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ORIGINAL ARTICLE

The arrangement of the interproximal interfaces in the human permanent dentition

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Abstract
Objectives The interproximal interface (IPI) is the interface between two adjacent teeth, i.e., the site where forces are transmitted along the dental arch. We investigated the IPI arrangement of the human permanent dentition. Specifically, the IPI morphometrical characteristics were studied and interpreted within a biomechanical framework.
Subjects and methods A novel in vivo IPI measurement was developed based on diversity in transillumination of Polyvinyl siloxane impression of the interproximal region. The study group included 30 subjects, aged 27, ±4.0 years. Eleven parameters were examined in each of the 26 IPIs of the permanent dentition.
Results The IPI showed intra-arch similarity and interarch diversity between the tooth groups. The IPI shape was predominantly oval (60–100 %), yet kidney-shaped in some molars (22–40 %). From incisors to molars: the IPI increased significantly ($p<0.001$) in size (1.72 to 6.05 mm^2), occupied more of the proximal wall (7.8–12 %), changed its orientation from vertical to horizontal (88.66–14.80°), and was mainly located in the buccal–occlusal quadrant of the proximal wall, chiefly in the molar teeth.
Conclusions The IPI is a product of proximal wall attrition and is dictated by the mastication forces, number of cusps, and crown inclination. IPI arrangement counteracts the adverse crowding effect of the anterior component of the mastication forces.
Clinical relevance The IPI characteristics found in the present study provide guidelines for crown and proximal filling restorations to meet dental physiology requirements. Further, IPI determines correct tooth alignment and proximal wall stripping applied to resolve arch length deficiency.

Keywords Interproximal interface · Contact area · Tooth attrition

Introduction

The term “interproximal interface” (IPI) relates to the common boundary area of two adjacent teeth. This boundary is dynamic and varies with age, teeth alignment, crowding, masticatory force, etc.

However, a clarification of the terminology is required before discussing the subject. We prefer to use the term IPI to describe the joint attrition facet between two adjacent teeth in the same arch and the term contact area (CA) to describe the facet on the proximal wall of a tooth that underwent attrition due to physiological activity.

CA and IPI most often differ from each other. For example, late mandibular anterior crowding refers to a condition in which the IPI of two adjacent mandibular incisors was changed due to the development of an overlapped position. In consequence, a new IPI is established and the CA of each

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incisor is the sum of the old IPI and the new IPI. In other words, only a certain portion of the CA of each of the two adjacent teeth build up the IPI. Another example demonstrates the first permanent molar with an initial IPI with the second deciduous molar and a subsequent IPI with the second premolar. Its CA is comprised of the change in IPI over time, i.e., the sum of the attrition that took place during its contact with each of the two teeth. A third example is the concave/convex pattern of the CAs when occlusally viewed that occasionally appears in the posterior dentition [1, 2]. Here, the CA differs between the two adjacent teeth; however, the size of the IPI remains the same.

Physiologically, contacts between teeth allow dissipation of masticatory forces along the dental arch [3, 4], preventing mesial migration of teeth [5], protecting arch integrity, and avoiding food impaction [6]. When IPIs continuity is distally interrupted, distal migration may overwhelm mesial drift [7]. This may occur despite of the fact that the mesial force is five times greater than the distal one [8]. Further, aberration in IPI physiological functioning can lead to loss of interdental crestal bone [9], periodontal breakdown of the interproximal gingival col [10], interdental black triangles [11], and teeth malalignment [12].

To our knowledge, no data exist on the morphometric characteristics of IPI and the arrangement of IPIs along the dental arches. The absence of direct information on IPI is possibly related to poor accessibility to the area and the lack of appropriate measuring techniques. In the present study, a novel in vivo method was developed to gain direct information on the IPI.

The objectives of the study were to define the arrangement of the IPI in the permanent dentition and to interpret the results from the biomechanics point of view. The null hypotheses postulated a common pattern for all IPIs and a lack of biomechanical rational.

Subjects and methods

Sample

Thirty students from the Goldschleger School of Dental Medicine at Tel Aviv University were enrolled in the present study (aged 27±4.0 years). All subjects were females due to gender diversity in maximal voluntary bite force [13], interproximal attrition [14], and secondary dentin reaction [15]. The inclusion criteria were: full permanent dentition, intact dentition, no intra-arch malalignment (no crowding), no periodontal diseases, no orthodontic therapy, no muscular parafunction (e.g., bruxism) and full interdigitation (e.g., no open bite that might decrease the IPI size due to low maximal voluntary bite force [16]). The study was approved by the Helsinki Committee of Tel Aviv University.

Data acquisition

In the posterior dental segments, elastomeric separators (3M Unitek Mantovia PI), with a thickness of 1.11±0.03 mm were placed for 24 h. Following the separators' removal, a two-stage polyvinyl siloxane (PVS) segmental impression was taken (Coltene Whaledent Germany). In the anterior dentition, a few days later, we repeated the procedure with thinner separators (0.75±0.05 mm) for 3 h. The segmental impressions were then sectioned in coronal slices (Fig. 1). Each slice contained two adjacent proximal walls of adjacent teeth with their common IPI. The impression was placed on a standardized illuminating viewer. Further, a digital camera (Olympus, Tokyo, Japan), fixed in constant distance from the viewer, was used to capture two images (IPI projected once on the proximal wall of the mesial tooth and once on the proximal wall of the distal tooth). For accurate measuring of the IPI the image was converted into negative imaging and then automatically analyzed by TINA software (Raytest, Straubenhardt, Germany), using standardized brightness (60 % scales; Fig. 1). The described measuring technique is a two-dimensional approach. Benazzi et al. [17] who analyzed the interproximal wear facet of adjacent mandibular molars comparing 3D and 2D outlines of the interproximal facet found that a 2D digital approach provides adequate results since the proximal facets possess only a shallow concavity.

For each digital image, the following six parameters were recorded: IPI shape (round, oval, kidney), IPI size (area), IPI angle (an angle created between the intersection of the IPI long axis and a line running parallel to occlusal plane), IPI quadrants (the four areas of the IPI within each of the four quadrants of the proximal wall), PW (the size of the proximal wall), IPI/PW (the ratio IPI size to proximal wall area) (Fig. 1).

The validation of the IPI measuring technique was carried out on 10 human skeletonized jaws at the P_1–P_2 interface in two examinations: a metal filler gauge of 0.75 mm thickness was placed at the mandibular P_1–P_2 interface, then removed and PVS impression was taken. Subsequently, a thicker gauge (1.1 mm) was inserted at the same place and the procedure was repeated.

In the second examination, the intraclass correlation coefficient (ICC) was calculated to determine the intra and intertester reliability of the measurement (repeated measurements of 10 casts). Intratester reliability was assessed by one investigator and intertester reliability involved two testers. Both testers were blinded to the results of each other. Kappa was calculated to determine the intra and intertester reliability of IPI shapes.

Descriptive statistics were performed to obtain the major statistics of each continuous variable. Independent sample *t* test and one-way ANOVA with Tukey post hoc analysis were applied to check for statistical differences in IPI size between the different teeth; chi-square test was carried out for discrete variable to check for significant association between IPI shape and tooth type and Pearson's correlation

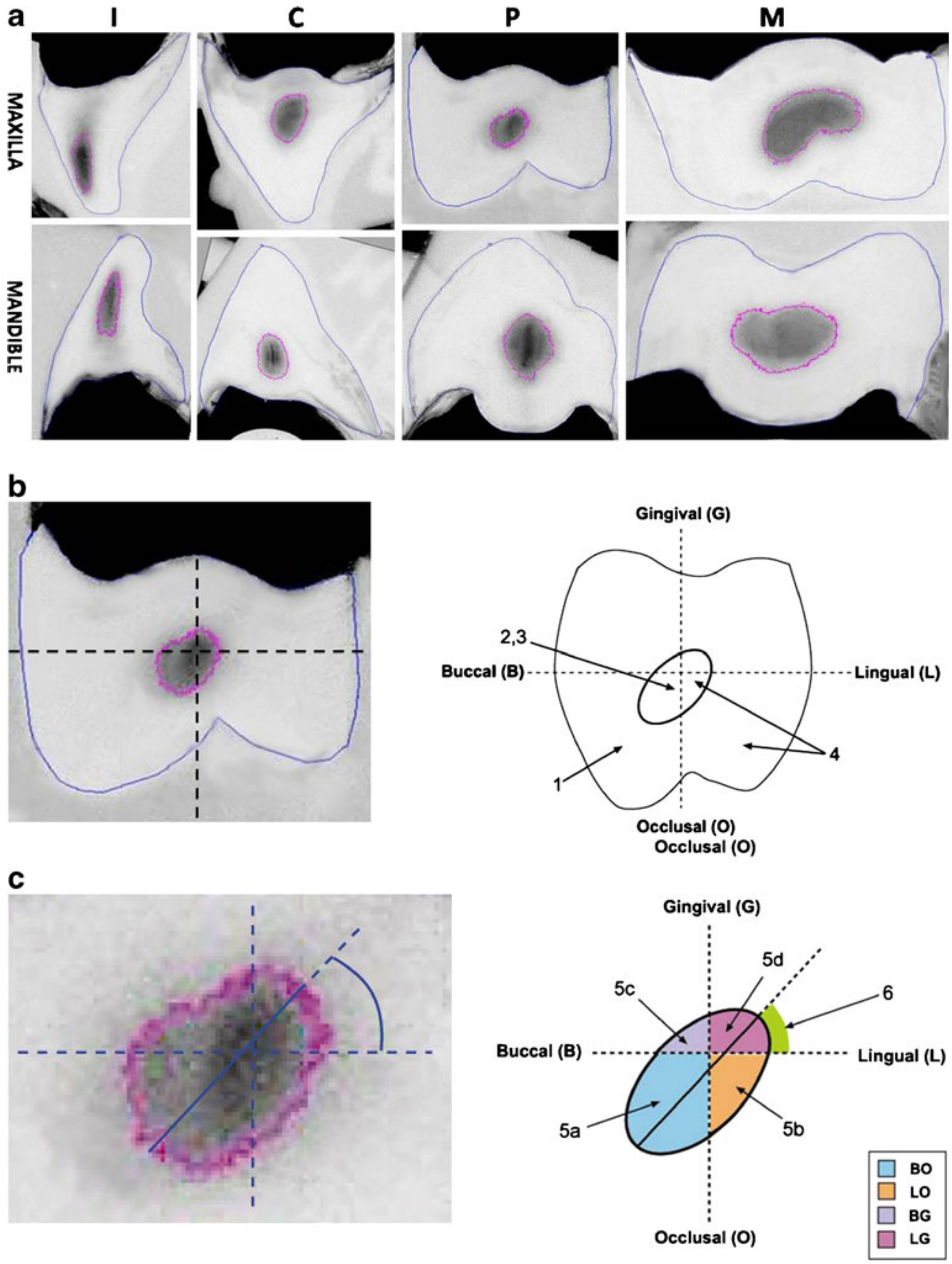

Fig. 1 **a** Transillumination images of the proximal wall (PW) and the interproximal interface (IPI) after being converted into a negative imaging and processed in the Tina software for the central incisor (*I*), canine (*C*), premolar (*P*), and molar (*M*) of the maxillary and mandibular dental arches. **b** TINA imaging and schematic drawings of four of the six examined parameters: *1* proximal wall area (PW), *2* IPI size, *3* IPI shape (oval in this example), *4* percentage ratio of IPI size to proximal wall area (IPI/PW%). **c** TINA imaging and schematic drawing (higher magnification of the IPI area) of two of the six examined parameters: *5a* IPI quadrant BO (buccal–occlusal), *5b* IPI quadrant LO (lingual–occlusal), *5c* IPI quadrant BG (buccal–gingival), *5d* IPI quadrant LG (lingual–gingival), *6* IPI angle

test for association between six variables. The significant level was set at $p<0.05$ for intra-arch comparison and 0.012 for interarch comparison (Bonferroni correction). All statistical procedures were calculated with the statistical software package SPSS (SPSS, Vs. 16 Chicago, IL, USA). Art work was done using Freehand MX software (11.0. Macromedia, Adobe Systems Incorporated, California, USA).

Results

Projection error Since the IPI is a 3D configuration projected on a 2D plane, each specimen was transilluminated once with the distal proximal wall of the mesial tooth facing the light viewer and once with the mesial proximal wall of distal tooth facing the light viewer. This was examined in all 330 IPIs of the study and the difference in projection between the two images was insignificant (1.7 %, $p>0.35$).

Validity Difference between the two separators used (0.7 and 1.1 mm) was found to be nonsignificant ($p=0.32$) for the IPI size (3.34 ± 1.72 and 4.32 ± 1.31 mm^2, respectively).

Reliability For area size measurement, ICC for intratester test was 0.956 and 0.916 for intertester test. For IPI shape, kappa for intertester was 0.725 and for intratester 0.859.

IPI shape

The relative frequencies of the three IPI shaped types (ovoid, round, kidney) differed significantly among tooth groups (incisors, canines, premolars, and molars) in each jaw ($p<0.006$) and were nonsignificant between jaws. The ovoid shape was the most common, ranging from 94 to 100 % in incisor and canine groups, 78–88.5 % in premolars, and 50–60 % in the molars. The round shape was absent in the incisors, appeared in low frequencies in the canines and premolars (6–8 %) and molars (10–18 %). The kidney shape appeared in low frequencies in the upper premolars (15 %) and molars (22 %) and high frequencies in the lower molars (40 %). The change in shape distribution between tooth groups was similar in both arches (Table 1).

IPI size

The IPI size increased gradually from the incisor to the molars regardless of jaw. The maxillary and mandibular incisor groups demonstrated a significantly smaller IPI size (1.89 ± 0.92 and 1.72 ± 0.77 mm^2, respectively) compared to the upper and lower molars (5.28 ± 1.9 and 6.05 ± 2.31 mm^2, respectively). In the same tooth, IPI on the mesial surface was always smaller compared to the distal one (Table 1).

IPI angle

The angulations between the long axis of the IPI and the occlusal plane changed significantly ($p<0.001$) from incisors to molars, being more obtuse in the former (84–88°) and more acute in the latter (14–26°). This implies that the ovoid shape IPI of incisors and canines are more vertically oriented, whereas the ovoid or kidney shapes IPI of the molars are more horizontally oriented. This pattern of progressive change in angulations was evident in both dental arches (Table 1).

IPI quadrant

Most IPI area was located in the BO and BG quadrants of the PW. For this reason, the four IPI quadrants differed significantly from each other in each group of teeth (Table 1). Moreover, in all eight groups of teeth of both jaws the sum of the IPI in the buccal quadrants (BO + BG) was always greater than the sum on the lingual quadrants (LO + LG). However, in the molar group, the LO quadrant was second in size to the major BO quadrant in both arches (Table 1).

IPI/PW

With the exception of the maxillary premolars, the IPI/PW ratio progressively increased from incisor to molar groups in both arches. The greatest and significant IPI/PW ratio was found in both maxillary and mandibular molars (Table 1).

IPI correlation

IPI size correlated highly and significantly ($p<0.001$) with proximal wall size ($r=0.71$), BO and LO quadrants ($r=0.74$, $r=0.69$) and IPI angle ($r=-0.47$). Additionally, PW size correlated highly with IPI angle ($r=-0.58$, $p<0.001$; Table 2).

Inter-arch comparison

With the exception of the premolar group, all other dental groups showed basically nonsignificant differences between maxillary and mandibular IPI characteristics (Table 1).

Discussion

The finding that diverse interproximal separation gaps did not alter the IPI size measurement provides justification to the use of our measuring technique. Thus, although individuals can demonstrate diverse contact point tightness [18] this will not affect IPI measurements. This finding is supported by the Mariath study [19] that showed high sensitivity, specificity, and predictive values when proximal caries was evaluated, using elastomeric impression after tooth separation.

The first finding of increased IPI size from incisor to molars can be explained by the diversity in bite force, acting on each group of teeth, which is greater in the posterior dentition than the anterior one [8]. That is, a greater attrition is expected to develop in the posterior dental units when the anterior component of the force (ACF) acting between pairs of teeth is considerable (following Coulomb law of friction; Fig. 2).

The second important finding is the significant progressive change in spatial orientation of the IPIs from a vertical (incisor group) to horizontal (molar group) in both arches. We assume that albeit bite force is generally vertically oriented, much of the teeth movement during mastication is dictated by their crown configuration. In anterior teeth, where only a single cusp is present, movements mainly occur in the superior–inferior direction (intrusive and extrusive force vectors), resulting in an oval vertically oriented IPI shape. In the posterior teeth with their multicusp crown, the biting forces are most likely distributed in different directions causing the teeth to move downward (intrusive, during biting) in an oblique lingual and oblique buccal direction and upwards (extrusive, during release) in the same directions. For this reason, when ovoid-shaped IPIs

Table 1 IPI parameters examined according to four groups of teeth for intra-arch comparison (maxillary or mandibular dental arches) and for inter-arch comparison (maxillary arch vs. mandibular arch)

Tooth groups (IPI)	Shape (%)			IPI (mm^2)	IPI quadrants (%)				Angle (°)	PW	IPI/PW (%)
Maxillary	Ovoid	Round	Kidney		BO	BG	LO	LG			
I (I2-I1)	100	0	0	1.89±0.9	26.5±18.9	31.2±21.6	16.9±20.2	21.1±18.6	84.93±4.8	20.24±5.9	10.01±4.9
C (C-I2)	94	6	0	2.43±1.0	3.0±8.10	58.1±32.0	0.9±2.9	36.8±31.8	78.4±7.5	30.12±7.6	8.36±3.7
P (P2-P1)	78	7	15	2.79±1.3	46.8±24.9	31.4±29.1	11.7±12.8	8.3±8.5	42.37±18.3	32.38±7.0	8.64±2.9
M (M1-P2)	60	18	22	5.28±1.9	41.5±26.2	15.3±10.6	27.2±24.4	14.3±16.0	26.0±20.4	39.15±9.2	13.80±4.7
Sig.	(χ^2) $p=0.006$			$p<0.001$	$p<0.001$	$p=0.001$	$p<0.001$	$p=0.007$	$p<0.001$	$p<0.001$	$p<0.001$
Tukey	$I \neq C, M$ $M \neq I, C$			$M \neq I, C, P$	$I, C \neq P \neq M$	$I, P, M \neq C$	$I, C, P \neq M$	$P \neq C, M$	$I, C \neq P \neq M$	$I \neq C, P \neq M$	$I, C, P \neq M$
Mandibular											
I (I2-I1)	100	0	0	1.72±0.7	55.6±28.8	17.2±18.6	16.0±21.4	10.3±22.1	88.66±1.6	23.03±4.8	8.17±3.1
C (C-I2)	100	0	0	2.7±1.5	19.8±18.7	48.7±27.4	3.1±5.4	28.9±29.8	78.51±2.8	27.71±6.1	10.57±7.2
P (P2-P1)	88.5	11.5	0	3.92±2.3	36.0±23.7	41.0±28.9	9.8±18.6	11.8±24.0	66.97±18.1	32.61±10.3	11.45±4.3
M (M1-P2)	50	10	40	6.05±2.3	37.7±10.0	20.6±13.2	24.3±14.5	14.2±10.7	14.8±10.8	46.20±11.0	13.27±4.2
Sig.	(χ^2) $p<0.001$			$p<0.001$	$p<0.001$	$p<0.001$	$p<0.001$	$p=0.003$	$p<0.001$	$p<0.001$	$p=0.016$
Tukey	$M \neq I, C, P$			$C \neq M$, $I \neq P \neq M$	$I, C \neq M$	$I \neq C, P, M$	$I, C, P \neq M$	$I \neq M, C$ $P \neq C$	$M \neq I, C, P$ $I \neq C$	$I \neq P \neq M$ $C \neq M$	$M \neq I$
Inter-arch comparison (sig)											
I (I2-I1)				0.500	0.010	0.032	0.960	0.059	0.001	0.159	0.365
C (C-I2)	0.310			0.570	0.030	0.300	0.250	0.720	0.880	0.360	0.284
P (P2-P1)	0.022			0.034	0.790	0.002	0.670	0.610	0.001	0.825	0.006
M (M1-P2)	0.012			0.220	0.950	0.186	0.430	0.510	0.037	0.040	0.954

IPI interproximal interface, *I* incisors, *C* canine, *P* premolars, *M* molar, *BO* buccalocclusal, *LO* lingual–occlusal, *BG* buccal–gingival, *LG* lingual–gingival, *PW* proximal wall, *IPI/PW(%)* percentage ratio of IPI size to proximal wall area, *angle* the angle created between the intersection of the IPI long axis and a line running parallel to occlusal plane

Table 2 Correlations between the five continuous parameters of IPI

	BO	BG	LO	LG	ANGLE	PW
IPI	r=0.74 p<0.001	r=0.40 p<0.001	r=0.69 p<0.001	r=0.39 p<0.001	r=−0.47 p<0.001	r=0.71 p<0.001
BO		r=0.10 p=0.17	r=0.36 p<0.001	r=−0.08 p=0.30	r=−0.40 p<0.001	r=0.54 p<0.001
BG			r=−0.14 p=0.07	r=−0.01 p=0.92	r=−0.05 p=0.52	r=0.24 p=0.001
LO				r=0.32 p<0.001	r=−0.42 p<0.001	r=0.55 p<0.001
LG					r=−0.14 p=0.09	r=0.22 p=0.004
Angle						r=−0.58 p<0.001

IPI interproximal interface, *BO* buccalocclusal quadrant, *LO* lingual–occlusal quadrant, *BG* buccal–gingival quadrant, *LG* lingual–gingival quadrant, *angle* the angle created between the intersection of the IPI long axis and a line running parallel to occlusal plane, *PW* proximal wall

are present in the premolars or molars, they are usually horizontally or obliquely oriented.

The kidney-shaped IPI in the molar group is most likely the outcome of buccoocclusal and linguoocclusal extension of a premature oval-shaped IPI. The occlusal direction is related to the increase in proximal tightness, i.e., the norm force (ACF) during biting [20] which is adjunct with a slight intrusion of the tooth [21], while the buccolingual direction is related to incline cusp [22] (Fig. 2).

It is noteworthy to mention that kidney-shaped IPIs were found in the maxillary premolars but not in the mandibular premolars. This can be attributed to the presence of a large buccal and a small lingual cusp in the mandibular premolars, translated by the vector force system as a single cusp tooth.

The third finding of the study, that IPI area is mainly located in the two buccal quadrants (BO + BG), gives emphasis to the major impact of tooth inclination in determining the attrition configuration of the proximal wall. Similar findings were shown in occlusal attrition [23]. Nevertheless, these force analysis interpretations are postulated as hypothesis and further in-depth biomechanical studies are required to confirm these theories.

The fourth finding of high correlations between IPI size and PW, angulation, and quadrants suggests that the four parameters are synchronized. The strong correlation between IPI size and BO or LO quadrants is related to the increased size of oval and kidney shapes in molar teeth on account of these two quadrants.

The fifth finding of similar blueprint of IPI characteristics between the two dental arches (with the exception of the premolar group, attributed to the singular vs. dual root configuration), suggests a similar attrition pattern that is related to common force transmission system acting on both arches.

The investigation of tooth-to-tooth contact array is of major interest as correct traverse of mastication forces via these interfaces is mandatory for preservation of physiological steady state of the dental system. Improper tooth-to-tooth linkage can produce periodontal breakdown, orthodontic malalignment or restorative/prosthetic failure [1–3, 5, 8–10, 12]. The by-product of a time-dependent dynamic system is the deterioration with aging. In the case of tooth-to-tooth contact, the material fatigue is expressed in the form of occlusal [22–25] or interproximal tooth wear [26–28]. This attrition develops progressively throughout life span [28, 29]. However, the results reported here are related to a single time point at a mean age of 27 years. At this age, diverse units of the permanent dentition underwent already attrition in a span of 15–20 years (for example, M_1, $I_{1,2}$ about 20 years; M_2 about 15 years). Thus, the interpretation of our data takes the attrition process into account, yet it is restricted to a single time point and part of our interpretation is postulated as a theory.

The question arises whether the attrition is a physiological or pathological process. The textbook of oral medicine [30] defines physiological attrition as a process which occurs due to normal aging and mastication; and pathological attrition as a process which occurs due to certain abnormalities in occlusion, chewing pattern, or some structural defects in teeth. In accordance with these definitions, we are more inclined to suggest that the attrition found in our sample is related to physiologic attrition; as pathologic factors such as bruxism and periodontal diseases were excluded from our sample. Interproximal pathological attrition is of major concern but is out of the scope of the present study.

Inadequate physiological interproximal attrition at the IPIs, especially in the posterior dentition of modern human, i.e., absence of sufficient tooth size reduction, led to the postulation of the Begg theory. Accordingly, tooth extraction is required to compensate for the developed crowded malocclusions [28]. Although reservation to this theory was raised [31], interproximal reduction techniques were recently introduced to correct arch length deficiency and increase stability by enlarging the IPIs [32].

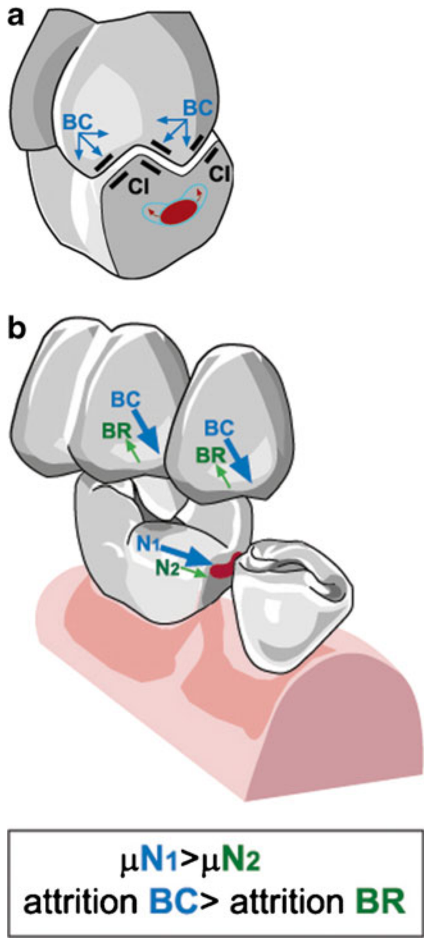

Fig. 2 **a** The kidney-shaped IPI developed most likely from an oval shaped IPI when the attrition at the buccal and lingual edges expands occlusobuccally and occlusolingually (*red arrows*) during bite closure (*BC*). The attrition (*red arrows*) is propagating inversely to the acting forces (*blue arrows*). The attrition in buccolingual direction is related to cusp incline (*CI*) and the attrition in occlusal direction to tooth intrusion. **b** The latter is related to the greater interproximal tightness (N_1=norm force) developed during BC in comparison to the low norm force (N_2) developed during bite release (BR). Increase in the norm force in occlusal direction, during tooth intrusion increases the friction and expands the IPI in the two occlusal quadrants (BO, LO). The increase in attrition follows Coloumb law (micro Newton) where μ = enamel coefficient of friction and N = norm, force = ACF

We further suggest that IPI arrangement is aimed at counteracting the hazard of mesial drift of the posterior dentition and consequently, minimizing late anterior crowding [33]. For this reason, in the posterior dentition of both dental arches, the mastication forces are diverged into bucco-vertico-oblique force vectors and mainly in the linguo-vertico-oblique force vectors [34] causing the attrition to be in a horizontal oval form, i.e., IPIs of molars, premolars, and the distal wall of the canine. This force dispersion pattern is supported by the lingual crown inclination of the posterior dentition and by the increased canine root size [8, 35]. These contribute to the inhibition of force transmission to the anterior dental segment. In line with this concept, in the anterior dentition, all IPIs mesial to the canine are converted into a vertical oval form. This type of arrangement is the outcome of vertical mastication forces acting on the single-cusp anterior teeth [36], and is rationalized as it prevents the development of overlapped incisor crowns. That is, if the anterior mastication force would have acted anteriorly in the same pattern as in the posterior dentition (buccolingual), breakage of tooth contact would have frequently developed due to the narrow labiolingual dimension of the incisors' proximal walls.

In conclusion, the unique arrangement of the interproximal interface array of the permanent dentition (size, shape, and inclination) is most likely a product of the physiological attrition. We assume that this attrition is dictated by the mastication forces (ACF, straight vertical force vector, buccal vertical–oblique force vector, lingual vertical–oblique force vector), the number of cusps (single vs. multiple) and the crown inclination (crown position in the dental arch). With respect to clinical implications, the IPI characteristics found in the present study provide guidelines for crown and proximal filling restorations to meet dental physiology requirements. For example, when a proximal filling is prepared in a posterior tooth, the matrix band and the wedge should be placed in such a way that after their removal, the established IPI will be mainly positioned in the buccoocclusal quadrant of the restored proximal wall. The accurate position of each IPI of the permanent dentition as found in the present study calls for a revision in the diverse wedges and matrices forms presently available [37] as outlined in Table 1. This is applied for amalgam or composite proximal restorations, and prosthetic crowns. Additionally, proper IPI determines correct tooth alignment and thus, should be considered when proximal wall stripping is applied to resolve arch length deficiency (crowding). For example, enamel interproximal reduction should be mainly performed in the occlusal half of the proximal wall in the case of mandibular incisors and in the gingival half of the proximal wall in the case of canine teeth. Clinically, the path of insertion of the slender diamond bur used for interproximal reduction (e.g., Z12, J10, Strauss & Co.) should be in occlusogingival direction in the former and in gingivoocclusal direction in the latter.

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

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