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Extraction force and its determinants for minimally invasive vertical tooth extraction.

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Running title: Extraction forces for vertical extraction

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Abstract

Background: Minimally invasive vertical extraction devices have been developed to minimise the need for flap surgery and trauma to alveolar bone during tooth extraction. The objective of this study was to measure the forces required for vertical tooth extraction and evaluate the determinants of these forces.

Methods: The investigators coupled a precision load cell with a Benex® extractor to record extraction forces for 59 consecutive routine extractions of tooth roots. Age, sex, tooth type, root surface attachment area (RSAA) and whether or not the tooth was in functional occlusion were evaluated as determinants of extraction forces using linear mixed models.

Results: Maximum extraction forces (F_{max}) varied widely from 41N to 629N. On average, maximum extraction forces were 104N (95% CI: 38N, 169N) higher for teeth/roots in occlusion vs. teeth not in occlusion. An increase in RSSA by one standard deviation was associated with a marked increase in F_{max} by 64N (95% CI: 34N, 94N). Extraction forces were not associated with age, sex or tooth type (maxillary vs. mandibular).

Conclusions: Extraction forces using the Benex® vertical extraction system vary widely and can be less than 50N or exceed 600N. On average, higher extraction forces are required to extract teeth with longer and thicker roots, as well as for teeth that are in functional occlusion.

Key words: atraumatic extraction, risk factors, socket healing, tooth extraction, wound healing

Background

The desire to minimise bone loss following tooth extraction to facilitate subsequent implant restoration has led to the development of novel vertical extraction techniques. These techniques aim to extract a tooth by applying a pulling force to the tooth root that is directed strictly along its long axis, resulting in the severance of Sharpey's dento-alveolar fibres and tooth extraction. Importantly, in case of a conical root without significant root curvature or undercuts, this extraction technique will minimise any direct trauma to alveolar bone.

The clinical procedure of vertical extraction with the Benex® system has been previously described in detail [1]. The system allows the predictable extraction of non-molar teeth, i.e., incisors, canines and premolars, as well as the extraction of some molar roots [2, 3]. Extractions are more likely to fail in multirooted and/or root-filled teeth; however, the overall need for flap surgery for the extraction of non-molar teeth may be reduced with the use of the system [2]. Due to its high predictability and the minimisation of trauma to root surface and alveolar bone, the system is also suitable for use with surgical extrusion [4, 5]. Clinical experience suggests that forces required for tooth extraction and pull time can vary widely [3], although extraction forces have never been directly measured.

The aim of the present investigation was to measure extraction forces occurring during vertical tooth extraction with the Benex device. A further aim was to evaluate putative tooth and patient level determinants of the maximum extraction force required for vertical tooth extraction.

Methods

Patient sample and clinical procedure

The extractions described here were performed between December 2008 and October 2009 as part of routine clinical care of patients referred for tooth extractions or attending emergency appointments at the Clinic of Oral Surgery, Department of Oral and Maxillofacial Surgery, University of Zurich. All patients required tooth or root extractions as part of their treatment plan and all provided informed consent to treatment. All procedures were performed under local anaesthesia.

The clinical procedures and success rates of Benex extractions have been described in detail previously [1-3]. Briefly, a specially designed self-tapping screw is anchored in the centre of the root to be extracted. A pull rope is attached to the screw head and a strictly vertical extraction force is then applied with the extractor device until the root yields. An optional support tray may be used to help stabilise the extractor and ensure optimal alignment of the pull rope as well as even distribution of extraction forces (Fig. 1).

All extractions were performed by a single surgeon (IS). If appropriate, multirooted teeth were sectioned and roots were extracted separately. Once the extractor was set up, the pull force was increased gradually by turning the extractor handle clockwise. When significant resistance was felt, pauses were made at the surgeon's discretion, before turning the handle further to increase the pull force. This procedure was followed until the root yielded. Roots that could not be extracted with the Benex® system [2, 3] were excluded from this study and extracted using a conventional approach with or without flap surgery.

Measurement of extraction force

In order to measure the forces on the pull rope/screw of the Benex® device, the device was coupled with a precision load-cell (Burster®-Sensor, Burster Präzisionsmesstechnik GmbH & Co KG, Gernsbach, Germany), which recorded the applied force every 50 milliseconds. These measurements were then exported into Excel-Software (Microsoft Excel, Microsoft Corp, Seattle, USA) to allow graphical representation of the extraction force over time. The sensor was first calibrated using a universal testing machine (Zwick/Roell Z010®, Zwick GmbH & Co KG, Ulm, Deutschland) in a setup that simulated the clinical scenario. To this end, a plaster model in conjunction with the support tray and silicon putty material was fitted to an upper premolar and 5 measurements each were taken for forces of 100N, 200N, 300N, 400N and 500N for calibration purposes. A calibration curve was fit using simple linear regression and the maximum extraction force was calibrated using the model estimates accordingly.

Other data

In addition to patient age, patient sex and type of extracted tooth, we recorded whether or not the tooth was in occlusion at the time of consultation. Furthermore, we used digital radiographs to estimate the root surface area of the tooth root to be extracted. To this end, the length of the periodontal attachment *i* and diameter *d* of the root was measured using image analysis software (Digora, SOREDEX, Tuusula, Finland)(Fig 2). Based on the formula for the lateral surface area of a right circular cone, the root surface attachment area (RSAA) with periodontal attachment was estimated as $RSAA \sim \frac{1}{2}\pi di$.

Statistical analysis

Summary statistics were calculated for all clinical variables as appropriate. A linear mixed model was fit to evaluate the association between maximum extraction force (F_{max}) as the dependant variable and root surface area, functional occlusion, jaw (mandible vs. maxilla), age and sex as independent variables, accounting for lack of independence between multiple roots in the same patient. In order to enhance interpretability of estimates, root surface attachment area was standardised to have standard deviation equal to 1. Distributional assumptions for linear regression were checked using graphical methods and Shapiro-Wilk's test. Pearson's correlation coefficient was calculated to evaluate the correlation between maximum extraction force and pull time. All statistical tests were two-sided at $\alpha=0.05$ and two-sided 95% confidence intervals were calculated using STATA 14.2 (STATA Corp., College Station, TX, USA).

Results

Sample characteristics

The sample included a total of 41 patients (28 Males and 13 Females) with a mean age of 45 ± 19 years (range 16-89 years). A total of 59 distinct roots of 55 teeth were extracted with the Benex® system, including 3 molars and one premolar, which each had two roots extracted separately. An additional 5 multi-rooted teeth had only one of their roots extracted with the Benex® system, and only these roots were therefore included in this analysis (Table 1). The majority of teeth required extraction due to caries or a combination of caries and periodontitis, other indications included failed endodontic therapy, root fractures, supernumerary teeth or orthodontic treatment. 59% of roots were in occlusion at the time of extraction (Table 1).

Qualitative analysis of extraction forces

Three main patterns could be identified that describe the extraction process with the vertical extraction system. The first pattern is characterised by a gradual increase of force leading to rupture of periodontal ligament fibres and tooth root delivery, typically at relatively low forces (Fig. 3a). The second pattern typically occurred when higher extraction forces are required and the operator pauses once significant resistance is felt. The curve indicates that the tension then slightly decreases over time, until the operator continues to increase the force until eventual fibre rupture and tooth delivery (Fig. 3b). The third pattern is more irregular, and typically occurs when some force is required to deliver the root out of the socket after fibre rupture has occurred (Fig. 3c).

Quantitative analysis of extraction forces

Maximum extraction forces (F_{max}) varied widely from just 41N for a mesial root of a lower first molar, to 629N for an upper first premolar tooth (Table 1). Pull time was highly correlated with F_{max} (Pearson correlation coefficient ρ=0.71).

In a multiple linear regression model, no differences between extractions forces were observed according to age, sex, or between maxillary vs. mandibular teeth. However, teeth with a larger estimated root surface attachment area and teeth that were in occlusion at the time of extraction required higher extraction forces (Table 2, Fig. 4). On average, maximum extraction forces were 296N (95% CI: 251N, 342N) and 193N (95% CI: 140N, 245N) for teeth/roots in occlusion and not in occlusion, respectively. An increase in the estimated root surface attachment area of one standard deviation was associated with a marked increase in F_{max} by 64N (95% CI: 34N, 94N) (Fig. 4, Table 2). Mean maximum stress was 1.36 N/mm^2 (SD 0.71, range 0.80, 1.89).

Discussion

The present study determined the forces occurring during tooth extraction with a vertical extraction system. We found that the required maximum extraction force varied widely between teeth, ranging from less than 50N to over 600N. Extraction force also increased linearly with increasing root surface attachment area. The corresponding maximum stress ranged from 0.8 to 1.9 N/mm^2. Larger forces were required for teeth that were in functional occlusion at the time of extraction, compared to teeth or roots not in occlusion. Age and sex did not affect maximum extraction forces.

It is important to note that technical difficulty and required extraction force are not synonymous. However, notwithstanding the strong negative association between perceived technical difficulty and operator experience and confidence, most clinicians will agree that technical difficulty and forces required for conventional exodontia are correlated and can vary widely. Although the literature on this topic is scarce, clinical experience and common sense can identify certain tooth and patient characteristics that predict extraction difficulty. Examples for tooth related factors are marked root curvature, root divergence and root bulbosity (e.g., due to hypercementosis). As conventional extraction technique relies on expansion of the bony socket, patient factors such as bone morphology (e.g., spongious vs. cortical bone) and bone mineral density, which is associated with sex, race/ethnicity and body mass [6, 7], are also important. However, vertical tooth extraction is fundamentally different to conventional forceps extraction in that it does not rely on socket expansion, and allows the application of a strictly vertical force vector, thereby minimising trauma to bone. Ideally, i.e., in case of a conical tooth root with no undercuts, extraction will be the result of overcoming the tensile strength of the periodontal ligament with no compressive forces on alveolar bone. Our finding that the required extraction force is associated with the root surface attachment area is therefore not surprising [Fig 4]. For straight tapering roots, movement axial to the applied force occurs when periodontal ligament (PDL) fibres rupture, following breaks in covalent cross-links in collagen and slippages between the unit molecular chains [8]. Studies into the various factors influencing the mechanical properties of the PDL agree that the content, direction and organisation of the collagen fibre component is critical to the observed mechanical response [8]. The contribution to resistance of tooth movement of individual PDL fibres varies with location, due to differing alignment within the tensile stress field, and with time due to cumulative fibre rupture (beginning apically) [9] and the intrinsic viscoelastic behaviour of the PDL [8, 10]. The PDL exhibits time-dependent stress-release following force application, which is a property considered to be protective to reduce PDL injury. Multiple stress-relaxation mechanisms have been proposed and can be categorised into short, medium and long-term components and viscous and elastic components [8]. Mechanical characterisations have shown that the response is sensitive to the stressing-rate, with rapidly applied forces associated with relative increases in effective PDL stiffness and an increased stress required to cause rupture [8, 11]. In this study, in cases when the operator chose to wait following an increase in force applied, it was consistently observed that following application of an extrusive force, an initial rapid decrease in the measured force occurred, followed by a more gradual stress relaxation (Fig 3b, 5). This behaviour is consistent with previous observations which have elaborated further to show that the amount of stress relaxation that occurs is inversely related to the magnitude of the initially applied force [8, 12]. This non-linear behaviour highlights the complex mechanisms underpinning the short and long-term relaxation components. Whilst factors such as water content [13] and PDL dimensions are certainly important to the observed behaviour, the response of collagen to the applied stress is central [8]. This is evidenced by studies exposing the PDL to collagenases prior to mechanical characterisation and showing significant increases in the magnitude of stress relaxation following loading [14]. The implications of this behaviour for tooth removal using controlled extrusion is that the PDL is adapted to accumulate damage sub-critically, prior to fibre rupture. This damage following masticatory loading cycles is likely reversible, with for example, re-crosslinking of collagen occurring. During tooth extraction the use of low stressing rates (applying force increases slowly) and maintained force application results in cumulative sub-critical damage resulting in a reduced force to cause fibre rupture. In this study when the operator chose not to continue to increase the force continuously, resulting in a static force application, stress relaxation was observed (Fig. 3b). Force-time plots show that as the loading increase paused, rapid stress relaxation occurred followed by a more gradual decay in measured force, which is consistent with animal-model (rabbit) data [12]. Minimising extraction forces may be desirable to minimise the risk of root fracture and reduce the stress transferred to the dento-alveolar complex and may have biologically favourable results in terms of reduced trauma and improved healing, in particular in the case of surgical extrusion [5]. Further investigations are required to identify whether or not slower extraction, i.e., longer periods of sustained input of force would result in a reduction in the maximum extraction force and whether this is clinically significant in terms of biological sequelae.

In the current study, reduced extrusion forces were associated with teeth that were not in functional occlusion. Numerous animal studies [15-17] and complementary observations in humans [18, 19] have demonstrated that decreased, or absence of, occlusal function leads to dimensional and structural changes in the both the PDL and alveolar process. Morphometric studies show that the PDL narrows with reduced function, and histology shows an associated reduction in the number [20] of collagen fibres, which are less organised [21-23] and are remodelled more slowly [24]. Experiments in rats have demonstrated a gradual decrease in required extraction forces within 8 days after loss of function [25]. Return to function is associated with increasing PDL thickness which is considered a protective adaptation to loading [26]. The reduced extrusion forces are likely to be a consequence of the changes to the collagen content of the PDL, although a contribution from changes in plasticity of the alveolar bone cannot be discounted. Explaining the observed behaviour solely on the mechanical response of the PDL is an over-simplification and tooth-related factors such as root curvature, root divergence or hypercementosis are also relevant for Benex® extractions. If these features are pronounced, vertical extraction may be impossible [2]. In case of minor undercuts or root divergence, sufficient force may be generated with the Benex® device to allow extraction via minimal socket expansion or even fracture (Fig. 5). The latter is an extremely rare complication and has been observed by the authors in only 2 cases in well over 500 extractions.

This is the first study to measure forces associated with tooth extraction in humans in vivo, facilitated by the use of an extraction device that allowed coupling to a load cell. However, our study has some limitations. Firstly, root surface attachment area was estimated based on 2 dimensional radiographs, which will have resulted in measurement error. Secondly, we did not ascertain root features likely to affect extraction forces such as hypercementosis or root divergence. Finally, the sample size in this study is limited and we cannot rule out relatively smaller effects of other factors, such as age and gender.

Conclusions

Extraction forces required to extract teeth or tooth roots using the Benex vertical extraction system vary widely and can be less than 50N or exceed 600N. On average, higher extraction forces are required to extract teeth with longer and thicker roots, as well as for teeth that are in functional occlusion.

List of Abbreviations

RSAA root surface attachment area

F_{max} maximum extraction force

PDL periodontal ligament

Availability of data and material

Raw data have previously been published and are available through the university of Zurich (Schmid I, Kräftemessungen bei Zahnextraktionen mit dem Benex®-Extraktor, Zahnmedizinische Dissertation, University of Zurich, 2010).

Competing interests

None declared

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Authors' contributions

I.S. and M.L. conceived the idea and collected the data. T.D. performed statistical analysis and led the writing with O.A. All authors contributed to data interpretation and critically reviewed and approved the manuscript.

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Tables

Table 1: Characteristics of extracted teeth/roots

Characteristic	Total N=59
Tooth, n (%)	
U1	0 (0%)
U2	2 (3%)
U3	5 (8%)
U4	9 (15%)
U5	6 (10%)
L1	1 (2%)
L2	1 (2%)
L3	4 (7%)
L4	6 (10%)
L5	12 (20%)
root [a]	13 (22%)
functional occlusion, n (%)	
No	24 (41%)
Yes	35 (59%)
indication for extraction, n (%)	
caries	25 (42%)
caries & periodontal	12 (20%)
endodontic failure	5 (8%)

root fracture	3 (5%)
supernumerary	8 (14%)
orthodontic	6 (10%)
maximum extraction force [N], mean (SD)	261 (152)
pull time [sec], mean (SD)	60 (44)
root surface attachment area [mm^2], mean (SD)	199 (75)
maximum stress [N/mm^2], mean (SD)	1.36 (0.71)

[a] single roots of multirooted teeth extracted following sectioning

Table 2: Association of age, sex, jaw and root surface attachment area and functional occlusion with maximum extraction force (multiple linear regression, dependent variable: F_{max})

Independent variable	β - coefficient	(95% CI)	p-value
age (years)[a]	- 7 N	(-27N, 13N)	P=0.50
sex (Female vs. Male)	4.5N	(-75N, 84N)	P=0.91
jaw (mandible vs. maxilla)	-11 N	(-75N, 54N)	P=0.74
root surface attachment area (mm)[b]	64N	(34N, 94N)	P<0.001
functional occlusion (yes vs. no)	104N	(38N, 169N)	P=0.002

[a] estimates for increase in age by 10 years

[b] estimates for increase in RSAA by 1 SD

Figure legends

Fig. 1 Clinical procedure

(a) carious upper right lateral incisor
(b) use of Benex® diamond coated bur
(c) Benex self-tapping screw and support tray in place
(d) pull rope and Benex® extractor assembled (note that the extractor needs to be moved slightly more towards the distal for perfect alignment of the pull rope)
(e) extraction of root.
(f) extraction socket after extraction

Fig. 2
Measurement of length of periodontal attachment (23.0 mm) and root diameter (5.2 mm) on a lower right canine for estimation of root surface attachment area (RSAA)

Fig. 3
Representative examples of the three main qualitative patterns of force/time curves observed during extractions

(a) constant increase in force leading to extraction
(b) increase in force followed by pauses during which a gradual linear drop in force can be observed
(c) irregular pattern.

Fig. 4

Linear association between root surface attachment area and F_{max} (F_{max} adjusted for age, sex and jaw)

Fig. 5

Force/time curve for an upper first premolar with two slightly divergent roots and undercuts. Benex extraction was ultimately achieved at high extraction forces. Note the fragment of the buccal plate attached to the root surface.