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Review Article

Cutting bone with drills, burs, lasers and piezotomes: A comprehensive systematic review and recommendations for the clinician

Abstract

Background: New tools for bone-cutting were introduced to oral and maxillofacial surgery in the last decade, such as lasers and piezotomes.

Purpose: to evaluate most recent evidence, when surgical procedures performed with drills or burs are compared with laser- and/or piezotome-surgical procedures in experimental and clinical studies and to assess possible advantages of their use in daily practice.

Methods: a systematic search of various medical databases with specific keywords was performed, excluding studies published before 2006 for their possible invalidity by technological progress. Systematic reviews were assigned to Group 1, experimental studies *ex vivo* to Group 2, *in vivo* to Group 3 and clinical studies to Group 4. All studies in each of the groups 2 – 4 were appraised regarding their evidence, starting with a value of 0 for no evidence of advantages of lasers and/or piezotomes compared to rotary instruments, 1 for moderate evidence with verified clinical impact and 2 for strong evidence and significant clinical impact and statistically processed for their Evidence Value (EV) in each group and their Overall mean Evidence Value (OmEV).

Results: 129 studies were finally included for evaluation. Two systematic reviews concluded lack of evidence for lasers to be advantageous over burs/drills. Nine reviews for piezotomes reveal strong evidence piezotome-surgery to significantly reduce morbidity and to enhance soft-tissue preservation. Comparative experimental and clinical studies of burs/drills vs lasers revealed a low EV in Group 2 (EV:0,8), Group 3 (EV:0,5) and Group 4 (EV:0,5) with an OmEV of 0,6. Comparative studies burs/drills vs piezotomes resulted in a significant EV in all groups (Group 2: 1,4, Group 3: 1,3, Group 4: 1,59) with an OmEV of 1,4.

Conclusions: the results suggest too little evidence to establish lasers as an alternative to rotary instruments. Piezotomes seem to define a possible new gold-standard in bone cutting due to their improved bone-healing, almost bone-lossless and precise osteotomy design, precise depth-control, soft-tissue protection as well as reduced intrasurgical and post-surgical morbidity.

Abbreviations

EL: Evidence Level; EV: Evidence Value; OmEV: Overall Evidence Value

Introduction

Performing bone-cuts and bone-trepanations is the very basis of the Oral and Maxillofacial surgeon's daily task and until recently were carried out exclusively with rotary instruments like drills and burs or slow-oscillating saws. Only in the last decade, new technologies evolved as commercially

available and certified devices for bone cutting such as lasers and piezotomes. Drills, burs, lasers and piezotomes act fundamentally different in their physical mechanism of cutting bone.

Drills, burs, slow-oscillating saws

Driven by micro-motors or air-pressure-turbines, drills, burs and slow oscillating saws cause a mere mechanical ablation by hacking, crushing and shearing bone with serrated or diamond coated rotational hard-metal bodies of spherical, conical, cylindrical or saw-like shapes. The speed of action

depends on the size and coarseness of the serrated surface (from macro-serration to diamond coating), speed of the handpiece and pressure exerted onto the bone, thus causing frictional heat, which might cause bone-necrosis [1]. Heat dissipation by water-beam cooling decreases significantly in surgical practice if the water-beam is not precisely adjusted to target exactly the cutting center of the bur, is blocked by soft-tissues or other surgical instruments, or is reflected by the adjacent bone-surfaces of the osteotomy line with increasing depth of the osteotomy or drill-hole [2].

Drills, burs or low-frequency oscillating instruments are difficult to handle when used on cortical and trabecular bone due to its procedural high physical torque-moment especially in the initial phase of the osteotomy-design on cortical bone. The more coarse the serration of the bur, the more difficult it is to design a perfect osteotomy-line or an anatomical precise drill hole for implant-placement especially for novices.

The major and unavoidable medical drawback of drills, burs and slow-oscillating saws is the enormous procedural bone loss due to the minimum necessary diameter of the instrument of at least 1,5 – 2 mm and the imprecision of the cut due to the high torque-moment, which has to be tamed by the hand of the surgeon as the author's demonstration *in vivo* shows (Figure 1). Additional, there is a high risk of soft tissue injury to important anatomical structures such as the inferior alveolar nerve (IAN) [3] or maxillary sinus-membrane and deposition of metal shavings and bacterial contamination [4].

Lasers

Compared to drills, burs and slow-oscillating saws, lasers act completely different on bone when performing bone cuts. Commercial available laser-devices for bone-cutting in dentistry and oral and maxillofacial surgery – commonly called “Erbium-laser”, “Neodymium-laser” and “Carbon-Dioxide-laser” – emit a coherent light-beam of a precisely defined wavelength in the invisible infrared spectrum of light. The invisible infrared heat beam is transmitted either by optical lenses, hollow tubes or quartz-fibers to the focus-spot on the bone, which typically has a diameter of 0,4 – 1,0 mm depending on the focus-mechanism, the precision of the quartz-fiber tip and distance of the laser-handpiece to the bone by divergence of the coherent infrared light beam [5].

Once the heat-beam hits the intra- and extracellular water-molecules in dentin (~20% H₂O), cortical or trabecular bone (~20–30% H₂O) and molecular composition of carbonated Hydroxyapatite (OH⁻, CO₃, PO₄, intercrystal free H₂O), the heat is instantly almost fully absorbed (Figure 2) and leads to micro-explosions of vaporized superheated water vapor (“plasma plume”). The micro-explosions – heat energy transformed into kinetic acoustic energy – are well audible by the patient and surgeon by achieving up to 120 dB in bone [5] and by this enormous kinetic sound-pressure shock wave – called “photoacoustic effect” – ablates the bone by shattering the Hydroxyapatite crystals and disrupting collagen fibers. Physically it is a heat-induced cavitation-effect creating cavitation-bubbles (Figure 3). Once the water in bone-tissue is consumed, the heat energy cannot be transformed into kinetic sound-energy anymore and thus leads to carbonization

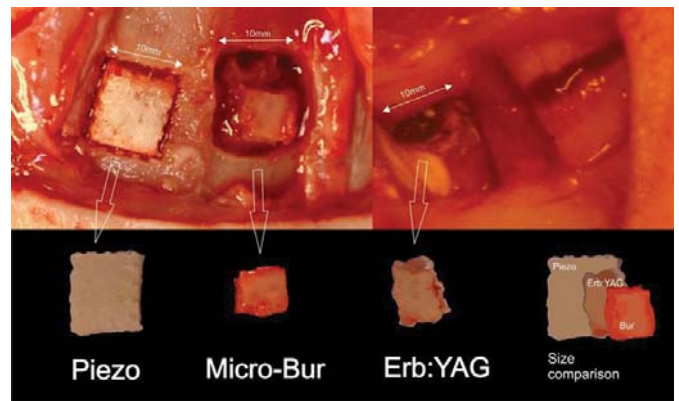


Figure 1: Comparison of procedural bone-loss when a bone block of 1 cm² is cut out by micro-bur, piezotome and Er:YAG-laser. Bone-cut on the most upper right side was performed with an experimental Excimer-UV-laser and is not included in the rating.

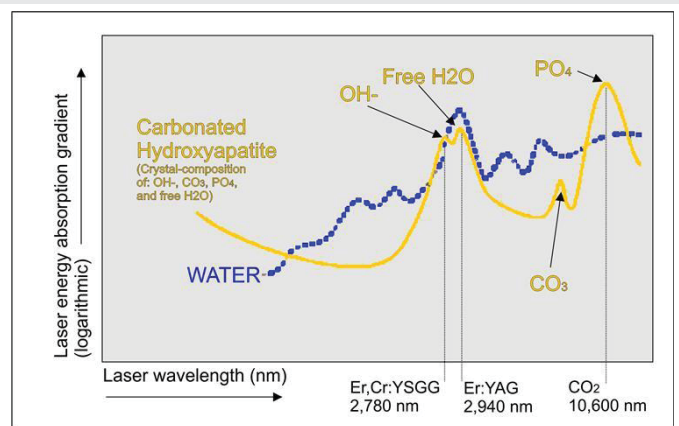


Figure 2: Laser energy absorption gradient in water for common, commercially available laser-systems for bone cutting (Er,Cr:YSGG, Er:YAG, CO₂). Depending on the infrared wavelength (“invisible heat radiation”), lasers act different on calcified tissues. Erbium-lasers have a high water-absorption-coefficient resulting in very little depth-penetration into tissues per single-pulse but sufficient energy-density on the focal spot to cause the photoacoustic- and cavitation-effect depicted in Figure 3.

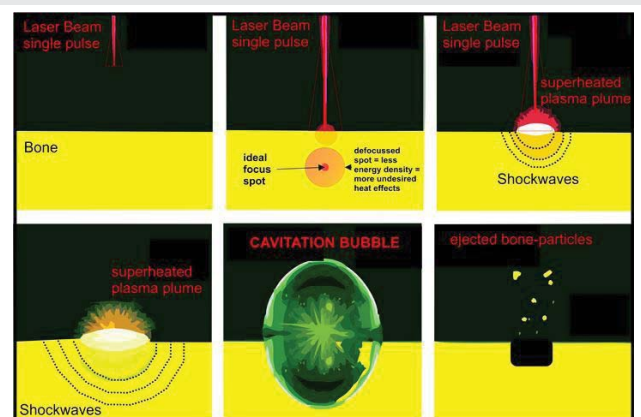


Figure 3: Depiction of the physical effects - photoacoustic effect and cavitation - caused by a single laser-pulse on bone. If the laser-pulse is well focused the heat energy at the target (bone-surface) is completely absorbed immediately and converted into a superheated plasma plume causing the generation of acoustic shockwaves sent into to bone. The rapid expansion of the plasma-plume leads to the creation of a cavitation-bubble, which finally collapses and ejects bone-particles. This is also the cause for the characteristic knocking sound when lasers are used for bone cutting while cutting lasers for soft-tissues have a more humming sound. In case the laser pulse is not precisely focused (dotted red lines) bone is only heated and carbonized.

and necrosis of the adjacent bone-layers [6], in case of dentin and enamel to vast cracks and unwanted separation of tissue-layers as the author's investigations on freshly extracted teeth show (Figure 4). To reduce the risk of heat-induced bone-necrosis by lasers (especially in deeper osteotomies) and to deliver water to the osteotomy-site, a water-spray-coolant is mandatory although this might lead to unwanted patient's body-liquid-splatter in the surgery room [5].

The efficacy of bone cuts with commonly used Erbium- or CO₂-lasers depend on the precision and cleanliness of the focal-system (mirrors or quartz-fibers), the focus-spot-dimension and energy-density in the focus-spot and the pulse quality of the intermittent blasting laser-beam (to allow dispersion of the heated "laser-plume" carrying the debris and cooling of the osteotomy-site between the intermittent laser-pulses [6]). Furthermore, focal laser energy cannot and must not be increased above the threshold of the laser-specific bone-ablation-property since an increase would only lead to detrimental bone-necrosis and not to faster bone cutting [5,6].

Although osteotomies with lasers allow a precise osteotomy-design (since only the laser-beam should touch the bone) [7] with substantial less procedural bone loss compared to drills and burs (Figure 1) and disinfection of the surgical site itself [6] (but dispersion of possible infective agents in the oral cavity and OR-room [5]), a major drawback is still the complete lack of osteotomy-depth-control, haptic feedback and soft-tissue preservation [8].

Piezotomes

Although on the macroscopic level piezoelectric surgical tools resemble drills, burs and slow-oscillating saws by their shape, their physical mechanism of action is merely mechanical only to the smallest part. Piezoelectric crystal rings - activated by electric current - initiate a precise unidirectional ultrasonic oscillation - especially in medical literature wrongly described as "vibrations" - at a rate of 28.000 - 36.000 modulated harmonic oscillations per second and a distance between 60 and 200 μm (Figure 5). Any rigid physical body oscillating at ultrasonic speed in liquids creates the physical phenomenon of the pressure-induced cavitation effect, which is very similar to the photoacoustic effect caused by infrared laser beams in liquids, but at significant lower temperatures [9]. Thus, the physical mechanism of cutting bone with Piezotomes is based on precise disruption of mineralized bone-components by harmonic acoustic shockwaves and cavitation - similar to ultrasonic kidney stone crushers - but completely preserves soft tissues from damage due to the ultrasonic frequency of the devices [10,11]. The pressure-induced cavitation effect - as demonstrated by the author's investigations of various piezotome-surgical tips (Figure 6) - enhances the clean separation of mineralized tissue formations, enables a significant improved bone healing [10, 11], and - at lower power-settings - an improved and non-destructive dissection of soft-tissues [12] with improved postsurgical hemodynamic microcirculation [13].

Possible heat generation caused by the ultrasonic oscillating instrument is sufficiently counteracted by the applied cooling-liquid, which adheres to the working-tip at the surgical site due to acoustic resonance-adhesion as demonstrated by the

author's investigations (Figure 7). Only improper handling of or faulty constructed piezotomes might lead to increased intrabony heat-peaks (e.g. too high manual pressure by the surgeon, reduction of cooling saline-flow beyond required minimum, faulty constructed piezotomes causing irregular vibrations instead of harmonic, modulated oscillations of the working tip).

Piezotomes provide least procedural bone-loss (Figure 1) due to working tips of a cutting width of only 0,1 - 0,2 mm and allow a precise osteotomy-design comparable to lasers but with precise depth-control and least risk to damage soft-tissues due to the oscillation frequency-range.

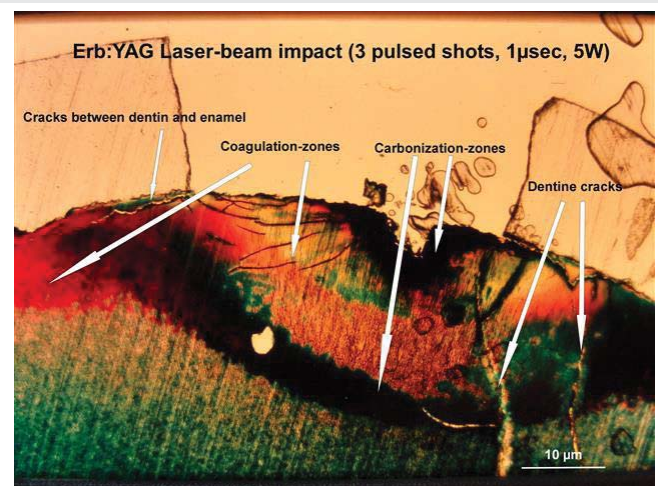


Figure 4: Histology of a freshly extracted tooth at the enamel-dentin-margin treated with 3 pulses of an Er:YAG-laser (Azan-staining) without copious irrigation: coagulation and carbonization-zones are visible as well as cracks between dentin and enamel and within dentin, caused by the plasma-plume and the initial shock-waves.

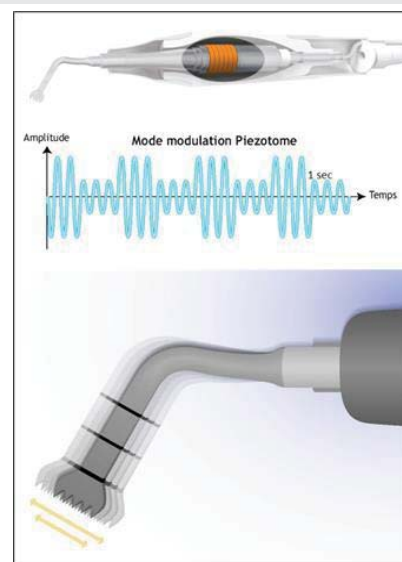


Figure 5: Schematic depiction of a piezotome-handpiece: six piezoelectric ceramic rings are activated by electric current for precise and only unidirectional modulated harmonic oscillations, which are intermittently modulated for their amplitude to match exactly the bone-quality (D1,D2,D3,D4) the piezotome is working in. It is the most important constructional quality criterion for piezotomes to provide precise only unidirectional harmonic oscillations instead of uncoordinated irregular vibrations which only generate heat but no cavitation effect.

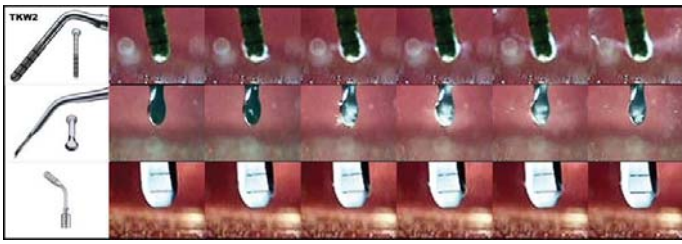


Figure 6: The pressure-induced bone-cutting cavitation-effect demonstrated on three different piezotome working-tips. The cavitation effect should be restricted to the small part of the surface of the tip in contact with bone to provide an optimum efficacy for smooth and fast bone-cutting without thermal side-effects and maximum soft-tissue preservation and is the major constructional quality criterion for piezotomes.

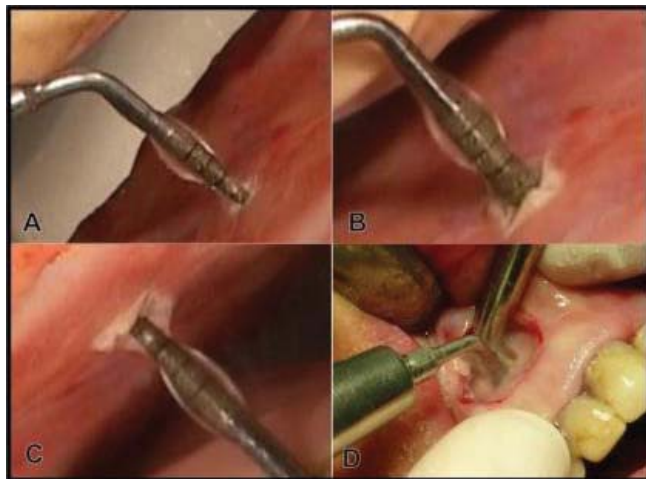


Figure 7: A. acoustic resonance-adhesion of the cooling liquid on the working-tip (diamond-coated TKW 1 tip for transcrestal hydrodynamic cavitation sinuslift), B. the acoustic resonance-adhesion is independent from gravity-vectors and applies proper cooling also in vertical-up-procedures. C. every working tip needs proof of proper cooling by acoustic adhesion of cooling liquid (TKW 4-tip). D. Apisectomy of a 2nd upper incisor. After bone-preserving removal of a square buccal bone-plate around the apex for later reposition and precise reconstruction of the local anatomy, the apex is resected with a serrated piezotome-tip. Due to the harmonic oscillations the irrigation-solution adheres to the entire surface of the working-tip and provides sufficient cooling and liquid to enhance the cavitation effect. With piezotomes no spray-fog emanates from the surgical site.

The purpose of the systematic review was to evaluate most recent comparative evidence in *ex vivo* and *in vivo* experiments on micro molecular, microscopic and macroscopic level and comparative clinical results regarding patient morbidity, when surgical procedures performed with drills or burs are directly compared with laser- and/or piezotome-surgical procedures. Furthermore, the range of applicability, advantages and drawbacks of the different surgical tools were investigated to provide up-to-date evidence and recommendations to the clinician.

Material and Methods

Literature search strategies

The databases, indexes and search engines MEDLINE, PubMed, Cochrane Library, Scopus, Web of Science (ISI), Trip, Dentistry and Oral Science Source, DOAJ, NSLC, OAJSE, Index Copernicus and Google Scholar were used to identify references

matching the keywords “osteotomy”, “bone”, “cut”, “cutting”, “crest”, “alveolar ridge”, “bur”, “drill”, “rotary instruments”, “saw”, “laser”, “Er:*”, “Nd:*”, “CO2*”, “piezo”, “piezoelectric”, “ultrasonic”, “Piezosurgery”, “Piezotome” alone (Boolean operator “NEAR”) or in dual/triple combination by Boolean operators “AND” and “OR”.

All references matching the keywords, but were being published before the year 2006, were excluded to avoid inclusion of studies with experimental and technological outdated devices or already analyzed in published systematic reviews and meta-analysis.

The abstracts of the remaining retrieved reports then were thoroughly scanned and a set of criteria applied for their inclusion in the preliminary reference list.

Inclusion criteria

The abstracts were assigned to four thematically different groups:

Systematic reviews and meta-analyses of rotary instruments vs. laser and/or piezoelectric instruments

Comparative experimental *ex vivo* studies of rotary instruments vs. laser and/or piezoelectric instruments

Comparative experimental *in vivo* studies of rotary instruments vs. laser and/or piezoelectric instruments

Comparative clinical studies (randomized controlled trials – RCTs, prospective and retrospective) of rotary instruments vs. laser and/or piezoelectric instruments.

Exclusion criteria

All abstracts reporting case studies, general reviews, overviews, technical notes, expert opinions, non-comparative experimental and clinical studies or published in non-peer-review journals were excluded.

Critical appraisal

The included systematic reviews and studies were retrieved as full text, critically evaluated separately by each author regarding procedural flaws, inadequate study- or review-design or too many potential biases. In case a unanimous assessment by the authors could not be achieved, an independent referee evaluated the report or systematic review for in- or exclusion.

Statistical evaluation

All included reports in each of the groups 2 – 4 were appraised regarding their evidence, starting with a value of 0 for no evidence of advantages of lasers and/or Piezotomes compared to rotary instruments, 1 for moderate evidence with verified clinical impact and 2 for strong evidence and significant clinical impact. The evidence-values for each type of surgical tool-comparison were added and divided by the number of publications comparing rotary instruments with lasers and/or Piezotomes.

Primary outcome evaluation

To assess weak or strong evidence if the use of lasers and/or piezotomes has advantages regarding precision of bone cuts, improves bone healing and reduces post-surgical patient-morbidity when compared with traditional rotary instruments.

Secondary outcome evaluation

To assess applicability, indications and restrictions of lasers and/or piezotomes in the daily work of oral and maxillofacial surgeons when compared with traditional rotary instruments to give evidence-based recommendations to the clinician.

Results

954 potential references were found in the databases of which 461 were published since 2006. 279 abstracts then had to be excluded in accordance with the exclusion-criteria. From the final 182 full-text publications 53 had to be excluded due to procedural flaws (e.g. imprecise study design with too many variables and/or wrong settings of the used devices), inadequate study design (e.g. primary outcome evaluation not focused on instrumentation-comparison bur vs laser and/or piezotome) and possible bias (e.g. product-related comparative studies with conflict of interest-background).

A total of 129 publications, meeting the inclusion-criteria and were agreed by all authors and the referee, were finally assigned to group 1-4 and group 2-4 for evidence-staging (Figure 8).

Group 1 (systematic reviews and meta-analyses)

Only two very recent systematic reviews were found comparing rotary instruments with lasers in general [14,15], pointing out that "additional research is necessary to evaluate different laser types with appropriate laser setting variables to increase ablation rates, with control of depth, change in bone type and damage to adjacent soft tissue" [14] and "because of the lack of clinical studies, it is not possible to make a conclusive result whether there is superiority of laser osteotomy in clinical practice" [15].

Nine very recent systematic reviews comparing rotary instruments with piezotome-instrumentation focused on comparative clinical studies regarding specific surgical procedures such as alveolar crest-split technique [16], lateral maxillary sinus-floor elevation [17,18], acceleration of orthodontic tooth movement [19] and surgical removal of impacted third molars [20-24] and conclude piezotome-instrumentation to significantly reduce post-surgical morbidity (pain, swelling, trismus) but to prolong surgery-time and the need for further randomized clinical studies with a precise study-design.

No systematic reviews were found directly comparing rotary instruments with lasers and piezotomes or piezotomes with lasers.

Group 2 (experimental studies ex vivo)

Burs/drills vs lasers: Comparative ex vivo studies burs/drills vs laser [25-29] suffer from the heterogeneity of used

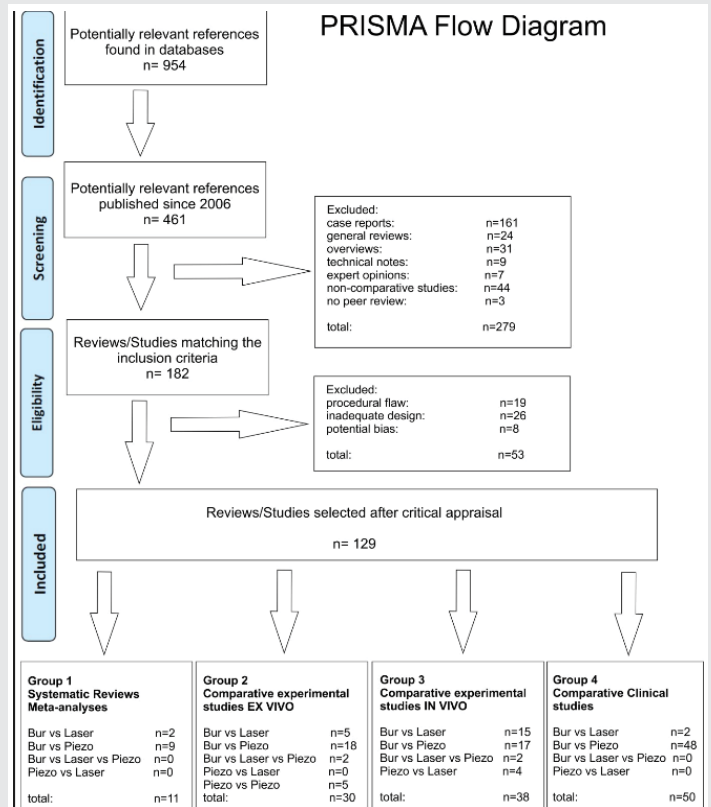


Figure 8: Selection scheme for reviews and studies included into the systematic review and assignment to the four groups under investigation.

laser-technology (Er:YAG, Er,Cr:YSGG - wavelength) and laser-settings (focus-spot-size/energy-density at focus-spot/laser-pulse-duration and -frequency). Ex vivo-studies are not comparable among each other, point out partly increased thermal bone necrosis depending on the power-settings, but state sharper and cleaner osteotomy lines with less debris when compared with rotary instruments. The evidence-value (EV) 0,8 (Table 1) indicates minor evidence of lasers to substantially improve bone-cutting procedures in oral & maxillofacial surgery.

Burs/drills vs piezotomes: EX VIVO comparisons between rotary instruments and piezotome-osteotomies [30-47] provide substantial evidence with possible high impact on clinical practice with an evidence value (EV) of 1,4 (Table 1). Although with piezotome-instrumentation there is still a risk of thermal bone-damage too (when used improperly), all comparative studies proved piezotome-osteotomies to lead to more precise, debris-free and less destructive bone-cuts as well as superior soft-tissue-preservation especially in the hands of novices in oral surgery.

Burs/drills vs lasers vs piezotomes: Only two studies were found investigating differences of microscopic osteotomy-morphology and temperature rise when burs, lasers and piezotomes [48, 49] are used to cut bone. One [49] revealed a minor procedural flaw in the piezotome-settings regarding flow-rate of saline-irrigation, which lead to a higher intrabony temperature-rise. Both studies present moderate evidence (EL=1, Table 1) and suggest advantages of Er:YAG-lasers over piezotome-instrumentation and burs, however pointing out comparable precise bone cuts with both lasers and piezotomes

Table 1:

Group 2					Group 3					Group 4					Overall mean			
Experimental Studies	Nr. of	Evidence level (EL)			Evidence value (EV)	Experimental Studies	Nr. of	Evidence level (EL)			Evidence value (EV)	Comparative Clinical Studies	Nr. of	Evidence level (EL)			Evidence value (EV)	Evidence Value
EX VIVO	ref(#)	0	1	2		IN VIVO	ref(#)	0	1	2		Studies	ref(#)	0	1	2		(OmEV)
	total #	#	#	#			total #	#	#	#			total #	#	#	#		
Bur vs Laser	5	2	2	1	0.8	Bur vs Laser	15	11	1	3	0.5	Bur vs Laser	2	1	1		0.5	0.6
Bur vs Piezo	18	3	4	11	1.4	Bur vs Piezo	17	4	4	9	1.3	Bur vs Piezo	48	8	6	34	1.5	1.4
Bur vs Piezo vs Laser	2		2		1	Bur vs Piezo vs Laser	2	1	1		0.3	Bur vs Piezo vs Laser						0.7
Piezo vs Laser	0					Piezo vs Laser	4	2	2		0.5	Piezo vs Laser						0.5

Statistic formula: $[(\# \times EL 0) + (\# \times EL 1) + (\# \times EL 2)] \div \text{total\#} = EV$

and the mandatory need of proper knowledge and training to handle lasers correctly in surgery.

Piezotomes vs Piezotomes

Five comparative studies investigate the cutting performance, osteotomy quality and intrabony temperature-rise of different devices from different piezotome-manufacturers [50–54], but were not rated for their evidence-level since the small number of published studies, different settings and study-designs do not allow a valid meta-analysis.

Group 3 (experimental studies in vivo)

Burs/drills vs lasers: Evaluation of evidence value in comparative in vivo studies [55–69] suffers mainly from the wide range of different laser-systems used (Er:YAG, Er,Cr:YSGG, CO₂, femtolasers) and laser-light delivery (free beam, optic fibers), lack of standardized protocols regarding focus-spot energy-density, pulse-rate and pulse-frequency used. There is not even moderate evidence (EV: 0,5, Table 1) for lasers to provide superior cutting performance on micromorphologic, microscopic and clinical level in vivo and most authors point out thermal damages and thermal bone-necrosis in histologic investigations. However, these laser-induced thermal damages do not seem to influence the overall bone-healing when compared to rotary instruments.

Burs/drills vs piezotomes: With moderate to strong evidence (EL: 1,3; Table 1) and consecutive substantial clinical impact piezotomes seem to provide an improved bone-healing, proved on molecular-biologic, micromorphologic and histologic level in vivo, when compared to rotary instruments. Furthermore, a superior soft-tissue-preservation is reported compared to drills and burs [70–86].

Burs/drills vs lasers vs piezotomes: Only two published studies provide a direct comparison of rotary instruments against Er:YAG-laser and piezotomes of which one [87] describes a significant delay in bone-healing when laser was used and a faster bone healing with piezotome-instrumentation, whereas a comparative study comparing implant drill-sites [88] finds no significant differences between the osteotomy methods. Due to the small number of studies the Evidence Value (EV) is insignificant (0,3; Table 1)

Lasers vs piezotomes

Four published studies [89–92] suggest Er:YAG-lasers in non-contact application with a computerized scanning-handpiece to provide faster bone-healing in vivo than piezotome-instrumentation, but was equal when Er:YAG-laser was used in contact-mode. The evidence value of these studies is low with EV: 0,5 (Table 1).

Group 4 (Comparative Clinical Studies)

Burs/drills vs Laser: Only two comparative clinical studies were published until now [93,94], both comparing Er:YAG lasers with rotary instruments in surgical removal of impacted third molars, with only little evidence (EV: 0,5; Table 1) of clinical advantages of laser-use.

Burs/drills vs Piezotomes: A total of 48 comparative clinical studies investigated molecular-biologic, biomechanical, histologic, radiologic, bone-densitometric and periodontal differences in the short and long-term-outcome between the use of burs/drills and piezotomes [95–107] as well as short and long-term effects on intra- and post-surgical morbidity (intra-surgical amount of bleeding, post-surgical pain, swelling and/or trismus) [108–142].

Both morphologic and morbidity related clinical studies conclude with significant evidence (EV: 1,5, Table 1) piezotome-instrumentation to have a significant clinical impact on improved bone-healing, reduced intra-surgical blood-loss, superior soft-tissue-preservation (e.g. IAN, sinus-membrane, brain-tissue) and significantly reduced post-surgical morbidity (pain, swelling, trismus) not only in oral and maxillofacial surgery but also in cosmetic, ENT and neurosurgery. The learning curve is short and novices in oral and maxillofacial surgery achieve better results with piezotomes than with rotary instruments.

No clinical studies were found comparing burs/drills with lasers and piezotomes as well as lasers with piezotomes.

Overall evidence rating (Group 2,3 and 4; Overall mean Evidence Value - OmEV)

There is only minor evidence with questionable clinical

impact that lasers might provide improved properties in bone-cutting when compared to burs/drills (OmEV: 0,6; Table 1) or piezotomes (OmEV: 0,5; Table 1) or both (OmEV: 0,7; Table 1).

Contrary, the use of piezotomes – also backed by the high number of experimental and clinical studies – seem to have a significant clinical impact on improved bone-healing, superior soft-tissue-preservation and reduced postsurgical morbidity with an OmEV of 1,4 (Table 1) when compared with rotary instruments.

(Table 2) gives an overview of evidence-based comparative properties of burs/drills, lasers and piezotomes with burs/drills as “baseline-values” as a descriptive result of this systematic review.

Discussion

As in abdominal surgery traditional surgical procedures with large transabdominal skin-incisions are more and more replaced by minimal invasive endoscopic procedures with reduced intrasurgical complications and post-surgical morbidity, advanced laser- and ultrasonic-technology might replace traditional surgical techniques performed with burs, drills or slow oscillating instruments likewise in oral and maxillofacial surgery and implantology.

For the clinician the consideration to change from usual rotary instrumentation with traditional surgical protocols to new technologies for bone cutting with new surgical protocols needs solid experimental and clinical evidence to justify the investment of time and funds to introduce these technologies into the individual daily practice.

Although tissue-cutting lasers proved their benefits over scalpel-blades in almost all specialties of surgery, their beneficial application is mostly restricted to soft-tissue-surgery due to their heat-induced precise micrometric soft-

tissue-ablation and blood-vessel-coagulation also in oral and maxillofacial surgery.

The application of mainly Er:YAG and/or Er,Cr:YSGG-lasers for surgical therapy of periimplantitis is discussed and applied to clinical practice as demonstrated by the author’s case-examples (Figure 9 A-C) but still lacking sufficient evidence to act superior compared to other surgical protocols [143].

The wide variety of available tissue-cutting laser-systems with different wavelengths (CO₂-, Diode-, Nd:YAG-, Er:YAG-, Er,Cr:YSGG-, Hol:YAG- (Figure 10A), experimental Femtosecond- and Excimer-lasers) and high acquisition cost (40.000.- US\$ and more) still lack clear evidence of “proof of concept”.

Although laser-systems for bone cutting in the current clinical routine can be narrowed down to CO₂-, Er:YAG-, and Er,Cr:YSGG-laser-types (Figure 10A), contradictory published experimental ex vivo and in vivo results suggest an investment in current laser-technology for bone cutting doubtful.

A total of 2 systematic reviews and 32 publications of experimental and clinical studies since 2006 – meeting the selection criteria of this critical review – do not provide even basic information on and results of standardized procedures with laser-types sold for and used in oral and maxillofacial surgery.

Too many parameters for the optimum setup of bone cutting lasers of each wavelength have to be taken into account to improve their performance over rotary instruments and might be corrupted by currently available laser technology.

Aside the specific infrared heat-wavelength of a laser-type, the performance of lasers on bone depend substantially on the infrared-heat-energy-density in the focus-spot, the time-span this energy is delivered on this focus-spot (pulse-duration), the geometry of the laser-pulse (sloped versus rectangular pulse = Q-switch) and the frequency the laser-pulse is delivered onto the bone (Figure 10B). Second, the type of delivery system of the infrared laser beam vastly influences the performance on bone: optical lenses and mirrors cause a divergence of the laser beam, leading to an unprecise focus-spot with varying diameters, which in the course of clinical work might completely counteract the desired effects on bone and revert them into increased heat-induced bone-necrosis as reported (Figure 3).

Fiber optical delivery can reduce the focusing problem (but not completely eliminate it), but once the fiber touches the bone, heat-coagulated fibrous tissue clots the optical fiber and corrupts the clean delivery of the laser-beam onto the bone. The plasma-plume, the photoacoustic and cavitation-effect might also splinter the polished surface of the fiber when it is made of quartz glasses.

Most of these technical problems in the application of laser-beams on bone were not taken into account in most experimental and clinical studies, which might explain the contradictory results even with lasers of a single type (e.g.

Table 2: Summary of evidence.

Evidence based properties with clinical impact	Rotary Instruments	Lasers	Piezotomes
least possible thermal bone necrosis	-	+	++
smooth osteotomy surface	-	++	++
improved bone-healing	-	-	++
bacterial contamination prevention	-	-	++
high precision osteotomy design	-	+	++
almost bone-lossless osteotomy	-	+	++
precise osteotomy depth-control	+	-	++
soft tissue preservation (e.g. IAN, sinus-membrane, brain-tissue)	-	-	++
reduction of intrasurgical blood loss	-	-	++
reduction of post-surgical morbidity (pain, swelling, trismus)	-	?	++

Summary of evidence regarding specific properties of lasers and piezotomes when compared to burs/drills. Traditional rotary instruments represent the “baseline value” (-). Evidence-rating was converted to “+” and “++”-symbols for better comprehensibility (0 = - : no evidence; + = 1 : moderate evidence with possible clinical impact; ++ = 2 : strong evidence with significant clinical impact; ? = no data available)

Er:YAG-lasers). The majority of studies report substantial heat-induced bone-necrosis compared to rotary instruments. The desired heat induced cavitation-effect, with its characteristic loud and intermittent knocking sound and least undesired thermal side effects, is generated only with a precise focus spot (Figure 3, Figure 10B).

For the clinician, the daily routine of bone-cutting close to delicate soft-tissue-structures such as sinus-membrane, trigeminal nerves and major intrabony blood-vessels, is the major challenge. The complete lack of any type of depth-control of the laser-beam and its ability to cut through soft-tissues faster than through bone might make a laser – beside the high acquisition-cost – the least instrument of choice for osteotomies in the daily routine, especially for novices.

The construction-principles of piezotomes are subject to tight technical parameters: the oscillation rate is restricted to 28.000 – 36.000 modulated harmonic oscillations per second (28 –36 KHz) and the distance of physical movement between 60 and 200 μm , to achieve the least risk of soft-tissue damage by frequency and working-tip-design. The separation or ablation of bone is also based on the cavitation-effect, but contrary to lasers is not heat-induced but pressure induced at much lower temperatures (Fig. 6). Heat induced bone-necrosis only occurs when no or too little continuous irrigation is supplied to the working tip, too high manual pressure is exerted onto the handpiece by the surgeon or a faulty constructed piezoelectric device for bone cutting generates irregular and uncoordinated vibrations instead of modulated harmonic oscillations.

Beside significant lower acquisition cost (starting with 8.000 US\$) compared to lasers, the surgeons investment in time to get acquainted with piezotome-surgical protocols seems to be a matter of a few training hours as studies report.

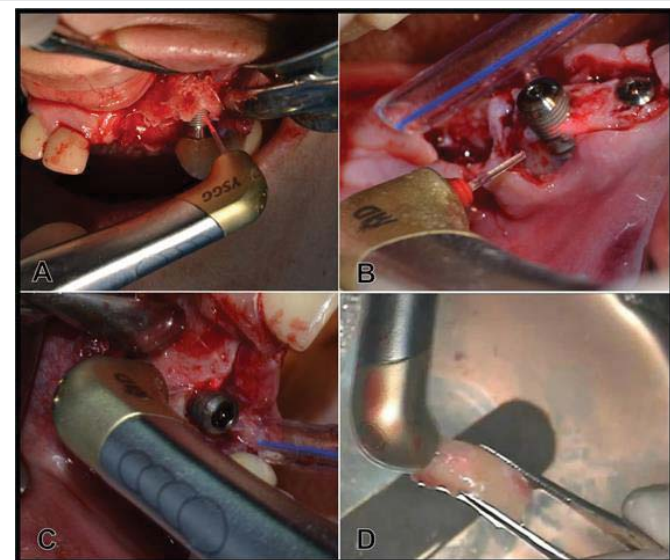


Figure 9: Depiction of appliances for commercial available Er,Cr:YSGG-lasers in surgical periimplantitis-therapy. A-C. resective periimplantitis-surgery both for granulation-tissue and infected bone-regions. The surface of the implant is decontaminated with a highly defocused laser beam utilizing the heat-effects of defocused laser-beams. D. use of lasers for extracorporeal shaping of bone-block-grafts.

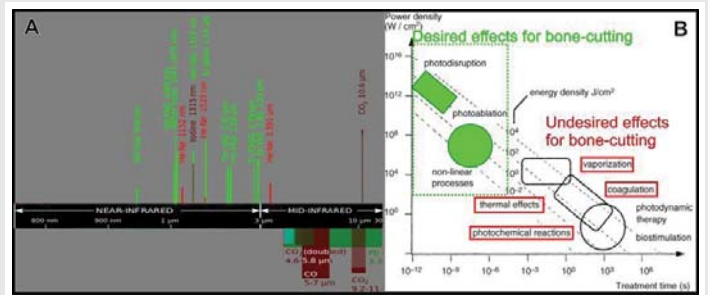


Figure 10: A. wavelengths of commercially available infrared heat-lasers for soft and hard-tissue-cutting; B: Both power density on the focal spot and pulse duration and -frequency highly influence the performance of lasers on calcified tissues. Defocused laser-beams with insufficient power density on the focal spot and too long pulse durations (or too high pulse-frequencies) lead to highly undesired effects on bone, such as coagulation, carbonization, thermal bone-necrosis and photochemical reactions which on the other hand might be useful in decontamination of implant-surfaces (Fig. 9 B). A well constructed laser provides mainly photoablative and photodisruptive effects on bone, provided the surgeon precisely keeps the distance for a perfect focus all the time during bone-cutting.

Novices in oral and maxillofacial surgery achieve better results with piezotomes than with rotary instruments when it comes to delicate procedures such as sinuslifting and IAN-lateralization as this systematic review revealed.

Microscopically the surfaces of bone cuts with piezotomes are as sharp and clean as reported for lasers, but with significant less or no procedural iatrogenic bone-loss due to scalpel-thin working-tips attached to the handpiece and without signs of heat-induced bone-necrosis. Like lasers, piezotomes allow an individual precise straight or curved design of any osteotomy, tuned to the needs of individual surgical procedures. Furthermore, the use of piezotomes for bone cutting seems to improve bone healing although the precise mechanism is not clear until now.

The ability to perform lossless bone cuts with superior soft tissue preservation lead to new bone-preserving surgical protocols for all kinds and subspecialties of oral implantology and oral and maxillofacial surgery, as demonstrated by the author's case-examples (Figures 11-13).

Both technologies for bone cutting – lasers and piezotomes – are significantly technology-sensitive: since the precision of the desired physical effects cannot be observed by the surgeon (lasers: precise focus-spot without divergence, precise and stable energy-density on the focus-spot, laser-pulse-characteristic/Q-switch, mechanical resistive and optical clean optical fibers; piezotomes: harmonic modulated oscillations, verified cavitation-effect at the acting part of each sold tip) enormous care has to be taken when considering a purchase without proof of these effects by the manufacturer.

Since this systematic review includes the most current and multidisciplinary literature and was not restricted to oral and maxillofacial surgery, experimental and clinical studies recommend piezotomes to be introduced as superior bone cutting tool also in ENT-, cosmetic – and neurosurgery for their proven property to reduce intrasurgical blood-loss, superior soft-tissue preservation and significantly reduced post-surgical morbidity.

Due to the lack of larger clinical split-mouth studies with precise and standardized surgical protocols for burs, lasers and piezotomes, evidence of improved bone healing in the clinical routine - as proven in experimental studies- is limited and cannot be answered by this review.

From the patient's point of view, any surgical instrument and procedure, that might significantly reduce intraoperative iatrogenic or procedural complications as mentioned above, will always be preferred. For the patient, the use of piezotomes implies less risk of iatrogenic lesions of the inferior alveolar nerve, mental nerve, sinus-membrane and major blood vessels and provides a proven significant reduction of post-surgical sequelae (trismus, pain, edema), allowing the patient to proceed with regular activities sooner after surgeries.

Conclusions

Lasers in their variety of available wavelengths and application modes still lack evidence to establish them as a

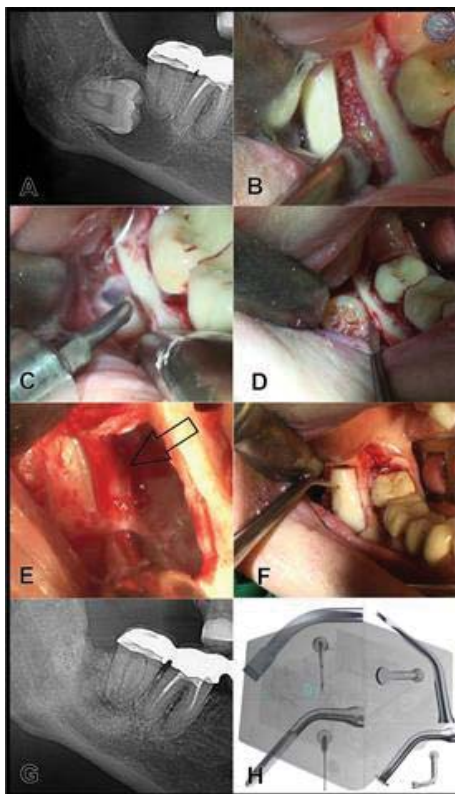


Figure 11: surgical removal of an impacted mandibular third molar and coronary cyst with piezotome. A. presurgical panoramic X-ray, B. bone-lossless removal of the buccal compact bone with the bone-scalpel-tip to reveal the cyst and the impacted third molar, C. loosening of the impacted third molar with a piezotome-periodontal ligament-cutter. D. forceless removal of the impacted third molar and removal of the cyst-tissue with a piezotome-tip designed for sinus-lifting. E. surgical site after removal of both impacted third molar and cyst in toto: adhering to the cyst-tissue before, the IAN and accompanying blood-vessels are fully intact after cyst removal including the enveloping connective tissue. Almost no bleeding occurs due to the superior soft-tissue preservation. F. anatomical correct full reconstruction of the mandibular angle after surgery. Due to the precise osteotomy-design and almost lossless bone cut no fixation of the reposed buccal compact-bone -plate with osteosynthesis plates is necessary. G. healing-result after 6 months. The second molar was preserved vital. H. piezotome-tips used for this surgery (clockwise: bone-scalpel, sinus-membrane-detachment tip used for cyst-detachment, angulated saw-tip for baseline-osteotomy, periodontal ligament-cutter).

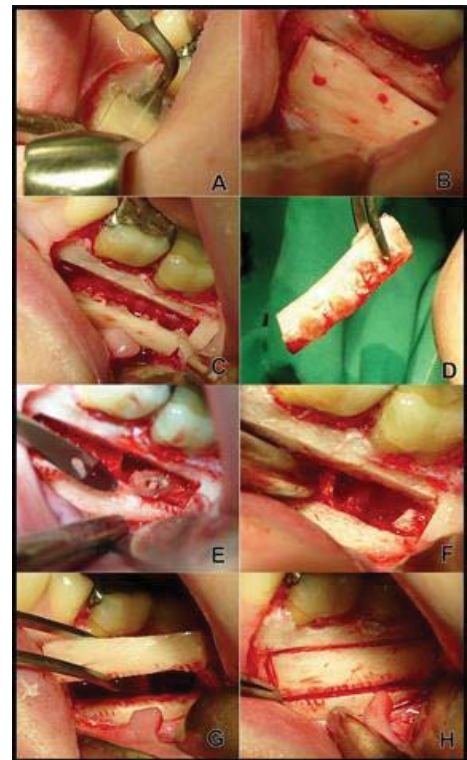


Figure 12: Apisectomy of first and second molar in the left mandible. A. bone-lossless osteotomy to remove the buccal compact bone adjacent to the apices. B. situation-specific osteotomy-design after periost-preserving detachment of the mucoperiosteal flap with piezotome. C. removal of the buccal bone-block. Almost no bleeding is visible due to the precise piezotome-cuts. D. bone-block removed and kept in saline solution for later reposition. (in case other parts of the alveolar crest would need augmentative surgery this bone-block could be used as autologous transplant). E. apisectomy and removal of the mesial apex of the second molar. Due to the precise histology-like microtome-cut the vertical root-fracture can be diagnosed with unaided eye. F. surgical site after completed apisectomies and curettage with piezotome. G. reposition of the buccal bone-block and anatomical correct reconstruction of the site. H. final result. Again, due to the precise individual osteotomy-design with piezotomes no additional fixation of the bone-block is needed as it is "self-arresting" for immobilization.

viable alternative to rotary instruments. Substantial research and development efforts as well as experimental and clinical studies are needed to define standards regarding power-density, laser-pulse duration and frequency and consistent focusing on bone to achieve better results than with rotary instruments in the clinical routine. If technological developments can overcome the major disadvantages of lasers - the complete lack of depth-control of any osteotomy and unacceptable risk of iatrogenic soft-tissue lesions - seems doubtful.

Piezotomes seem to inherit the potential to establish the new gold standard in bone cutting in the oral and maxillofacial surgeon's clinical routine. Backed by experimental and clinical studies, piezotomes provide least thermal side effects on bone, a smooth osteotomy surface, improved bone-healing, and almost bone-lossless and precise osteotomy design with superior depth-control and soft-tissue protection. The reduced intraoperative blood loss and significant reduction of post-surgical morbidity - when compared with rotary instruments - suggest piezotomes to be the instrument of choice also from the patient's point of view. However, also for piezotomes further studies have to be undertaken to shed light on the

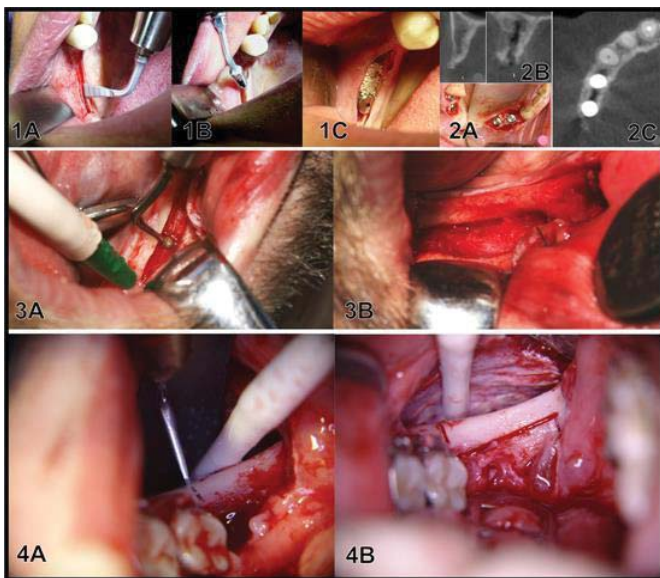


Figure 13: Various surgical procedures enabled by piezotomes and described in published studies. 1a-c flapless piezotome-enhanced vertical crest-split and horizontal distraction of narrow mandibular crest of only 1,5mm width. 2 A-C same type of flapless crest-split as depicted in 1 but performed in the narrow maxilla (crest-width: 1,2mm) with intra- and post-surgical CBCT-control. 3 a-b. Safe IAN-transposition with piezotomes to enable implant insertion into the vertical atrophic alveolar crest. Due to the superior soft-tissue preservation of piezotomes mid-term and permanent damages to the IAN can be avoided. 4a-b BSSO with piezotomes with evidence-proven significant reduced blood-loss, IAN-damage and post-surgical morbidity.

molecular biologic mechanisms of the improved bone healing and to further optimize the oscillation-characteristics.

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