility (Tisza-Maros Hús Kft., Szeged, Hungary, **Figure 17a**). The animals were not sacrificed for the sake of the experiments. Altogether 8 mandibles were used, 4 in the conventional trephine group (control group) and 4 in the stop trephine group (study group). After the experiments, the remnants were disposed of according to the pertinent regulations regarding the treatment of organic waste. Twenty-one procedures were performed in the study group, and twenty-three in the control group (5-9 apicoectomies per mandible, depending on the anatomy of the given specimen as judged from an initial CBCT scan).

5.4.1 *Imaging and surgical planning*

To provide imaging input for the digital planning, a double CBCT scan protocol was followed with an individualized impression tray with gutta-percha markers made from Photopolymerizable Resin Trays (Elite LC Tray, Zhermack, Italy, **Figure 17b**). The markers served the purpose of digital image registration. First, a silicone impression was taken into the individualized tray (Zetaplus, Zhermack, Italy). The first CBCT scan was taken of the mandible with the impression on (in the tray) and the second scan was taken of the impression in the tray (without the mandible). For the CBCT scans, an i-CAT Next Generation device was used (Imaging Sciences- Kavo, Hatfield, PA, USA) with standard settings (tube voltage: 120 kV, tube current: 5mA, exposition time: 14.7 s, voxel size: 250 μm, FOV: 160x130 mm).

Preparation of the input images for planning, the process of surgical planning itself and 3D printing of the surgical templates happened entirely according to the surgical guide production of dicomLAB Dental Ltd. (Szeged, Hungary)[46]. Specifically, surgical planning was done in SMARTGuide 1.26 (dicomLAB Dental, Szeged, Hungary, **Figure 17c**), and the surgical templates were 3D printed with a multijet technology printer (ProJet MD3510, 3D Systems). All procedures were planned with the help of a cylindrical implant model (as shown in Fig 1c), regardless of whether the given procedure was to be performed in the study group or the control group. This way, it was possible to avoid the bias caused by the method of planning (i.e.: we did not use the digital model of the new instrument for planning, as no such model was available for the conventional trephine). In any given case, the physical dimensions of the cylindrical model corresponded to those of the body of the trephine to be used.

5.4.2 *Instruments and instrumentation*

In both groups, trephines of 20 mm working length were used through a surgical template (**Figure 17d).**

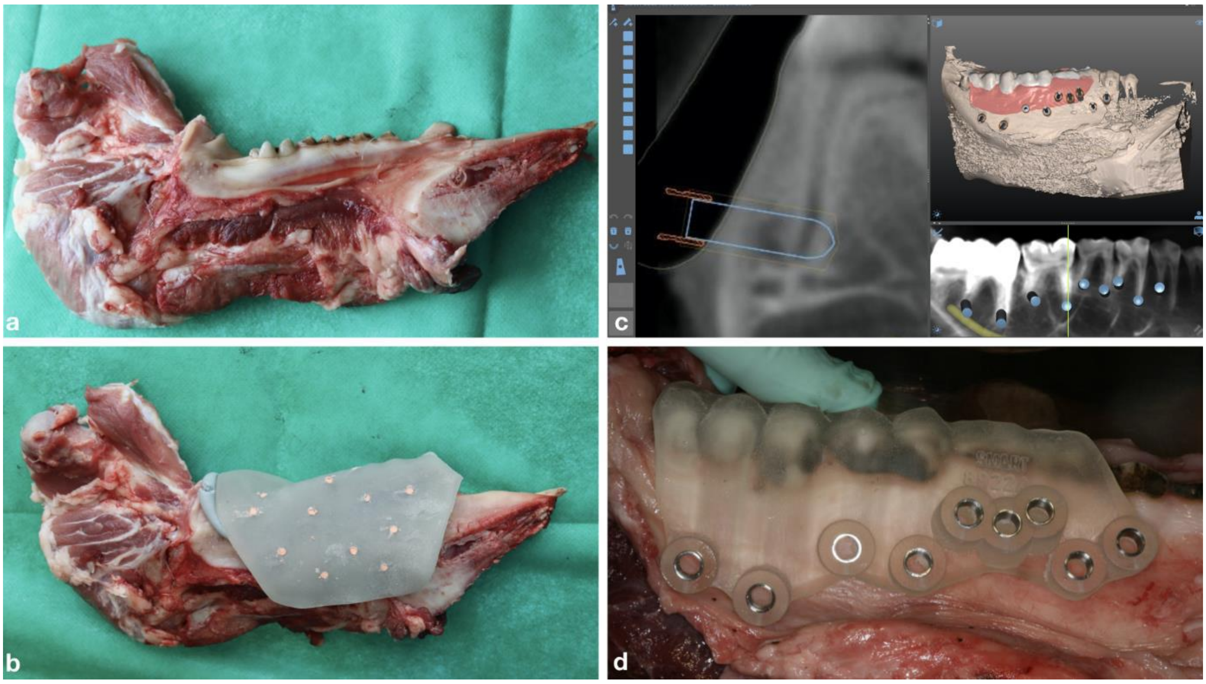


Figure 17. Preparations for the apicoectomies. ***a)*** *a porcine mandible with teeth;* ***b)*** *impression taking in an individualized tray with gutta-percha markers;* ***c)*** *digital planning;* ***d)*** *the 3D printed, tooth-supported surgical guide on the porcine mandible.*

In the control group, commercially available, 4.21 mm diameter bone trephines were used (Hager & Meisinger, Neuss, Germany) through a 4.25 mm guiding sleeve embedded in the surgical template. (**Figure 18a)**

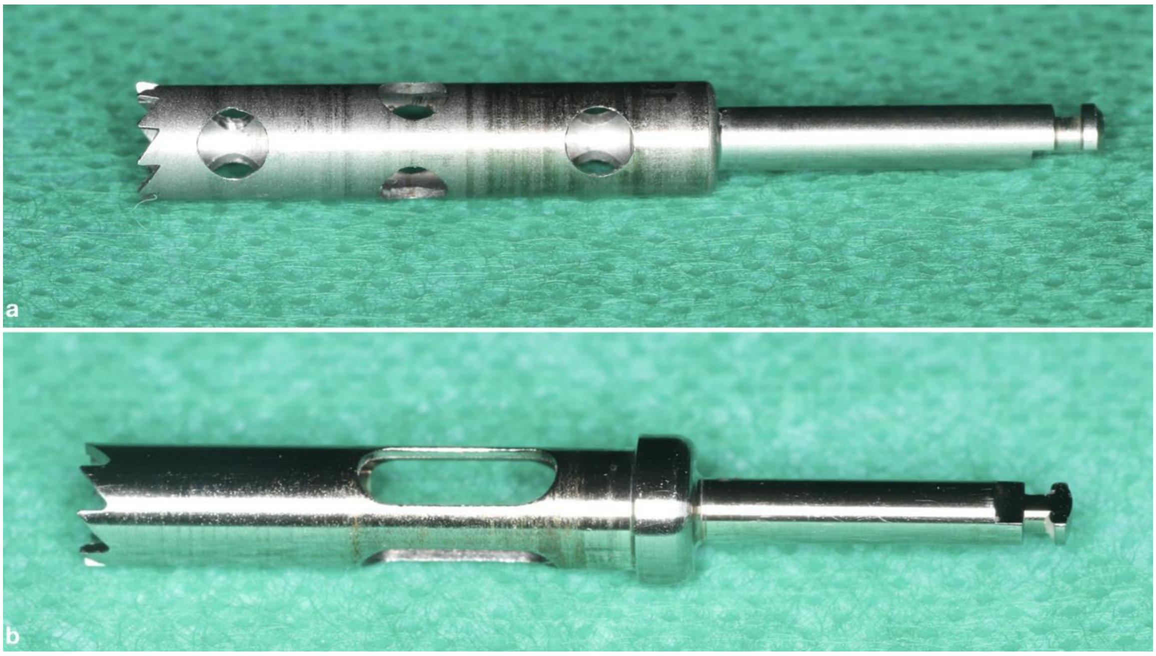


Fig. 18. *The trephines used in the study.* ***a)*** *the conventional trephine used in the control group;* ***b)*** *the endo-trephine used in the study group. Note that the body of the instrument widens at the proximal end to form a shoulder. When this shoulder (the stop) meets the outer rim of the guiding tunnel of the surgical template, it prevents the instrument from being introduced any deeper (see also* ***Figure 19b****).*

In the study group the 4.46 mm endo-trephine from our set [47] was used (**Figure 18b**) through a 4.50 mm guiding sleeve embedded in the surgical template. This way, the difference between the diameter of the sleeve and that of the trephine's body was the same as in the control group. This difference is large enough to allow frictionless rotation but small enough not to risk efficient guidance. All trephines of the set are made of sulphur-alloyed martensitic stainless steel with 13 % chromium content and high corrosion resistance (W.nr. 1.4197) and have a stop at 20 mm above the working end. The bits are manufactured by a local company specializing in metal surgical devices (Lajos Döme EV, Szeged, Hungary). **Figure 19a** and **figure 19b** demonstrates how the endo-trephine fits in the sleeve of the surgical guide and how the built-in stop works. **Figure 19c** and **figure 19d** shows how the conventional trephine fits in the sleeve of the surgical guide and that without a built-in stop, it is possible to insert the instrument beyond its working length. In both groups, the trephines were used in a surgical handpiece (WS-75L, W&H, Austria) connected to an implant motor (Implantmed, W&H, Austria). The drilling speed was 800 RPM. The implant motor provided constant external irrigation throughout the procedures (**Figure 19e**). As for the depth of the osteotomy, in the control group the operator relied on the depth markings of the instrument and in the study group, the instrument was pushed in until the stop prevented further penetration. Most of the time, the apex was removed along with the bone when the trephine was removed from the canal, but if it did not happen or bone fragments remained in the canal, debridement was performed with a periotome.

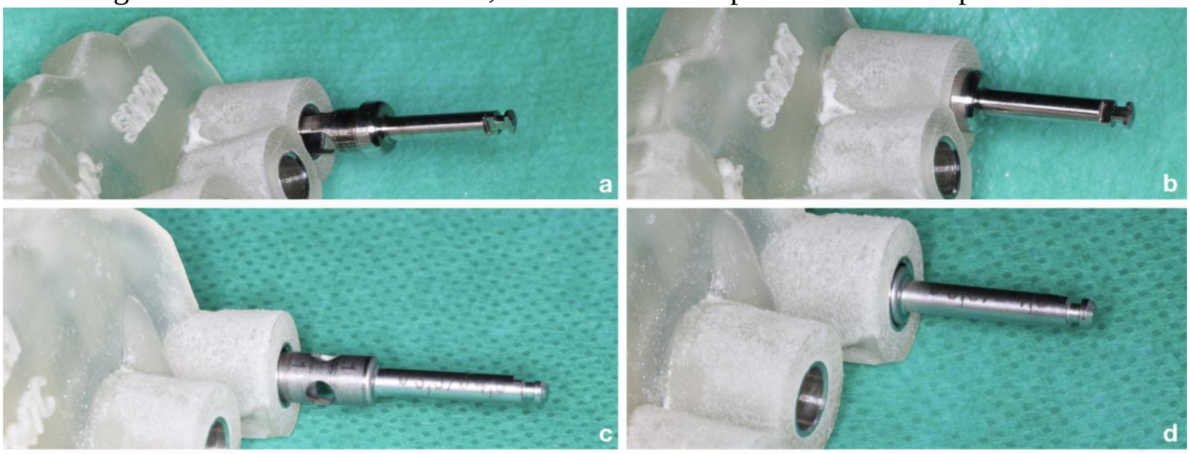


Figure 19 a-d. *The trephines in use. Panels **a)** to **d)** illustrate how the instruments fit in the surgical guide. Note that the endo-trephine cannot be introduced into the guide any further than what the shoulder of the trephine allows, so the degree of insertion cannot exceed the instrument's working length (**a** and **b**). In contrast, there is nothing to prevent the conventional trephine from being introduced beyond its working length (**c** and **d**). This is what makes overpenetration possible.*

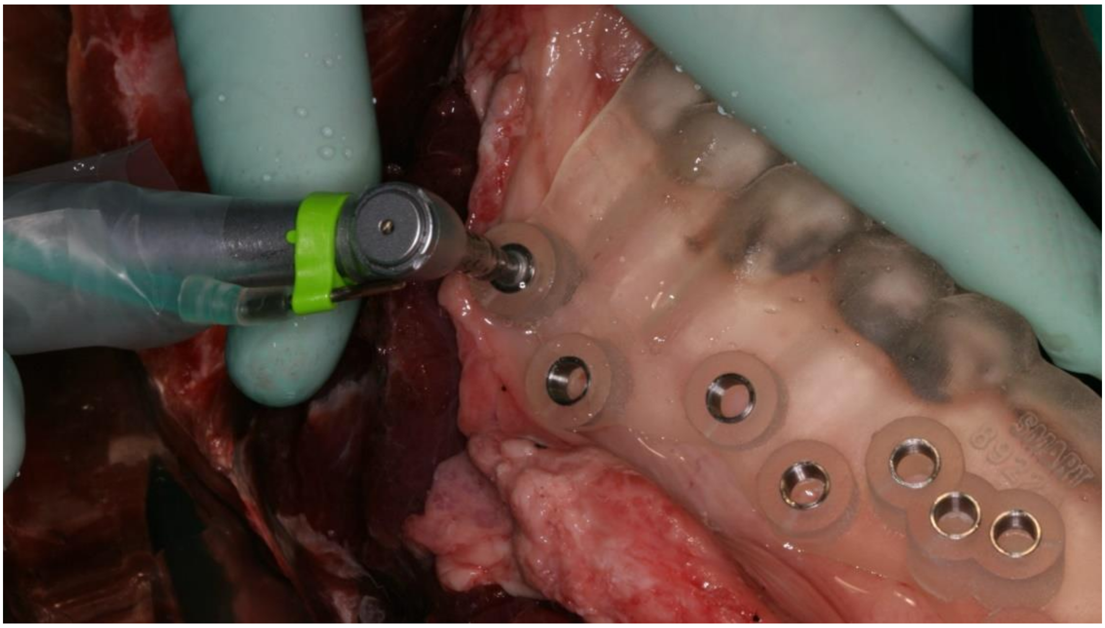


Figure 19 e. *Experimental setup for the guided trephine apicoectomy being carried out on a porcine mandible.*

5.4.3 Analysis

Control CBCT scans for the analysis were taken with the same settings as described before. For the scans, metal cylinders of the same length and diameter as the body of the trephine used were inserted in the canals formed by the osteotomies. This was necessary because the analysis was segmentation-based, that is, it used grayscale values to differentiate between objects. Without the insertion of these cylinders, the inside of the canals would have appeared continuous with the surrounding air in the analytical software, rendering analysis impossible. By applying a metal cylinder of the same dimensions as the trephine, the end-position of the trephine inside the bone was reproduced, which could then be digitally compared to the planned end-position. Analyses were conducted in Amira 5.4 (ThermoFisher Scientific, USA), with dedicated algorithms (dicomLAB Dental, Szeged, Hungary). First, the pre-and postoperative CBCT scans were registered so that they were in the same coordinate system. Next, the metal cylinders placed for the postoperative scans were segmented (**Figure 20a**) and transformed into virtual bodies **(Figure 20b).** It was in this step that the virtual reconstruction of the trephines' end-position was obtained inside the bone. This was followed by the reconstruction of the planned positions. For this, virtual cylinders corresponding to the dimensions of the given trephine's body were used. The spatial coordinates of the plan were applied to the virtual cylinder. This step yielded the end-position of the trephine as planned. After this step, it was possible to compare the end- positions of the cylinder as planned and as actually placed in three dimensions **(Figure 20c**).

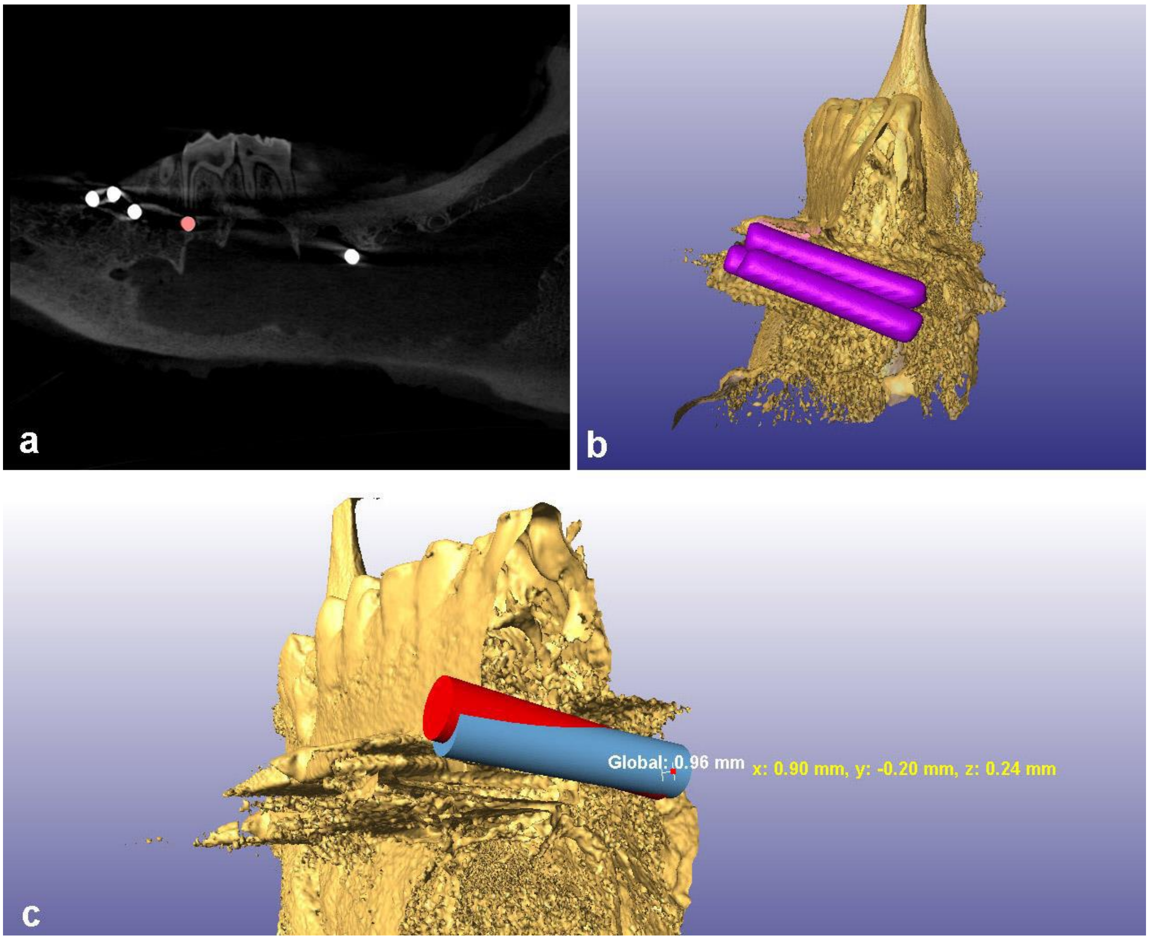


Figure 20. *Accuracy analysis in Amira.* ***a)*** *segmentation is based on the difference in radiodensity between the tissues and the inserted metal cylinders;* ***b)*** *the segmented cylinders are transformed into three-dimensional bodies that correspond to the cylinders in the bone;* ***c)*** *a cylindrical model of the same dimensions as the body of the trephine is aligned with the segmented cylinder in the position to be analysed (blue) and compared to an identical model positioned according to the surgical plan (red) with a custom algorithm. The algorithm returns the global apical deviation and deviation along the axes x, y and z in millimetres.*

The analysis concentrated on the imaginary apical (distal) central endpoint of the trephine conceptualized as a solid cylinder. The basis of comparison was the spatial position of this point according to the surgical plan. Deviation along three axes (x, y, z) and global deviation were calculated. Global deviation (GD) was defined as the square root of the summed squares of the deviations along the three axes. As for the axes, x represented the horizontal (bucco-lingual) dimension, y represented depth (mesio-distal deviation) and z represented the vertical (craniocaudal) dimension. The analysis paid special attention to the bucco-lingual dimension (x), as this dimension allowed the assessment of over-/underpenetration. The statistical analyses were performed in SPSS 23.0 (IBM, USA). First, the frequency and magnitude of over-and underpenetration were calculated for both groups. These were characterized descriptively. Then linear regression analysis was used for GD (as a summed measure of deviations along the three axes) with group and surgical template ID as factors to exclude the possibility that the poor fit or some manufacturing issue of the surgical templates interfered with the results. Having excluded the confounding effect of the templates themselves, the variables (GD, x, y, z) were compared with one-way ANOVA by group. Descriptive statistics (means and standard deviations) were also calculated by group. Accuracy was defined as the closeness between the planned and the actual spatial position of the apical endpoint.

6 Results

6.1 Efficacy measurements of semilunar apical resection

From the initial pool of 200 teeth, 12 specimens were excluded for meeting one or more exclusion criteria. The remaining 188 teeth (57 central incisors, 73 lateral incisors, 58 canines) were visually inspected under 13.6X magnification. 112 specimens were excluded in this way, due to the lack of visible extra foramens on the surface. The remaining 76 specimens were radiologically tested. The micro-CT pre-scan narrowed the sample down to 66 specimens. These 66 teeth underwent full micro-CT scan. The presence of SNCs in the most apical 3 mm portion of the root could be verified this way in 33 teeth, which became the final study sample. The frequency of SNCs in the entire 188-specimen sample was, thus, 17.6%. Broken down by tooth type and referring to the entire 188- specimen sample, 24.6% of the central incisors, 9.6% of the lateral incisors and 20.7% of the canines contained SNCs. For a summary of the selection procedure, see **Table 2**. The study sample (N=33) consisted of 14 central incisors (42.4%), 7 lateral incisors (21.2%) and 12 canines (36.4%). The mean number of SNCs was 1.86 (±0.77) in central incisors, 1.86 (±1.06) in lateral incisors and 2.90 (±2.30) in canines. One or two SNCs were the most frequently observed (in 23 cases, 69.7%). The highest observed number of such canals was 8 (in one canine, 3%). The 33 teeth contained 72 SNCs altogether. Descriptive statistics of the study sample are given in **Table 3**. The repeated CT-scans after the semi-circular sections indicated two residual SNCs in two specimens, one in each. These specimens underwent a second (straight) section, which eliminated the residual SNC in one. In the other one it persisted, as it was located precisely above the section line. This means that the semi-circular section eliminated all SNCs in 94% of the study specimens, and it eliminated 97.3% of the total number of SNCs in all study specimens

Table 2. *Specimen counts after each step of the progressive selection process. The steps served to verify the presence of ramifications/lateral canals (see also text).*

	Included	After visual screening	After transillumination	After CBCT prescan	After full scan (with CBCT)
Tooth (N)	200	188	76	66	33
Percentage (%)	NA	100%	40.4%	35.1%	17.6%

Table 3*. Specimen and supernumerary canal (SNC) counts and the corresponding percentages by tooth type for the study sample (N=33).*

SNC count	**CENTRAL INCISOR (N=14)**				**LATERAL INCISOR (N=7)**				**CANINE (N=12)**				**TOTAL (N=33)**			
	N TEETH	%	N SNC	%	N TEETH	%	N SNC	%	N TEETH	%	N SNC	%	N TEETH	%	N SNC	%
1	5	35.7	5	19.2	3	42.9	3	23.1	6	50.0	6	18.2	14	42.4	14	19.4
2	6	42.9	12	46.2	3	42.9	6	46.2	0	0.0	0	0.0	9	27.3	18	25.0
3	3	21.4	9	34.6	0	0.0	0	0.0	3	25.0	9	27.3	6	18.2	18	25.0
4	0	0.0	0	0.0	1	14.3	4	30.8	1	8.3	4	12.1	2	6.1	8	11.1
5	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
6	0	0.0	0	0.0	0	0.0	0	0.0	1	8.3	6	18.2	1	3.0	6	8.3
7	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
8	0	0.0	0	0.0	0	0.0	0	0.0	1	8.3	8	24.2	1	3.0	8	11.1
Total	14	100	26	100	7	100	13	100	12	100	33	100	33	100	72	100

6.2 Guided modern endodontic microsurgery with a trephine bur. Introduction of the surgical technique

The patient did not mention any significant post operative pain or long recovery. She became asymptomatic. 1x50mg Diclofenac-potassium containing NSAID (Non-Steroidal Anti-Inflammatory Drug) was taken after the surgery. No more painkiller was felt necessary according to the patient. No antibiotics were prescribed. On the 6 months check-up X-ray (**Figure 21.)** bony regeneration can be detected with the healing of the previous radiolucent lesion. The 1-year CBCT revealed the regenerated bone structure, and the patient is still asymptomatic. On the 3-year periapical control x-Ray (**Figure 22.)** a healthy periodontal space and a visible lamina dura can be seen around de rounded surface of the apicectomy. According to Molven et al. this is considered to be a complete healing in the 2D radiological assessment [48].

Figure 21. *6-month check-up: dense bone formation at the periapical region*

Figure 22. *Complete regeneration: lamina dura and well-defined periapical space can*

6.3 Accuracy and clinical safety of guided apicectomy

Thirteen teeth were treated in 11 patients, resulting in altogether 14 apicoectomies. The root end was successfully and completely resected by the trephine in all cases, and in most of the cases, the resected piece was also removed with the trephine (**Figure 23.).**

Figure 23. *Bone cylinders removed with the trephine containing the resected root ends.*

In 3 cases, the root end was removed with a periotome. No intraoperative complications were observed in any of the cases. In all cases, the surgery resolved the preoperative swelling and pain, and the patients were free of symptoms indicating recurrence or complications at the 5-month follow-up. In two of the cases, a key-hole extension of the trephine tunnel had to be performed in order to allow enough vertical space for the piezo tip for the retrograde preparation. In three cases, due to the extensive lesion and excochleation during the operation, the digital segmentation of the cavity was not possible as the borders could not be properly defined. Accordingly, in these cases, the angular deviation was not calculated. Some postoperative radiographs showed overpenetration (**Figure 24**).

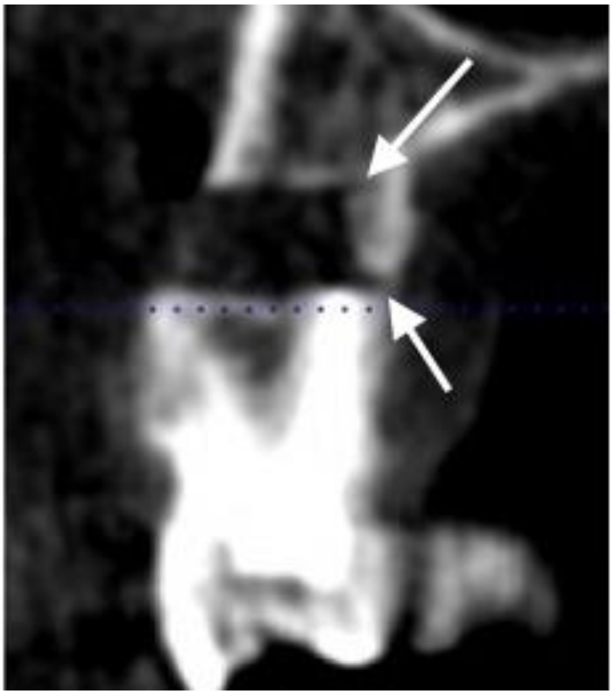


Figure 24. *Overpenetration: note the trephine markings in the palatal cortical (arrows).*

The median angular deviation was 3.95° (95% CI: 2.1-5.9). (**Table 4.)** The median apex removal error in the vertical plane (ARE) was 0.19 mm (95% CI: 0.03-0.07). The highest overcut was 0.93 mm, and the shortest cut fell behind the plan by 0.94 mm. In one case, exactly the planned length was cut. In 10 cases (71.4%), a longer piece of the apex was cut than planned, by a mean of 0.34 mm. In 3 cases, the resected piece was shorter, by a mean of 0.44 mm. The median osteotomy depth error (ODE) was 0.37 mm (95% CI: 0.15-1.35). Of the 13 remaining depth values, 9 (69.2%) indicated shallower osteotomy than planned by a mean of 0.71 mm, while the rest of the osteotomies were deeper than planned, by a mean of 0.31 mm. The highest overpenetration was 0.51 mm, while the shallowest penetration fell behind the plan by 1.56 mm.

Table 4. *Results of the measurements. AD: angular deviation (degrees); ARE: apex resection error (mm; -: longer than planned; +: shorter than planned); ODE: osteotomy depth error (mm; -: deeper than planned; +: shallower than planned). In Case #11, two roots of the same tooth were treated. NA: in these cases, the given parameter could not be measured (see Results). *Two roots of the same tooth were treated. Medians and corresponding confidence intervals were calculated from absolute values to express the degree of error regardless of its direction.*

Case	Tooth	AD	ARE	ODE
1	22	NA	-.033	+0.29
2	12	4.0	-0.08	+1.35
3	11	6.3	-0.70	+0.13
4	21	2.1	-0.76	-0.15
5	11	NA	-0.29	+0.56
6	11	3.9	-0.06	-0.06
7	12	5.3	-0.03	+1.43
8	22	4.0	+0.15	+0.57
9	44	NA	-0.41	+1.56
10	34	2.4	0.00	-0.53
11	14*	1.5	-0.93	+0.23
11	14*	1.5	-0.15	+0.23
12	11	2.9	+0.94	+0.23
13	22	5.9	+0.23	-0.51
median		3.95	0.19	0.37
95%CI		2.10-5.90	0.03-0.70	0.15-1.35
min-max		2.10-6.30	-0.93-0.94	-0.51-1.56

6.4 Introduction of the new technique with a custom-made trephine

No intraoperative complications occurred related to the applied technique or otherwise. The pre- and postoperative status can be compared in **Figure 25.** The immediate postoperative periapical radiograph showed good clinical results.

Figure 25. Periapical radiographs. ***a)*** *Before the surgery.* ***b)*** *Immediately after the surgery.* ***c)*** *Three months after the surgery.* ***d)*** *Six months after the surgery. Bisecting angle technique. The crown has also been replaced for aesthetic reasons*

To check positional accuracy the following parameters were analysed: deviation of the distal endpoint (DD, mm), deviation of the proximal midpoint (PD, mm), and angular deviation (i.e.: the deviation of the principal axes, ANG, degrees). Proximal and distal refer to the ends of the trephine bur. PD and DD were broken down to x, y, z vectors, where x: horizontal, y: depth (mesio-distal) and z: vertical (cranio-caudal). The results were as follows: PD: −0.006, 0.08, 1.18 mm; DD: −0.25, −0.097, 0.014 mm; ANG: 3.5°. (**Figure 26.**) At the 6-month follow-up it was found that periapical inflammation had not recurred, the healing had been uneventful, and no complications were observed.

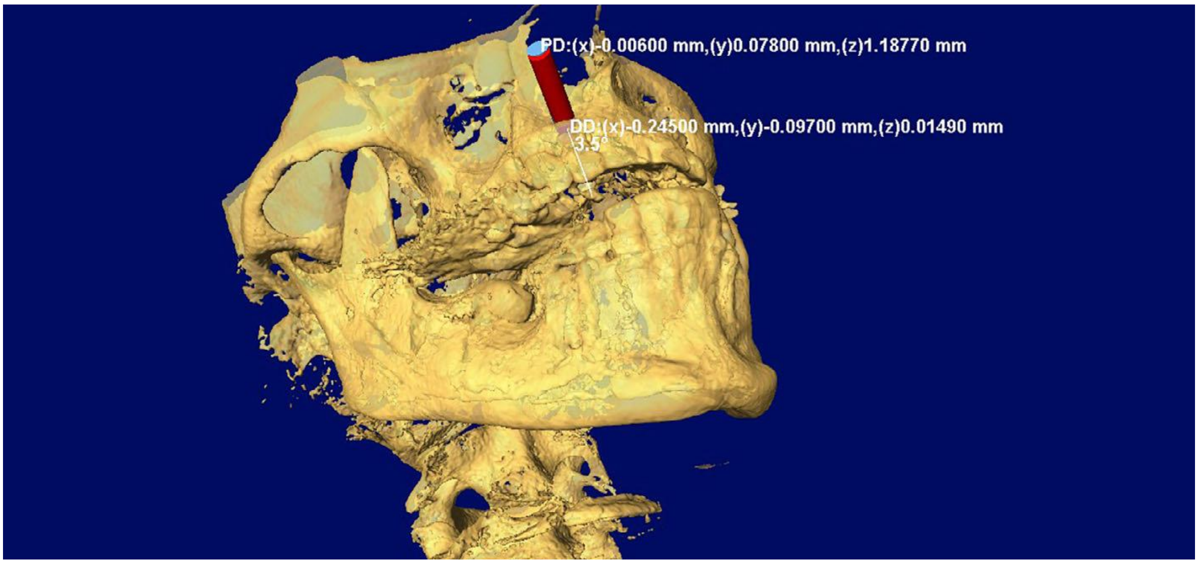


Figure 26. Accuracy analysis in Amira. ANG, angular deviation; DD, distal deviation; PD, proximal deviation. Coronal and apical deviations are broken down to x (horizontal), y (depth), z (vertical) vectors

6.5 Accuracy of template guided resection with custom-made trephines

6.5.1 Over- and underpenetration

The observations regarding the frequency and magnitude of over- and underpenetration by group are given in **Table 5.** Both over- and underpenetration occurred in both groups, but there was a vast difference in their occurrence: in the study group, underpenetration was more frequent (in 62% of the procedures), while in the control group, the situation was just the opposite: overpenetration was the predominant finding (in 70% of the procedures). The degree of underpenetration was quite similar in the two groups, approximately 0.7 mm, while the degree of overpenetration differed vastly. In the study group, the mean overpenetration was 0.36±0.31 mm, while the control group overpenetrated by a mean of 2.45±1.88 mm.

	S (N=21)		**C (N=23)**	
	OVER	**UNDER**	**OVER**	**UNDER**
N (%)	8 (38%)	13 (62%)	16 (70%)	7 (30%)
Mean	0.36	0.76	2.45	0.75
SD	0.31	0.54	1.88	0.97

Table 5. *Over- and underpenetration (deviation along the x axis) in the study and control groups. Means and standard deviations are given in millimetres.*

6.5.2 Accuracy

The results of the linear regression analysis indicated that the model was a significant predictor of GD (F (2,41) = 7.21, P=0.002, $R^2 = 0.26$. Group contributed significantly to the model (β = 0.53, p= 0.040), but surgical template did not (β = -0.02, P= 0.951). Considering this result, all further analyses were done by group.

As for GD, ANOVA indicated significant difference between the groups (F= 14.77, df=1, P= 0.0004, two-tailed). According to the descriptive analysis, the significant difference stemmed from the higher global accuracy of the study group: the mean global deviation in the study group was 0.92±0.60 mm [95% CI: 0.64-1.18 mm], in contrast to 2.45±1.88 mm [95% CI: 1.66-3.05 mm] in the control group.

ANOVA also indicated significant difference in deviation along the x axis (F= 12.01, df=1, P= 0.001, two-tailed). This, again, reflected the higher accuracy of the study group. In contrast to a mean deviation of 1.47±2.22 mm [95% CI: 0.51-2.43 mm] in the control group, the study group exhibited a mean deviation of only -0.28±0.72 mm [95% CI: -0.61-0.5 mm] (the negative value indicates that most of the procedures were characterized by slight underpenetration, see above).

As for the x and y axes, no significant difference was found between the groups. **Table 6.** provides the descriptive statistics for all studied parameters by group, with the significance levels for the between-groups comparisons.

Parameter	Group	N	Mean	SD	95% CI of mean	Significance
GD	S	21	0.92	0.60	0.64-1.18	P= 0.0004
	C	23	2.35	1.61	1.66-3.05	
x	S	21	-0.28	0.72	-0.61-0.5	P=0.001
	C	23	1.47	2.22	0.51-2.43	
y	S	21	0.03	0.32	-0.12-0.17	P= 0.510
	C	23	0.14	0.70	-0.17-0.44	
z	S	21	0.51	0.50	0.28-0.74	P=0.317
	C	23	0.31	0.76	-0.18-0.64	

Table 6. *Descriptive statistics of the studied parameters by group and the significance levels of the between-groups comparisons (one-way ANOVA). S: study group (stop trephine); C: control group (conventional trephine); GD: global deviation of the apical endpoint (millimetres); x: deviation of the apical endpoint along the bucco-lingual axis; y: deviation of the apical endpoint along the mesio-distal axis; z: deviation of the apical endpoint along the cranio-caudal axis. Means and standard deviations are given in millimetres.*

7 Discussion

The previously introduced surgical technique is a great curiosity itself because it combines the guided surgery, the usage of trephine burs and the principles of modern endodontic apicoectomy. Any of these can increase to success rate of apicoectomy, but we cannot find much evidence in the literature about the combination of these aids. Only few studies agree that guided root-end resection is efficient and superior to the freehand surgery [24, 49, 50]. The necessity of modern microsurgical methods is inevitable by now. However, data on guided interventions performed with a trephine is scarcely available[51]. Based on this our 1st hypothesis was the following: There is no significant difference between the 90 degrees cut and the semilunar resection line with trephine bur, regarding the elimination of apical accessory canals.

Based on our results, the hypothesis was accepted. The tested method eliminated all SNCs in 94% of the study specimens, and it eliminated 97.3% of the total number of SNCs in all study specimens. These percentages correspond almost exactly to those in the literature in connection with the conventional approach [52]. The treatment of only 2 teeth of the 33-teeth sample (6.1%) was unsuccessful, but these two failed cases were not related to the method per se. In one case, the residual SNC was located exactly above the section line, so it was impossible to eliminate because of the experimental design. The other SNC remained intact due to operator error: the trephine bur was not perfectly aligned to the midline of the root, which resulted in an asymmetric section (**Figure 27**).

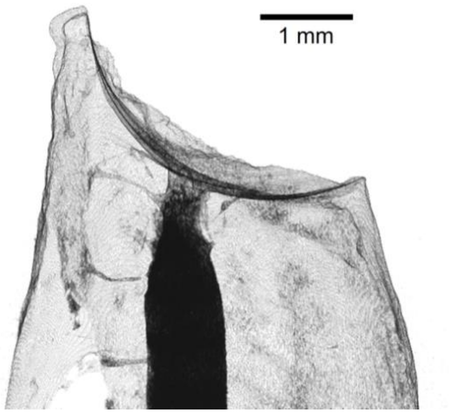


Figure 27. *Residual supernumerary canals due to operator error: the trephine was misaligned to the right, and this resulted in an asymmetric section*

This way, the apex was eliminated on one side, but a thick, triangular piece remained on the opposite side, containing the canal. Had the trephine been positioned properly, the SNC would have been eliminated. This type of failure can mostly be prevented by careful digital planning followed a guided resection with the help of a 3D-printed surgical template. At the same time, Tavares and colleagues point out that there are cases when apicoectomy is best performed with intentional misalignment, to preserve neighboring anatomical structures [53]. The conventional drill-based approach with a surgical guide is obviously more favorable in such cases.

Following from the experimental design, our results describe the optimal case, that is, if the section is made at as close to 3 mm as possible. This presupposes considerable accuracy. Apicoectomy with a trephine bur, *in vivo*, is a guided intervention, where normally a static surgical guide is applied. The guide itself is 3D- printed from the surgical plan, which is based on the patient’s individual anatomy. In the field of guided implant dentistry, this approach is considered to yield excellent accuracy [54], so, theoretically, static guidance should allow good enough accuracy to make the described high SNC elimination rates possible. As the approach is relatively new in endodontic surgery, we have little empirical evidence to draw firm conclusions from. Our own published clinical data suggest that static guidance does indeed provide accuracy to trephine- apicoectomy comparable to the documented accuracy of static guide-assisted implant placement [47, 55]. While further studies are necessary beyond doubt, it does not seem far-fetched to assume that the way trephine- apicoectomy is performed in practice (with static guidance) allows enough accuracy for the high efficiency was observed in our study.

To have comparable results, it was important that our sample should reflect the incidence of SNCs described in the literature. Vertucci found that the incidence of SNCs in maxillary central incisors was 24%, in lateral incisors 26%, and it was 30% in canines [56]. Adorno and colleagues found comparable ratios of accessory canals in their study: SNCs were detectable in 46% of central incisors, 29% of lateral incisors and 38% of canines [57]. Kasahara and co-workers reported that SNCs were observable in over 60% of teeth they examined [58]. In the present study, we found SNCs in 24.6% of the central incisors, 9.6% of the lateral incisors and 20.6% of the canines. The incidence of SNCs was obviously lower in the canines of this sample than what is reported in the literature. This is a relative limitation of the study, which is most probably traced back to the fact that lateral incisors became under-represented in the selection process. Thus, conclusions specifically related to this tooth type should not be drawn from the results.

While the description of the number of SNCs by tooth type was not an explicit goal of this study, we consider it an interesting finding that the mean number of SNCs in canines (2.75±2.30) was higher than in central incisors (1.86 ±0.77) or in lateral incisors (1.86 ±1.06). Furthermore, it was only in canines that we observed >4 SNCs (up to 8). Whether this finding indicates a unique characteristic of this tooth type is difficult to tell, as the (scarce) literature discussing canine root canal anatomy concentrates almost exclusively on morphology [59, 60].

While the in vitro examination proved the validity of the semilunar cut, the precision and applicability of the surgical procedure itself, should have been introduced via in vivo cases and measurements.

Whit the help of our first in vivo surgery we could plan and execute root resection, resulting in excellent long-term result. The indication of 3D planned and stereolithographically printed endodontic guides in dentistry was still not evidence based. However, Pinsky et al. found significant evidence on the precision of CAD/CAM guided resection compared to freehand surgery in 2007. Results showed that distance from the apex was 0.79 mm (+/-0.33 SD) using guidance and 2.27 mm (+/-1.46 SD) using freehand drilling. This technical aspect only had a renewal when stereolithography became more popular for medical aims. The insecure application of endodontic surgical guides started with a surgical retractor [29], continued with 3D pre-planned osteotomy window [30] and resulted in a completely 3D planned and guided apicoectomy in 2018 [32]. With the above introduced case we wanted to present our long-term result of a previously resected tooth's surgery. The planning software provided precise localization of the surgical field, the use of trephine bur via the sleeve of the template could execute the cut with high precision. The aim was to keep the adjacent anatomical structures (e.g.: Greater palatal artery, Mental nerve) sound in any case. Even complicated anatomical structures (e.g.: aligning apices, dens in dente or fusioned roots) can be removed with the help of the trephine. In this specific case, the main difficulty of the case was to keep the proper crow-root ratio, since the tooth has already been resected once. The software allowed us to plan the position of resection-line, while keeping the optimal ratio. The minimal necessary amount of root structure to be removed to eliminate most of the apical accessory canals can be planned with the help of the digital planning software (SmartGuide, dicomLAB Ltd, Hungary). The precise execution could be guaranteed by the surgical template. The importance of this novel technique is that we can minimalize the bone loss during the osteotomy window preparation and the apicectomy[61], so that we can facilitate the healing process. The reduction of operative time and the surgical field also has a beneficial effect on the postoperative healing period.

To get further information on the precision of guided endodontic surgical procedures, we have planned a targeted clinical trial regarding drilling parameters that can be measured with 3D evaluation.

The few available studies agree that guided root-end resection is efficient and more accurate than freehand surgery [49, 50]. To our knowledge, we are the first to report a series of clinical cases where osteotomy and root-end resection were carried out at the same time, with the same instrument (a bone trephine), using 3D printed surgical guides. Our first hypothesis for this in vivo study was that intra- and postoperative complications would be no more frequent and severe with the studied method than what is usual in freehand cases as reported by the literature and as shown by our own clinical experience. As we observed no complications at all during surgeries, we consider this hypothesis confirmed.

The second hypothesis was that the method would allow the resection of the root with the trephine in all cases, so no further manipulation to this end would be necessary. This hypothesis was also confirmed; the root end was successfully resected in all cases, and in most of the cases it was also removed with the trephine. This is practically important because this way the root-end resection and removal procedure can be carried out in one simple step. However, we also have to note here, as a limitation, that in our study, we have included front or premolar teeth only. To our current knowledge, this is a limitation in the interpretation of our results, but not a limitation to the technique itself. No study has indicated that the described method is not suitable for molar teeth, though we have to understand, that due to the anatomical difficulties it might be more challenging to implement the same surgical performance in the molar region. However, some of the case reports presented, were involving the periapical surgery of molar teeth [31, 32].

Our third hypothesis was that by utilizing this method, the vertical error of root-end resection and the error of osteotomy depth would not be greater than ±1 mm. This hypothesis was only partially confirmed, regarding the error of root end resection, which remained within 1 mm in both directions in the vertical plane (− 0.93mm to + 0.94 mm). This indicates that the guidance was quite efficient (as reflected also by the angular deviation measurements, see below). The error of the depth of the osteotomy, however, exceeded the ±1mm limit in three instances, which indicates that the method was less accurate in the horizontal dimension. These deviations indicated underpenetration (the fact that this did not affect the success of resection indicates that the planned depth was excessive in these cases). At the same time, overpenetration was also a recurrent finding, even if within the ±1mm limit (see **Figure 24**). What these results suggest in general is that repeated depth check with a periodontal probe and observing the markings on the trephine are not enough to make the surgeon confident about this dimension. We propose that trephines with a stop (like implant drill bits) could resolve this problem.

Our last hypothesis was that the angular accuracy of the osteotomies would be close to that of template guided dental implantation. As our study was the first to assess this parameter for guided trephination, there was nothing else to compare our results against. At the same time, this is a very important parameter, as it can determine if the root-end resection is successful (i.e.: if a large enough part is resected to get rid of all the accessory canals, the very aim of the procedure). This last hypothesis was also confirmed. Tahmaseb et al., in their meta-analysis on guided implantation with tooth-supported guides, reported an overall angular deviation of 3.5° (studies of full and partial edentulousness included) [54]. Endodontic surgical guides cannot be considered entirely tooth-supported guides. Of course, it is the teeth that the template rests on, but the direction of the operation is not perpendicular to the occlusal plane, which would help to keep the guide in place. Rather, the operation happens perpendicular to the soft tissue, which adds instability to the system. The poorer accuracy of mucosa-supported guides is a known problem in guided implantology [62].

Following from these, one would expect the angular deviation to be slightly poorer than but still comparable to that of implant guides. The median deviation of 3.95° we found confirms that expectation. Beyond addressing our hypotheses, we would like to point out a practical difficulty we often faced. Obviously, to have the guiding sleeve at the level of the apex, the impression (that serves as the model for the template) must contain information on the tissues at that level.

As the above-mentioned study has revealed, the guided apicectomy has a tendency for errors in the horizontal plane. The depth of penetration is crucial, if the under- or overpenetration is more than 1mm, the microsurgical apicectomy can be incomplete or can jeopardize important anatomical structures, or even the oral cortical bone plate [55]. This feature can be multicausal, effected by the soft tissue thickness of the surgical field or by the lack of proper stop during the application of the trephine bur. However, with the position of the sleeve on the template we can pre-set the depth of penetration, the operator factor can modify the endpoint of the movement. The idea of custom-made trephine with a definitive stopper to hit the sleeve can be a solution to this problem.

The approach demonstrated with the apicectomy of the lateral incisor has been developed to reduce user error and thus make root end surgery safer and more accurate by applying custom-made trephines with a stopper feature in combination with digital planning and static guidance. Based on our initial results, our approach appears to be fit for that purpose. Of the elements of the system, the custom-made endo-trephines mean to be the real innovation. The necessity of a stop to prevent overpenetration does not require further explanation, but we think that it is important to briefly discuss the diameters and the shape and design of these instruments. As for the diameters, our goal was to define diameters that could be used in most of the patients we see without risking damage to neighbouring anatomical structures (the roots of neighbouring teeth, the alveolar nerve, or the sinuses). As the aim is to cut a 3 mm piece of the apex, the starting point was that the diameter should be larger than 3 mm. Initially, we planned 3.5- and 4.5-mm trephines, but we reduced these values to 3.46 and 4.46 mm to allow for the 0.4 mm distance from the sleeve and the horizontal motion of the pieces. 5.0 mm we considered as the upper limit, as with such a large diameter it would be difficult to keep the 3 mm rule, and we could have ended up eliminating the accuracy benefit of the guidance and minimal invasiveness as well. Working with smaller diameters also leaves room for further extension, if need be, while repairing damage done by a larger-diameter instrument is not always possible - if at all. As for the shape and design, it was established before that we sought to create a guided trephine that could be inserted into the guiding sleeve from the front side. We approached this problem in the most straightforward fashion, by designing a trephine without the usual slight widening at the working end. While the exact function of that design element is not clear, (we have found nothing about it in the literature), it is reasonable to assume that it is related to cutting efficiency or heat dissipation. In our experience, this modification has not decreased the cutting efficiency of the instrument. We have no data regarding heat generation and heat dissipation, but it is safe to assume that with copious irrigation it should not be a problem [36, 63, 64]. However, this question needs further exploration. The only difficulty we experienced with this design is that the cylindrical piece of tissue that was removed often stuck into the instrument and could be removed only with great difficulty. The problem of removal needs to be solved, possibly with some simple pushout mechanism. However, we do not wish to eliminate the excessive adherence of the instrument to the removed tissue, as this is probably the very feature that makes it possible to resect and remove in one step. All in all, our overall (if limited) experience with the new design is positive.

The primary indication of the presented intervention is the periapical surgery of single-rooted teeth. In the case of multi-rooted teeth, we recommend this technique only for the treatment of one root at a time, preferably a buccal root. The treatment of palatal roots is theoretically not excluded (with buccal access preparation or even with palatal access as Giacomino et al. have presented [32]), but we have no experience with such cases. A foreseeable limitation is that in some cases access in the molar region will be limited (i.e.: the soft tissues of the face cannot be retracted enough to allow the insertion of the guide with the trephine and a hand piece). The problem may be addressed by using shorter trephines (readily handled by the software too), but this naturally limits the possible depth of penetration.

A technical issue to be mentioned is that we CBCT scanned the patient's impression, but this is only one of the possible protocols [65], which we followed because we have prior experience with it [46, 55]. Optical scanning of the impression or of a poured model, however, is just as possible, and may even allow more accurate 3D models, as the latest studies suggest [66]. Still, we would not recommend intraoral optical scanning, given the difficulties with soft tissue movement during scanning.

Application of the custom-made trephine corroborates the findings of Giacomino et al. regarding guided endodontic surgery with a trephine [32]. Digitally assisted, guided endodontic surgery with a trephine appears to be an easily performed, safe, and complication-free method, which allows the resection and removal of the root tip in a single step. The approach itself is a step toward a standardized digital system and workflow dedicated to guided endodontic surgery. The system at that point was still under testing and was not yet commercially available. Three-dimensional accuracy measurements (i.e.: comparison of the digital plans with the end results) could not provide enough data at that point to draw firm conclusions. The available data indicated that surgical accuracy achievable this way is like that observed in connection with full guided implant placement. This suggested that the enhanced fit of the trephines also enhances accuracy, but this can be stated only when a statistically meaningful number of cases has been reached.

As it is clearly highlighted in the previous case that the promising results should be investigated via bigger number of samples. In vitro examination of porcine mandibles with control (conventional trephine) and test (custom-made/endo-trephine) bur-holes. The endo-trephine used in this study was designed to prevent such overpenetration. It must be noted that bone trephines of varying working lengths and diameters are available. Our endo-kit, for instance, contains altogether six pieces (2 diameters and 3 working lengths) [47]. It can be hypothesized that a shorter working length (especially with a wider diameter) allows more accurate outcomes. In the in vitro animal model study, we used only one working length (20 mm) and two negligibly different diameters (4.21 and 4.46 mm). The concrete, numerical accuracy results, therefore, are best interpreted as characterizing instruments of similar dimensions, which is a limitation of this study. Further research is necessary to clarify how the working length and the diameter of the applied instrument influence the accuracy of these procedures.

We hypothesized that overpenetration would be a frequent finding with a conventional trephine, and less frequent or absent with the trephine equipped with a stop. The results confirmed this hypothesis: while overpenetration did occur in the study group, it occurred less frequently, and its degree was well within a safe 1 mm margin. In contrast, overpenetration was seen in 70 percent of the interventions performed with the conventional trephine, and its degree was considerably higher. The explanation for this tendency of overpenetration is probably quite simple: as the operator uses the instrument, the operator applies pressure on the handpiece to push the trephine forward in the bone. Even if the pressure is not excessive and is applied evenly, the hardness and structure of the bone are not completely homogeneous. If the working end of the instrument meets an area of lesser resistance (which the operator cannot see and thus applies the same amount of pressure), it might cause the instrument to slip forward in the bone. This cannot be prevented by observing the depth markings on the trephine, while the addition of a physical stop does efficiently prevent major overpenetration. Underpenetration was present in both groups and to a notably similar degree. We have concluded that this is not a real problem, but a consequence of a minor flaw of our measurement method. During the planning phase of the apicoectomies, the depth the trephine should penetrate into the bone, was determined with the help of solid cylindrical models. We conceptualized the trephines as solid cylinders and used the distal endpoint of these cylinders for our measurements. However, the trephines are, in fact, not solid but hollow and they have a cutting working end. This way, the final depth of penetration is defined by how deep the working end cuts, not where the endpoint of the body conceptualized as a solid cylinder is. Following from this, if a solid body of the same length and diameter as the trephine is introduced in the tunnel (like we did for the postoperative control scans), it cannot penetrate just as deep as the trephine, as it will be blocked by the small piece of unreduced bone left behind by the non-working inside of the trephine (**Figure 28**). To put it simply, it is safe to assume that in most cases, the trephine penetrated slightly deeper than what we could measure because the metal cylinders we used as segmentation aids were solid. The difference is obviously negligible, and it probably has no clinical relevance, but it is both a reasonable explanation to part of the findings and a limitation we need to mention.

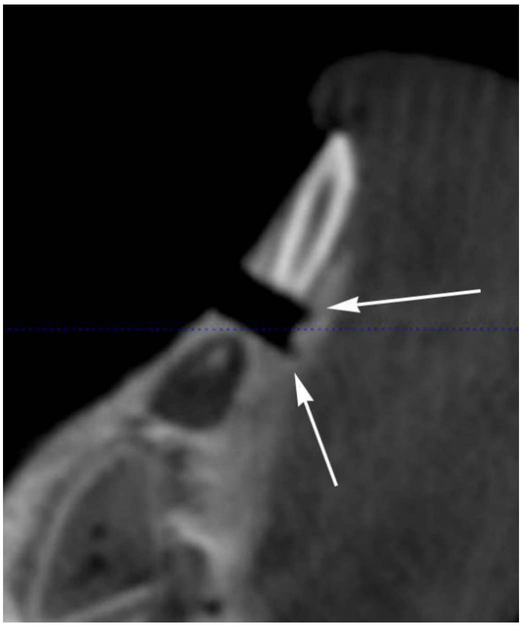


Figure 28. *The characteristic mark that the trephine leaves in the bone. The serrated working end makes a circular cut that surrounds a small piece of unreduced bone. The figure also illustrates the problem of overpenetration: a shallower penetration would have been enough for a successful procedure, but there was no stop to prevent overpenetration and the instrument stopped in the cortical bone on the opposite side. Any further penetration could have ended up in perforation, which is not a desirable outcome in a clinical setting.*

We also hypothesized that the accuracy of the procedures performed with the stop trephine would be no different. This hypothesis was not confirmed. Significant difference between the two groups was found in global apical deviation and in deviation along the x axis (bucco-lingual depth, as discussed above). Note that the two instruments were characterized by almost identical accuracy along the y and z axes, which means that considerable deviation along the x axis in the control group had been the source of error that resulted in the significant global difference between the two instruments. This suggests that the control of penetration depth is indeed the key issue of the accuracy (and safety) of trephine apicoectomy. It is also noteworthy that the standard deviations for GD and x in the control group are much higher than in the study group, indicating that the lack of appropriate depth control resulted not only in poorer accuracy but also in poorer precision. How accurate and satisfactory is the global apical deviation of 0.92±0.60 mm [95% CI: 0.64- 1.18 mm] achieved with the endo-trephine? Given the novelty of the approach, a direct comparison with the literature is not possible. However, it makes sense to compare the results against those of studies that examined the accuracy of digitally planned guided implant placement through a tooth-supported surgical template, because a goal of key importance in both procedures is to position a cylindrical body in the human mandible or maxilla as accurately as possible. Global apical deviation is a frequently reported measure of accuracy in the literature of implant surgery[46, 67-69]. In their latest systematic review and meta-analysis, based on the analysis of 20 studies, Tahmaseb and co-workers concluded that the mean error of apical position for partially edentulous cases (i.e., cases where a tooth-supported template could be used) was 1.2 mm [95% CI: 1.11–1.20 mm] [54]. In a previous randomized controlled clinical trial of our co-workers, where the same software and digital workflow for implant placement were used as here for apicoectomy, a mean of 1.59 mm global apical deviation for both partial and full guidance was found (the two comparable study arms of the four, where the surgical guide was used for the entire process of osteotomy) [46]. For this discussion, we re-analysed the old dataset for partial and full guidance only. As the analysis did not indicate significant difference in global apical deviation between the two groups, we treated them as a single group and found a mean global apical deviation of 1.66±0.84 mm [95% CI: 1.44–1.88 mm]. The results may make the impression that the accuracy of guided trephine apicoectomy is somewhat higher than that of guided implant placement. It must be taken into consideration, though, that *in vitro* results tend to show higher accuracy than what is clinically achievable. It appears more proper to conclude that the guided use of the endo-trephine allows results approximately of the same accuracy as guided implant surgery. Clearly, it is not possible to reach the same level of accuracy when a conventional trephine is used.

8 New findings

- Regarding our research on the precision of the trephine bur apicectomy, we can conclude that the semi-circular cutting line can eliminate the accessory canals and ramifications of the critical 3 mm of the root apex with great efficacy. This is equal to the 90 degrees cutting method which is the guideline to be followed in modern endodontic surgery so far.

- We can state that the guided apicectomy in endodontic microsurgical procedures with stereolithographic templates increase the precision of the surgical intervention similarly to guided implantology.

- The accuracy of the procedures performed with the stop trephine is higher compared to conventional trephines regarding osteotomy depth. Results suggest that the usage of a stop-trephine can prevent overpenetration.

- Intra- and postoperative complications are no more frequent and severe with the studied 3D guided method with the usage of a trephine, than what is usual in freehand cases as reported by the literature.

- The periapical surgery performed with static guidance allows the resection of the root with the trephine, without the necessity of further manipulation.

- The vertical error of static guided root-end resection and the error of osteotomy depth performed with a trephine is not greater than ±1 mm

9 Summary

In the era of implant restorations, we consider conservative treatment of teeth highly important. Not only because of the financial withdraws of implant supported restorations, but for the physiological well-being of the patient. Fortunately, with the word-wide spreading modern instruments and theories the success rate of conservative therapy is steeply rising.

Following the modern principles of apicectomy, the chance for minimal invasive surgical endodontics is already available for most of the experts. The help of high-resolution magnification and the evidence based 90 degree-resection line can provide better bacterial sealing and significantly better prognosis in terms of healing.

Our research was based on a new approach of microsurgical endodontic treatments. With the help of the well-known implant planning software and the data from CBCT images the precision of apicectomy can be increased. By using surgical templates, modified for endodontic surgery, the angle, the depth and the size of the apicectomy can be determined in advance. Our research revealed that with the help of these 3D planned guides a more precise and standardised surgical intervention is available for everyone.

The novum of our technique is the usage of trephine burs. By using trephines, the semi-circular cutting line can eliminate the accessory canals and ramifications of the critical 3 mm of the root apex with great efficacy. This is equal to the 90 degrees cutting method which is the guideline to be followed in modern endodontic surgery so far. This bur can be easily implemented into 3D planning software, and can transform the bony window preparation, the apicectomy and the biopsy taking into a one-step procedure. The initial prototype's imprecision regarding overpenetration with the trephine bur into the oral cortical plate was fixed by the usage of trephines with a definitive stop. With this continuous development of the above-mentioned technique, we tried to eliminate all the possible risk factors of microsurgical endodontic interventions and to lessen the severity of postoperative complications.

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