

Statistical signal processing methods for intraoral pressure curve analysis in orthodontics

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SUMMARY A thorough understanding of the intraoral pressure conditions of patients with different forms of malocclusion may help to characterize their aetiology in more detail and improve orthodontic treatment approaches by adding strategies to achieve a normalization of intraoral pressure levels. These pressure curve analyses should not only provide information on intraoral activity or during rest but also detail characterization of swallowing features and pressure plateau stages. For this purpose, algorithms for extracting swallowing peaks and plateau stages were developed and evaluated. Established curve characteristics such as the average or maximum pressure as well as the number of swallowing peaks or resting phases were compared between each other. Their usefulness and correlation (Kendall's τ) were evaluated in a data example of different occlusal groups (Angle Class I: $n = 30$; Angle Class II division 1: $n = 12$; and Angle Class II division 2: $n = 13$). Curve characteristics were compared among these groups using the Kruskal–Wallis test.

Some of the derived curve characteristics were found to be uncorrelated, thus providing different information concerning the intraoral pressure condition of subjects. Based on these findings, it is recommended to employ the curve characteristics described in this study to obtain a holistic image of factors that may affect the formation of the dentition.

Introduction

Human teeth are susceptible to pressure exertion; the exertion of a constant low force between 0.1 and 0.5 N results in a change in tooth position (Proffit, 1978). Therefore, tooth alignment in subjects who have not undergone orthodontic treatment is a product of an equilibrium of forces exerted on the teeth. Beside pressure from the lips (Thüer and Ingervall, 1986), the cheeks, and the tongue (Thüer *et al.*, 1999), a rarely considered factor is subatmospheric intraoral pressure. Subatmospheric pressures arise naturally in intraoral compartments, e.g. in the subpalatal space (SPS) and interocclusal space (IOS; Engelke *et al.*, 2010), and can be measured by a digital measuring instrument (Fröhlich *et al.*, 1991; Figure 1).

Pressures are measured within a predefined time interval, yielding time-dependent pressure curves that can be denoted by p_t ($t = 1, \dots, T$). Curves from patients with different forms of malocclusion can be compared by certain characteristics, for example, the average (Thüer *et al.*, 1999) or maximum (Kieser *et al.*, 2008) pressure. Further curve characteristics are for example the area under the curve (AUC) and the number of swallowing peaks and plateau phases (Engelke *et al.*, 2010; Knösel *et al.*, 2010).

Swallowing peaks are characterized by a rapid increase followed shortly after by a rapid decrease of negative pressure. Plateau phases represent a level of oral negative pressure with balanced forces from the lingual and vestibular directions in which there is a state of equilibrium. The persistence of these plateau phases can be explained by a passive lowering of the tongue after swallowing with a resulting SPS between the back of the tongue and the hard palate, which is a part of normal physiology. Nevertheless, plateau phases can contain small swallowing peaks.

The aim of this study was to provide a more detailed description of the diverse curve characteristics and to study their correlation. A non-correlation between curve characteristics would indicate that they contain different information about the intraoral pressure condition of patients. If they are correlated, some of them can possibly be omitted within the analysis of pressure curves. Furthermore, improved algorithms for extracting swallowing peaks and plateau phases from the curves are proposed. In detail, the applicability of a peak detection algorithm developed for data from mass spectrometry was a focus of this research. These algorithms should detect approximately those peaks or plateau phases that would be identified by visual inspection but of course with more

objectivity and consistency. The evaluation of curve characteristics was performed on data of distinct occlusal groups.

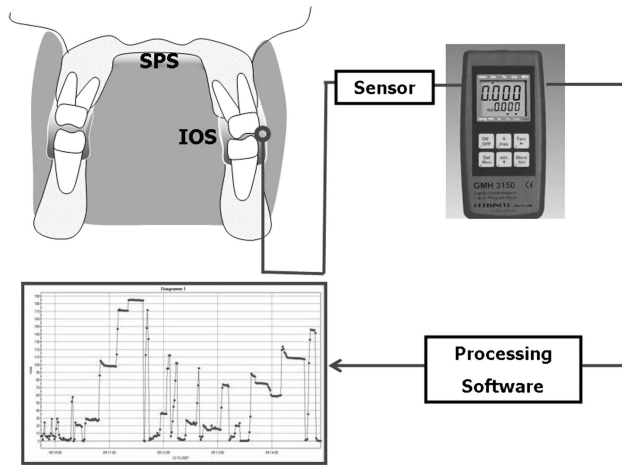


Figure 1 Schema for measuring intraoral pressure subpalatal space (SPS) and interocclusal space (IOS) with a digital measuring instrument.

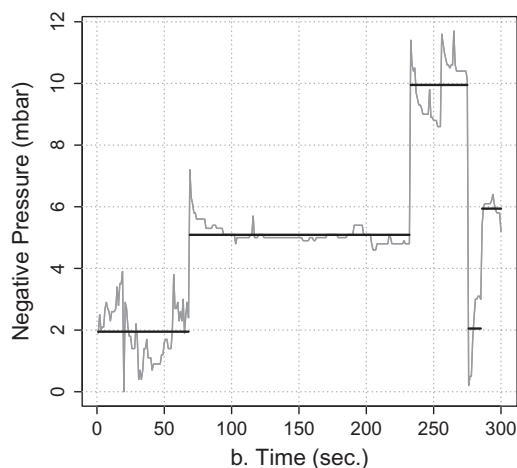
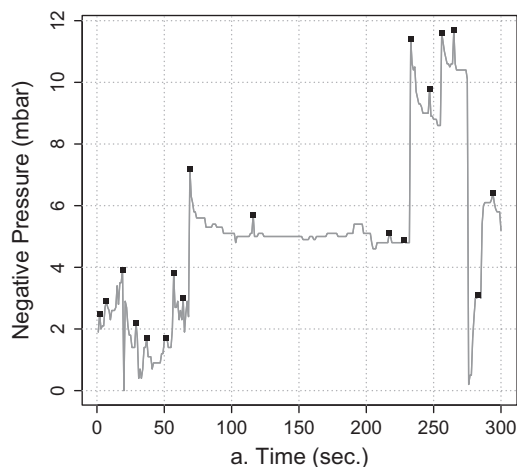


Figure 2 Negative intraoral pressure recorded in one patient within a time interval of 5 minutes: (a) detected swallowing peaks and (b) detected plateau phases.

Materials and methods

Signal extraction of pressure curves

Before signal extraction, removal of the first and last 5 seconds is acceptable, due to increased noise at the start and end of the measurement. After this preprocessing, two simple characteristics of a pressure curve p_t ($t = 1, \dots, T$) are the average pressure,

$$\bar{p} = \frac{1}{T} \sum_{t=1}^T p_t, \quad (1)$$

and maximum pressure,

$$p_{\max} = \max_{t=1, \dots, T} (p_t). \quad (2)$$

A further, easy to derive, curve parameter is the AUC, i.e. the area restricted by the curve itself and the abscissa. It can be simply approximated by numerical integration, e.g. by the trapezoidal rule. Because the employed measuring device records the intraoral pressure once per second, the recordings are equidistant and the trapezoidal rule reduces to

$$\text{AUC} = \frac{1}{2} \left(p_1 + 2 \cdot \sum_{t=2}^{T-1} p_t + p_T \right). \quad (3)$$

In order to determine the number N_{Rest} of resting plateaus, it is necessary to introduce a noise parameter ε . Sections on the curve with oscillations less than or equal to ε millibar can be regarded as plateau phases. A simple algorithm for determining N_{Rest} is given by the following pseudo code:

Set $N_{\text{Rest}} = 0$ and $s = 1$.

For $t = 2, \dots, T$

- { – Calculate the maximal difference δ of all pressures p from s to t .
- If $\delta \leq \varepsilon$, then go next.
- If $\delta > \varepsilon$, increment N_{Rest} by 1, set $s = t$ and go next. }

Resting plateaus that persist for a period shorter than 4 seconds should subsequently be removed because they can be just small peaks. Engelke *et al.* (2010) studied pressure curves during intraoral inactivity in 20 individuals. They found that pressure during intraoral inactivity can vary within a range of 0–5 mbars. Thus, the recommended value for the noise parameter ε is 5 mbar. An example of detected resting plateaus within a pressure curve is given in Figure 2a.

The detection of peaks is more difficult. Recently, an algorithm for peak detection developed for mass spectrometric data was employed (Engelke *et al.*, 2010). A simple algorithm was proposed by Coombes *et al.* (2003, 2005) which needs however baseline correction before peak detection. A more complex algorithm, using wavelet transformations, has been suggested by Du *et al.* (2006). Their approach manages peak detection without previous baseline subtraction and is more sensitive to small peaks. The algorithm is implemented in the package

Table 1 Correlation matrices of curve characteristics in the three distinct occlusal groups.

Occlusal group	Curve parameter	Area under the curve	N_{Peak}	N_{Rest}	P_{max}
I ($n = 30$)	N_{Peak}	$\tau = 0.10$ ($P = 0.4524$)			
	N_{Rest}	$\tau = 0.36$ ($P = 0.0067$)	$\tau = 0.54$ ($P < 0.0001$)*		
	P_{max}	$\tau = 0.37$ ($P = 0.0051$)	$\tau = 0.32$ ($P = 0.0157$)	$\tau = 0.54$ ($P < 0.0001$)*	
	\bar{P}	$\tau = 1.00$ ($P < 0.0001$)*	$\tau = 0.09$ ($P = 0.4742$)	$\tau = 0.36$ ($P = 0.0075$)	$\tau = 0.37$ ($P = 0.0045$)*
II/1 ($n = 12$)	N_{Peak}	$\tau = 0.26$ ($P = 0.2426$)			
	N_{Rest}	$\tau = 0.45$ ($P = 0.0452$)	$\tau = 0.66$ ($P = 0.0036$)*		
	P_{max}	$\tau = 0.18$ ($P = 0.4590$)	$\tau = 0.50$ ($P = 0.0233$)	$\tau = 0.48$ ($P = 0.0323$)	
	\bar{P}	$\tau = 1.00$ ($P < 0.0001$)*	$\tau = 0.26$ ($P = 0.2426$)	$\tau = 0.45$ ($P = 0.0452$)	$\tau = 0.18$ ($P = 0.4590$)
II/2 ($n = 13$)	N_{Peak}	$\tau = -0.05$ ($P = 0.8065$)			
	N_{Rest}	$\tau = 0.41$ ($P = 0.0562$)	$\tau = 0.31$ ($P = 0.1552$)		
	P_{max}	$\tau = 0.28$ ($P = 0.2044$)	$\tau = -0.05$ ($P = 0.8065$)	$\tau = 0.36$ ($P = 0.0964$)	
	\bar{P}	$\tau = 1.00$ ($P < 0.0001$)*	$\tau = -0.05$ ($P = 0.8065$)	$\tau = 0.41$ ($P = 0.0562$)	$\tau = 0.28$ ($P = 0.2044$)

Displayed values are Kendall's rank correlation coefficient τ . All P -values with * are significant with respect to a Bonferroni-adjusted significance level of $\alpha_{Bonf} = 0.005$.

'MassSpecWavelet' from the free statistical software R (www.r-project.org). The number of detected peaks is denoted by N_{Peak} . Figure 2b presents an example of a pressure curve with detected swallowing peaks.

Data example: swallowing activity in different occlusal groups

The established and new signal extracting methods were applied to pressure curves recorded from three distinct occlusal groups (Knösel *et al.*, 2010). Thirty patients with a normal occlusion as characterized by an Angle Class I, 12 patients with a distal occlusion of at least a half cusp in combination with incisor proclination (Angle Class II division 1), and 13 subjects with an Angle Class II division 2 malocclusion were studied (mean age \pm standard deviation: 28.4 ± 5.2 ; 26 males and 29 females). Intraoral pressure was recorded for 300 seconds in each subject. The study received the approval of the local Ethics Committee and the patients gave informed consent to participation.

Pressure curves were recorded using a small-dimensional probe located intraorally at the vestibulum in the premolar region. All measurements were performed at the chair-side in the natural head position and by the same orthodontist (MK) who determined the eligibility of the subjects to participate in the study. The probe was connected to a digital measuring instrument that comprised a piezo-resistive relative pressure sensor (GMSD 350 MR; Greisinger; Regenstauf, Germany) capable of recording pressures in a measuring range of 500 mbar and with a resolution of 0.1 mbar. Pressure data were processed using the software GSOFT3050 (version 2.7, Greisinger).

Statistical analysis

After removing the first and the last 5 seconds from the pressure curves, curve characteristics (i.e. \bar{P} , p_{max} , AUC, N_{Rest} , and N_{Peak}) were extracted using the above methods.

Correlations between the distinct curve characteristics were assessed using Kendall's correlation coefficient τ , separately for each group. As a large number of correlations were tested simultaneously, P values were compared to a Bonferroni-corrected significance level to reduce the number of false positive results. Distributions of the individual characteristics were compared between the three groups using the Kruskal–Wallis test. Statistical tests were either performed with a nominal significance level of $\alpha = 5$ per cent or with the Bonferroni-corrected level of $\alpha_{Bonf} = 0.05/10$. All analyses were performed using the free software, R.

Results

Evaluation of curve characteristics

For each of the three groups, significant correlations between some of the curve characteristics were detected (Table 1). There was however no significant correlation between the AUC and N_{Peak} in any group. These two parameters seem therefore to be independent from each other. A significant correlation was observed between N_{Peak} and N_{Rest} in the Class I and Class II division 1 groups. The AUC and \bar{P} were perfectly correlated in each group ($\tau = 1.00$, $P < 0.001$). In addition, a significant correlation was observed between N_{Rest} and P_{max} in Class I ($\tau = 0.54$, $P < 0.001$).

The performance of the algorithms for detecting swallowing peaks and resting plateaus was inspected visually and found to be acceptable. The algorithms detected approximately those peaks or plateau phases that were found visually but more objectively. In particular, the peak detection algorithm was able to automatically detect even small peaks.

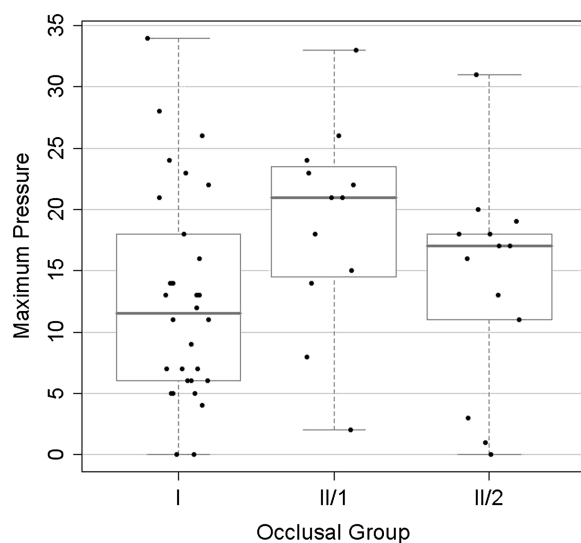
Comparison of occlusal groups

There was no significant difference between the three groups for any parameter (Table 2). Solely, for the number

Table 2 Comparison of curve characteristics in the three distinct occlusal groups.

Curve parameter	Occlusal group			<i>P</i>
	I (<i>n</i> = 30)	II/1 (<i>n</i> = 12)	II/2 (<i>n</i> = 13)	
Area under the curve	452 (38–3744)	402 (134–3499)	475 (38–7662)	0.56
N_{Peak}	12 (0–34)	21 (2–33)	17 (0–31)	0.07
N_{Rest}	5 (1–11)	6.5 (1–28)	5 (1–16)	0.66
P_{max} (mbar)	30.4 (0.4–72.6)	52.4 (3.6–111.7)	41.7 (0.4–71.1)	0.14
\bar{P} (mbar)	3.0 (0.3–25.0)	2.7 (0.9–23.3)	3.2 (0.3–31.1)	0.56

Descriptive values are the median (minimum–maximum).

**Figure 3** Distribution of the number of swallowing peaks in the three distinct occlusal groups, with a tendency for more peaks in the Class II division 1 subjects ($P = 0.07$).

of peaks (N_{Peak}), there was a tendency for a difference ($P = 0.07$). There seemed to be more peaks in the Class II than in Class I group (Figure 3). The median number of peaks was 21 in the Class II division 1 subjects and 17 in the Class II division 2 group, while the median was only 12 in the Class I group. The AUC as well as the number of resting plateaus, maximum, and average pressure were not significantly different between the three malocclusion Classes.

Discussion

Intraoral pressure and its interaction with the surrounding soft tissues affect, among other factors, the formation of the dentition and are therefore considered in orthodontic studies (Proffit, 1978). Several characteristics of intraoral pressure curves were investigated in the present study and their correlations with each other were analysed including the pressure curves from individuals of three different occlusal groups. The correlations between these characteristics,

although partly significant, were weak, except for that between the AUC and \bar{p} , which were perfectly correlated. Thus, the calculation of only one of the two latter parameters is sufficient in studies of intraoral pressure. Since the other parameters each contain independent information concerning intraoral pressure, it is therefore necessary to study all of these parameters.

For the calculation of N_{Peak} , the applicability of a peak detection algorithm from mass spectrometry has been demonstrated. This algorithm is fast (the calculation time was less than 1 minute for the complete data example) and detects approximately all those peaks, which can be observed by visual inspection of pressure curves. In addition, an algorithm for the detection of resting plateaus which also performs adequately and at sufficient speed was introduced. For both algorithms, the specification of a noise parameter, ϵ , is necessary. While, in the presented example, the choice of ϵ was based on pressure measurements from previous research, it is recommended for future investigations to directly estimate ϵ from the subjects being studied.

From a previous study (Knösel *et al.*, 2010), it is known that the intra-individual variance of the described curve characteristics is quite large. It seems therefore to be beneficial to perform several measurements per patient, provided that this is practical (for very young children this would be difficult). In addition, it should be remembered that it requires time to become familiarized with the measurement instrument. Therefore, when setting a time interval for the measurements of a trial, it should also be taken into account that the first and the last 5 seconds should be excluded.

Comparison of pressures curve features during swallowing showed very small differences in terms of subatmospheric pressure peaks at the vestibulum for the different occlusal subjects. However, previous research suggests that, during swallowing, at least two intraoral compartments are formed: firstly, an interocclusal compartment surrounding the dental arches and bordered by the cheeks, lips, and tongue and secondly, a subpalatal compartment between the dorsum and palate (Engelke *et al.*, 2010). As no significant malocclusion related

differences in swallowing characteristics for IOS were found, future research should analyse intraoral pressure for both functional compartments simultaneously.

Conclusions

Distinct characteristics derived from intraoral pressure curves recorded at the premolar vestibular region were found to be largely independent from each other. It is therefore recommended to calculate each of the proposed parameters in studies on intraoral pressure (except for the AUC and \bar{p} , which were perfectly correlated). Resting plateaus and swallowing peaks can easily be calculated using the proposed algorithms.

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