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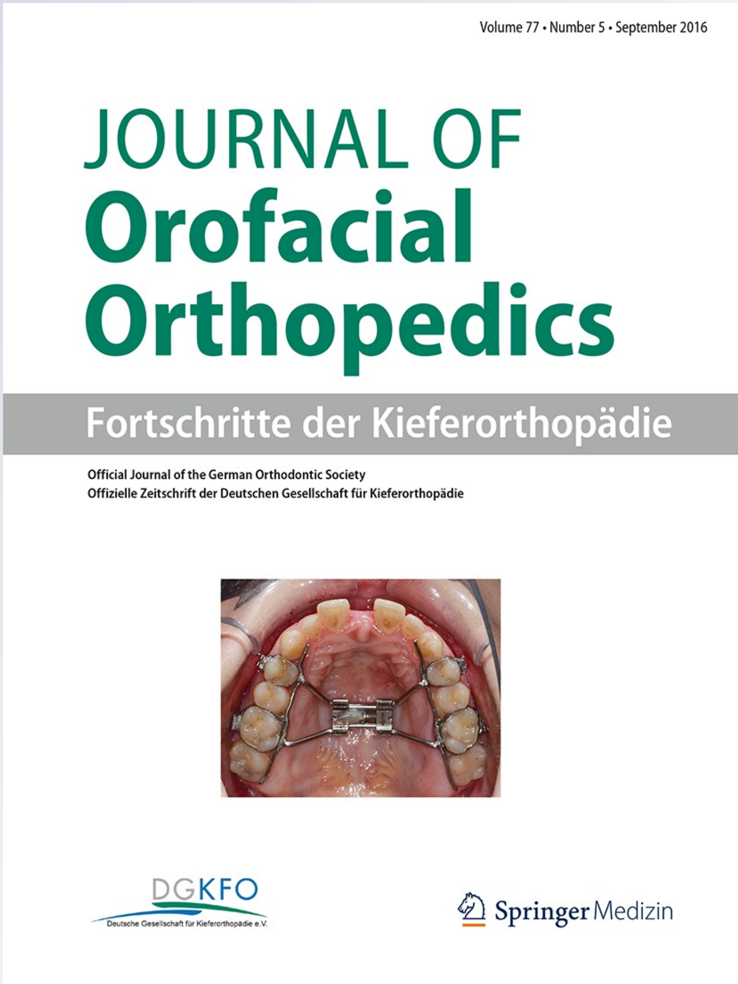
Journal of Orofacial Orthopedics / Fortschritte der Kieferorthopädie
Official Journal of the German Orthodontic Society / Offizielle Zeitschrift der Deutschen Gesellschaft für Kieferorthopädie

ISSN 1434-5293
Volume 77
Number 5

J Orofac Orthop (2016) 77:314-324
DOI 10.1007/s00056-016-0037-1



Springer

J Orofac Orthop (2016) 77:314–324
DOI 10.1007/s00056-016-0037-1

ORIGINAL ARTICLE

Differential treatment effects of two anchorage systems for rapid maxillary expansion: a retrospective cephalometric study

Differenzialtherapeutische Effekte zweier unterschiedlich verankerter Gaumennahterweiterungsapparaturen: Eine retrospektive kephalometrische Studie

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Received: 22 July 2015 / Accepted: 3 December 2015 / Published online: 7 June 2016

Abstract
Objectives The purpose of this study was to compare cephalometric changes resulting from treatment with two appliances for rapid maxillary expansion: (1) a strictly tooth-borne appliance and (2) a combined tooth- and bone-borne appliance.
Patients and methods Pre- and posttreatment lateral cephalograms of 100 patients were analyzed by cephalometry. Of these patients, 50 were treated with strictly tooth-borne and another 50 with combined tooth- and bone-borne appliances. Mean pretreatment age was 13.04 ± 4.82 years, and mean treatment duration was 7.12 ± 2.37 months. To identify any implications for clinical therapy, additional subgroups were formed based on the pretreatment cephalometric findings for skeletal Class I ($0° < ANB \leq 4°$) or Class III ($ANB \leq 0°$). Paired *t*-tests were used for intragroup and analysis of variance (ANOVA) for intergroup comparisons. Results were considered statistically significant at $p \leq 0.05$.
Results Both appliance types resulted in significant cephalometric changes in the maxilla and mandible. Compared to the strictly tooth-borne appliances, the combined tooth- and bone-borne appliances were found to cause more pronounced advancement of the maxilla (SNA angle) notably among the Class III patients.
Conclusions Hybrid (combined tooth- and bone-borne) appliances for rapid maxillary expansion might be preferable in the treatment of skeletal Class III patients, since they possibly exert a more pronounced skeletal effect on the sagittal position of the maxilla.

Keywords Cephalometric study · Analysis of cephalograms · Rapid maxillary expansion · Angle class I · Angle class III

Zusammenfassung
Zielsetzung Ziel dieser Studie war die vergleichende Untersuchung kephalometrischer Veränderungen durch die Behandlung mittels zweier Gaumennahterweiterungsapparaturen: einer rein zahngetragenen und einer kombiniert zahn- und knochengetragenen Ausführung.
Patienten und Methoden Prä- und posttherapeutische Fernröntgenseitenaufnahmen von 100 Patienten wurden kephalometrisch ausgewertet. Fünfzig Patienten wurden mit einer rein zahngetragenen, 50 mit einer kombiniert zahn- und knochengetragenen Ausführung behandelt. Das Alter vor Behandlung lag im Mittel bei 13,04 ± 4,82 Jahren, die Behandlungsdauer bei 7,12 ± 2,37 Monaten. Um mögliche Implikationen für die Therapie ableiten zu können, wurden die Patienten über eine prätherapeutisch kephalometrisch diagnostizierte Zughörigkeit zur skelettalen Klasse I ($0° < ANB \leq 4°$) bzw. Klasse III ($ANB \leq 0°$) weiter unterteilt. Für Intragruppenvergleiche kamen gepaarte t-Tests zum Einsatz, während für Intergruppenvergleiche unabhängige *t*-Tests respektive die

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Varianzanalyse (ANOVA) zur Anwendung kamen. Statistische Signifikanz wurde bei $p < 0{,}05$ angenommen.
Ergebnisse Es konnten signifikante kephalometrische Veränderungen in beiden Kiefern nach Behandlung mit beiden Apparaturen verzeichnet werden. Verglichen mit der rein zahngetragenen Gaumenerweiterungsapparatur verursachte die kombiniert zahn- und knochengetragene Ausführung eine stärker ausgeprägte anteriore Verlagerung der Maxilla (SNA-Winkel), insbesondere bei Klasse-III-Patienten.
Schlussfolgerungen Die kombiniert zahn- und knochengetragenen Gaumennahterweiterungsapparatur könnte bei skelettalen Klasse-III-Patienten aufgrund eines möglicherweise stärkeren skelettalen Effektes auf die sagittale Lage der Maxilla die Behandlung dieser Patientengruppe begünstigen.

Schlüsselwörter Röntgenkephalometrische Studie · Fernröntgenseitenbildauswertung · Forcierte Gaumennahterweiterung · Angle Klasse I · Angle Klasse III

Introduction

Rapid maxillary expansion (RME) dates back to American dentist Emerson C. Angell [2]. Following an initial period of controversy [66], the concept has become an integral part of the orthodontic treatment armamentarium [40]. It functions on the principle that a force applied through an appliance will move the left and right halves of the maxilla apart. Anchorage for this force application may be provided by different structures, as by four teeth (Hyrax type) [6], by a combination of teeth and palatal mucosa (Haas type) [24], or by jawbone only [28, 70]. Another anchorage type combines teeth with jawbone [45, 68], resulting in so-called hybrid RME appliances [68] that combine formal and design elements of the strictly tooth-borne (conventional) and the strictly bone-borne variants [51]. The latter, due to their anchorage in maxillary bone, reportedly have more pronounced skeletal effects than strictly tooth-borne designs [47], which could be desirable notably in the treatment of Class III or, specifically, maxillary retrognathism.

Various studies [3, 19, 61] have compared sagittal and vertical effects of different RME appliances based on lateral cephalograms. To our knowledge, however, no comparison has been made between strictly tooth-borne and hybrid appliances. Hence the objective of this study was to compare the cephalometric changes brought about by treatment with two differently anchored RME appliances, namely (1) a strictly tooth-borne appliance and (2) a combined tooth- and bone-borne appliance. Retrospective cephalograms were to be analyzed, as these are routinely obtained in the context of orthodontic therapies. The study hypothesis was that more pronounced treatment-related cephalometric changes would be identifiable among patients treated with hybrid RME appliances due to the additional anchorage directly in maxillary bone.

Materials and methods

Patients and group assignment

Approval for this retrospective study of cephalograms was obtained from the institutional review board (Ethics Commission of University of Aachen, ref. 171/08). A total of 100 patients (59 girls and 41 boys) with transverse deficits of the maxilla were included; all had been treated by RME without surgical support in the context of orthodontic treatment indications. Two groups of 50 patients were formed, including a conventional group of 29 girls/21 boys treated with strictly tooth-borne appliances (Orthodontic Practice Prof. Dr. G. Kinzinger/Dr. A. Schroeder, Tönisvorst, Germany) and a hybrid group of 30 girls/20 boys treated with appliances anchored in both teeth and jawbone (Orthodontic Practice Dres. B. Ludwig/B. Glasl, Traben-Trarbach, Germany). These two groups were recruited from two orthodontic practices, whereby each practice exclusively used one of the two methods. To identify any implications for clinical therapy, the patients were further divided into skeletal Class I ($0° < \text{ANB} \le 4°$) or Class III ($\text{ANB} \le 0°$) subgroup based on their pretreatment cephalometric findings (Table 1) [46]. Other inclusion criteria were Caucasian descent and bilateral posterior crossbite. Excluded were any patients with a history of orthodontic treatment, previous extraction of permanent teeth, planned extractions, congenital agenesis of permanent teeth, craniofacial malformation or trauma, systemic disease, dental trauma in the anterior segment with or without tooth loss, or measures for maxillary protraction (facemask).

Conventional and hybrid appliances

The strictly tooth-borne RME appliance used in the conventional group are illustrated in Fig. 1a. This design featured a central expansion screw (Forestadent, Pforzheim, Germany) with anterior and posterior connectors bilaterally joined/welded in a loop-shaped configuration that made contact bilaterally with the palatal surfaces of the premolars and first molars. Additional weld joints connected the structure to orthodontic bands on the first molars and to occlusal support wires bonded, from a mesial direction, into the central fissures of the first premolars using a flowable composite. The combined tooth- and bone-borne RME structures (Fig. 1b) used in the hybrid group are also

Tab. 1 Group assignment. Depending on the type of rapid maxillary expansion (RME) appliance used, the patients were assigned to two groups of 50 cases each. These were further subdivided into skeletal Class I and Class III cases

Tab. 1 Gruppenzuordnung der Patienten: Zuordnung in Abhängigkeit von der verwendeten Gaumennahterweiterungsapparatur zu 2 gleich großen Patientengruppen („konventionell“, „hybrid“) à 50 Patienten, weitere Subklassifikation nach skelettaler Klasse I und III

All patients ($n = 100$)			
Conventional group ($n = 50$) Strictly tooth-borne RME appliance		Hybrid group ($n = 50$) Tooth- and bone-borne RME appliance	
Class I subgroup ($n = 32$) Skeletal Class I	Class III subgroup ($n = 18$) Skeletal Class III	Class I subgroup ($n = 32$) Skeletal Class I	Class III subgroup ($n = 18$) Skeletal Class III

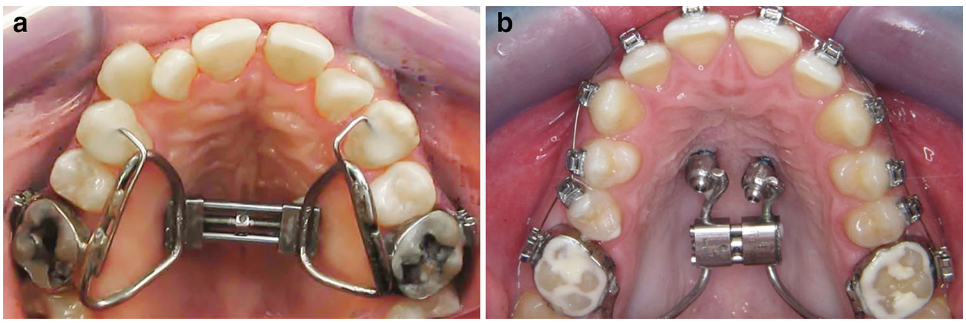

Fig. 1 **a**, **b** Two types of rapid maxillary expansion appliances were investigated: a strictly tooth-borne conventional design (**a**) and a tooth- and bone-borne hybrid design (**b**). Note that the orthodontic archwire used with the latter appliance type—also known as hybrid hyrax—is separated between the central incisors during daily activation of the expansion screw. An unseparated archwire is used thereafter

Abb. 1 Untersuchte Apparaturen: konventionelle zahngetragene Gaumennahterweiterungsapparatur (Gruppe „konventionell“, **a** und kombiniert zahn- und knochengetragene hybride Gaumennahterweiterungsapparatur (Gruppe „hybrid“, **b** Anmerkung: Im Falle der „Hybrid-Hyrax“ist der orthodontische Bogen in der Phase der täglichen Aktivierung der Splitschraube immer zwischen den zentralen Schneidezähnen geteilt. Danach wird ein ungeteilter Bogen verwendet

known as hybrid hyrax [68]. These were supported by two miniscrews 1.7 mm in diameter and 8 mm in length (Ortho Easy®; Forestadent) inserted at paramedian sites in the anterior palate. The anterior side of these appliances were supported by these miniscrews, while the posterior side was connected to the orthodontic bands on the first molars, the force for RME being applied via a centrally located expansion screw (Forestadent).

Screw activation and clinical protocol

Following insertion, the patients were instructed to activate the expansion screw of the RME appliance three times a day, for a change of 0.2 mm per activation. Once the required expansion distance had been achieved, the appliance was left in situ over a retention period of at least 5 months.

Radiographs and cephalometric analysis

Two cephalograms were available for each patient. The first cephalogram (T1) was taken in the mandatory pretreatment diagnostic stage prior to insertion of the RME appliance. The second cephalogram (T2) was taken immediately upon removal of the RME appliance. Accordingly, a total of 200 radiographs were evaluated. Cephalometric analysis was performed by an investigator with the help of appropriate software (fr-win®, v. 7.0; Computer Konkret, Falkenstein, Germany) under constant environmental conditions, using an officially certified

Tab. 2 Overview of cephalometric results based on all patients. Treatment-related changes observed with the conventional and hybrid appliance types and an intergroup comparison are listed

Tab. 2 Vergleich kephalometrische Parameter—„konventionell“ vs. „hybrid“ (alle Patienten)

	Conventional group (tooth-borne RME appliance)				Hybrid group (tooth-/bone-borne RME appliance)				Conventional versus hybrid	
	ΔT2–T1		*p* value		ΔT2–T1	SD	*p* value		*p* value	
Maxilla										
S-Spa	−0.93	4.83	0.179	NS	+2.15	3.90	<0.001	***	<0.001	***
S-Spp	−0.79	3.07	0.075	NS	+1.12	2.09	<0.001	***	0.006	**
N-Spa	+1.47	3.58	0.005	**	+1.52	2.96	0.001	**	0.941	NS
N-Spp	+0.75	5.23	0.317	NS	+2.00	3.31	<0.001	***	0.143	NS
SN-Spa	−0.97	3.16	0.035	*	+0.77	3.26	0.101	NS	0.008	**
NL/NSL	+1.76	2.93	<0.001	***	+0.01	2.13	0.971	NS	0.001	**
SNA	−0.12	2.02	0.026	*	+1.30	2.05	0.009	**	0.001	**
Mandible										
S-Go	+1.08	5.00	0.133	NS	+2.98	4.44	<0.001	***	0.047	*
N-Me	+2.49	7.69	0.027	*	+4.35	5.47	<0.001	***	0.165	NS
N-Pog	+2.49	7.61	0.025	*	+4.52	5.54	<0.001	***	0.130	NS
SNB	−1.14	3.06	0.011	*	−0.17	2.23	0.590	NS	0.100	NS
ANB	+0.07	2.08	0.743	NS	+1.14	2.15	0.001	**	0.013	*
SN/Pog	−0.86	3.16	0.060	NS	−0.02	2.18	0.961	NS	0.128	NS
ML/NSL	+1.81	3.53	0.001	**	+0.85	2.36	0.015	*	0.111	NS
ML/NL	+0.07	2.77	0.863	NS	+0.84	1.97	0.004	**	0.026	*
Björk sum	+1.81	3.53	0.001	**	+0.85	2.36	0.014	*	0.112	NS
N-S-Ar	+0.65	3.38	0.179	NS	−0.12	2.94	0.781	NS	0.229	NS
S-Ar-Go	+1.39	4.77	0.045	*	−0.21	7.33	0.840	NS	0.326	NS
Ar-Go-Me	−0.21	5.33	0.787	NS	+1.18	6.30	0.191	NS	0.232	NS

NS not significant, *RME* rapid maxillary expansion, *ΔT2–T1* positive or negative values indicate increases or decreases respectively

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

image viewing system for radiographic diagnostics. Analysis was based on a standard set of dentoskeletal linear (mm) and angular (°) parameters [64].

Reliability test and statistical analysis

To verify their reliability, the measurements were repeated 3 months after the first run. Then the measurement error (ME) was calculated by applying the Dahlberg formula ($\mathrm{ME} = \sqrt{\sum d^2/2n}$) [13], where d is the difference of the repeated-measurement pairs and n the number of measurements. The method error was 0.91 mm or degrees, respectively. Data were collected in a structured fashion with the help of spreadsheet software (Excel® 2007; Microsoft, Redmond, WA, USA). Intragroup comparisons were performed with *t*-tests for connected samples. Intergroup comparisons were performed either with *t*-tests for independent samples or, for multiple group comparisons, by analysis of variance (ANOVA). Statistics software was used for analysis (SPSS, v. 18.0; SPSS, Chicago, IL, USA) on a Microsoft Windows® platform. Differences were considered statistically significant at *p*-values ≤0.05.

Results

Patients and treatment

The patients' mean age was 13.04 ± 4.82 years at the start of treatment when the RME appliance was inserted (T1) and had reached 13.54 ± 4.78 years by the end of treatment when the appliance was removed (T2). All treatments of maxillary expansion were successful and uneventful. In all cases, a medial diastema was observed at the end of treatment, indicating separation of both jaw halves.

Conventional versus hybrid appliances (all patients)

The cephalometric changes based on all patients are summarized in Table 2, Figs. 2 and 3. Caudal movement of the

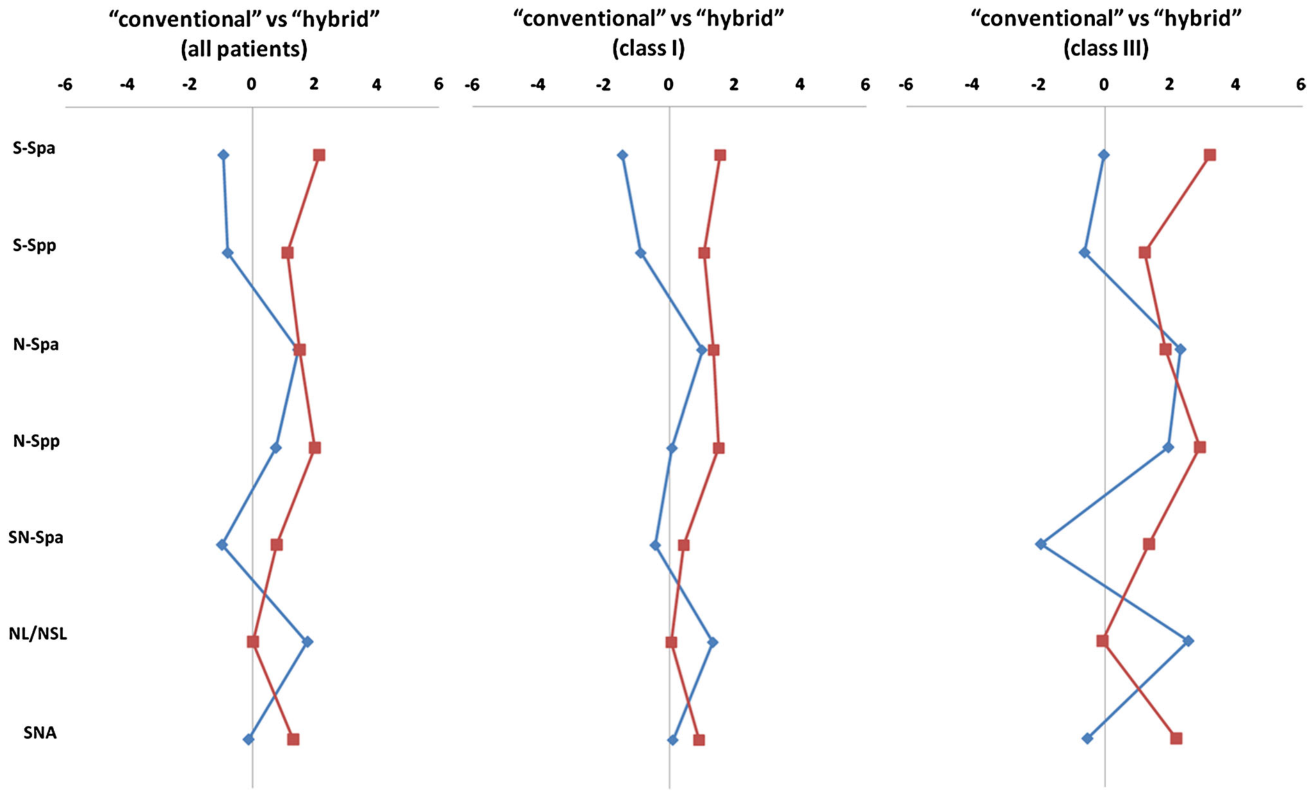

Fig. 2 Graphic representation of the results obtained in the maxilla: conventional appliance type (*blue*) and hybrid type (*red*). The most pronounced increases of the SNA angle (by a mean of 2.17°) were observed in the subgroup of skeletal Class III patient treated with the hybrid appliance

Abb. 2 Grafische Darstellung der Ergebnisse – Maxilla: konventionell (*blau*); „Hybrid-Hyrax"(*rot*). Vergrößerung des SNA-Winkels mit im Mittel 2,17° am deutlichsten bei skelettalen Klasse-III-Patienten, die mit der „Hybrid-Hyrax"behandelt wurden

maxilla (S-Spa, S-Spp, N-Spa, N-Spp) was noted in both groups but was more pronounced in the hybrid group. While the mean sagittal position of the maxilla (SNA angle) remained almost unchanged in the conventional group, a statistically significant mean advancement (SNA increase by a mean of 1.30°) was seen in the hybrid group. The conventional group showed a mean retroclination of the maxilla (NL/NSL) by approximately 2°, whereas upper-jaw inclination remained almost unchanged in the hybrid group. Both groups showed increases in the vertical parameters ML/NSL, ML/NL, and Björk sum.

Conventional versus hybrid appliances (Class I)

Results for the skeletal Class I patients are summarized in Table 3, Figs. 2 and 3. The maxilla underwent statistically significant amounts of caudal movement (S-Spa, S-Spp, N-Spa, N-Spp) by over 1 mm in the hybrid subgroup of Class I patients. While the mean sagittal position of the maxilla (SNA) remained almost unchanged in the conventional subgroup, a mean advancement (SNA increase by 1°) was seen in the hybrid subgroup. The conventional subgroup showed a mean retroclination of the maxilla (NL/NSL) by approximately 1.32°, whereas upper jaw inclination remained almost unchanged in the hybrid subgroup. Both subgroups of Class I patients showed increases in the vertical parameters ML/NSL, ML/NL, and Björk sum.

Conventional versus hybrid appliances (Class III)

The results for the skeletal Class III patients are summarized in Table 4, Figs. 2 and 3. The maxilla underwent statistically significant amounts of caudal movement (S-Spa, S-Spp, N-Spa, N-Spp) in the hybrid subgroup of Class III patients. While the mean sagittal position of the maxilla (SNA) remained almost unchanged in the conventional subgroup, a mean advancement (SNA increase by 2°) was seen in the hybrid subgroup. The conventional subgroup showed a mean retroclination of the maxilla (NL/NSL) by approximately 2.54°, whereas upper jaw inclination remained almost unchanged in the hybrid subgroup. Both subgroups of Class III patients showed increases in the vertical parameters ML/NSL and Björk sum.

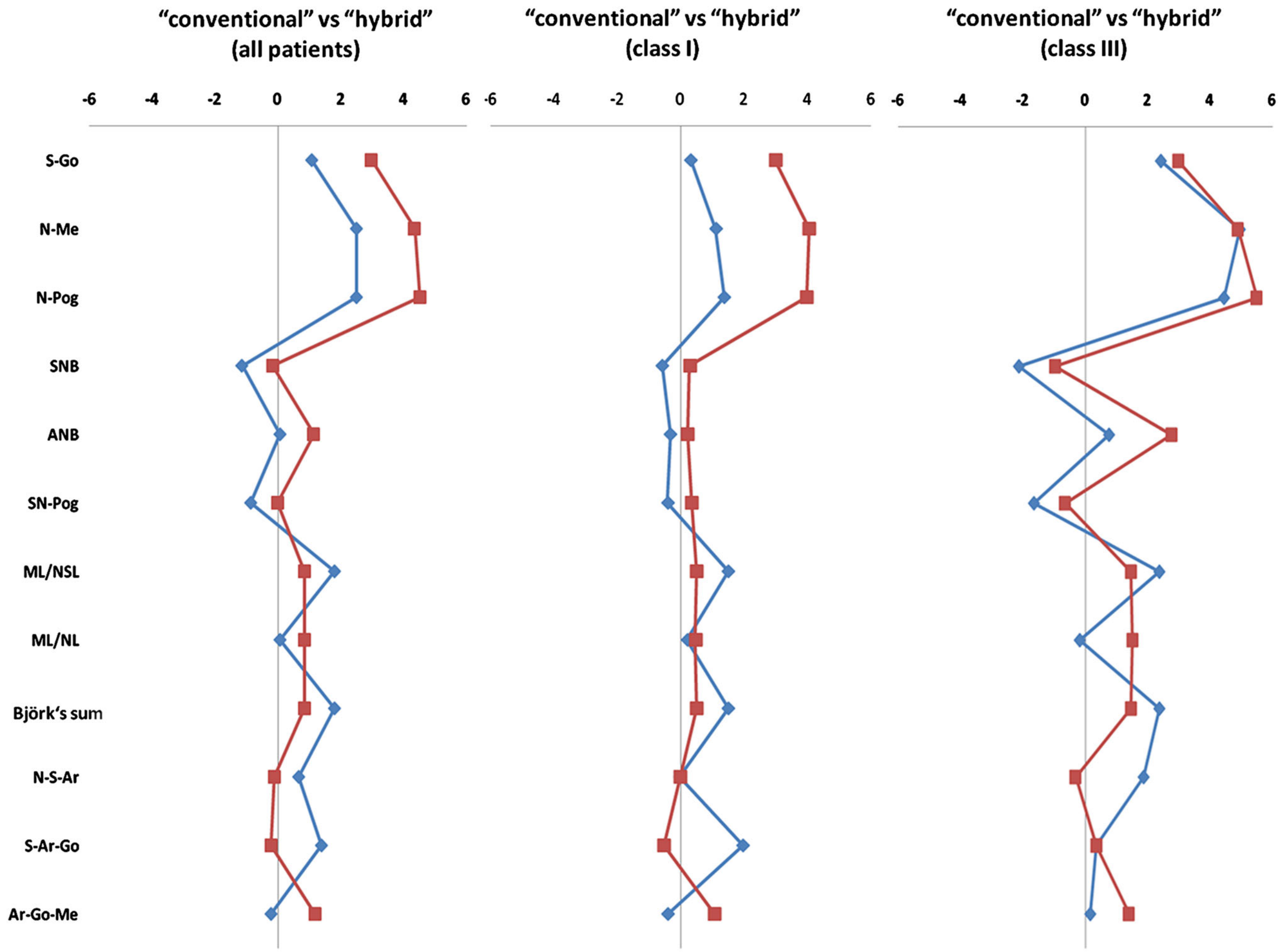

Fig. 3 Graphic representation of the results obtained in the mandible: conventional appliance type (*blue*) and the hybrid type (*red*). All groups and subgroups were, on average, found to undergo posterior rotation of the mandible

Abb. 3 Grafische Darstellung der Ergebnisse—Mandibula: konventionell (*blau*); „Hybrid-Hyrax"(*rot*). Im Mittel posteriore Rotation der Mandibula in allen betrachteten Gruppen und Subgruppen

Discussion

The treatment strategy of RME made popular by Derichsweiler [17, 18] and Haas [24] in the 1950s and 1960s. Hence, it was foreseeable for us that studies performed on cephalograms would be the main basis of comparison for our results [3, 8, 11, 19, 20, 61–63]. Caudal movement of the maxilla was a consistent finding only in our hybrid group of patients treated with a combined tooth- and bone-borne appliance. Wertz [67] found that a caudal movement of 1–2 mm occurred routinely, which is consistent with a 0.35–2 mm range of mean values reported in other studies [3, 11], although it should be noted that the methods of measurement behind these findings differed.

In the present study, the sagittal jaw relationship via the ANB angle as recorded because this parameter has been used in most other studies of this type, thus, being a standard approach [64] and ensuring comparability with previously reported data [1, 3, 8, 14, 24, 62, 67]. Another option—whether alternatively to ANB or as an additional linear parameter [34]—to determine the anteroposterior jaw relationship would be Wits appraisal [32, 33]. Despite the availability of studies on the pros and cons of these two methods [29, 36], opinions as to which of the two should be preferred are clearly divided [53]. It has been demonstrated that interrater measurements of the SNA, SNB, and ANB angles will not substantially differ, whereas considerable variation should be expected in determining the occlusal plane required to evaluate Wits appraisal on cephalograms [65].

Although our results concur with the literature [1, 3, 8, 14, 24, 62, 67] in indicating advancement of the maxilla based on SNA increases by a mean of 0.9–2.17°, these increases were found almost exclusively in our hybrid group of patients treated with a combined tooth- and bone-borne appliance. However, the information given in the literature about maxillary advancement [1, 3, 8, 10–12, 14, 24, 61–63] is inconclusive or contradictory [15].

Tab. 3 Overview of cephalometric results based on skeletal Class I patients. Treatment-related changes observed with the conventional and hybrid appliance types and an intergroup comparison are listed
Tab. 3 Vergleich kephalometrische Parameter—„konventionell“vs. „hybrid“(skelettale Klasse I)

	Conventional subgroup (Class I) (tooth-borne RME appliance)				Hybrid subgroup (Class I) (tooth-/bone-borne RME appliance)				Conventional versus hybrid	
	ΔT2–T1	SD	*p* value		ΔT2 − T1	SD	*p* value		*p* value	
Maxilla										
S-Spa	−1.44	4.56	0.085	NS	+1.55	2.57	0.002	**	0.006	**
S-Spp	−0.88	3.14	0.122	NS	+1.06	1.92	0.004	**	0.018	*
N-Spa	+1.00	3.53	0.119	NS	+1.34	2.72	0.009	**	0.668	NS
N-Spp	+0.08	5.22	0.933	NS	+1.50	2.68	0.004	**	0.169	NS
SN-Spa	−0.43	3.37	0.472	NS	+0.44	3.45	0.472	NS	0.307	NS
NL/NSL	+1.32	2.37	0.004	**	+0.05	2.44	0.911	NS	0.038	*
SNA	+0.11	2.18	0.163	NS	+0.90	2.11	0.298	NS	0.001	**
Mandible										
S-Go	+0.32	4.60	0.694	NS	+2.98	4.13	<0.001	***	0.018	*
N-Me	+1.10	7.40	0.408	NS	+4.05	4.39	<0.001	***	0.058	NS
N-Pog	+1.38	7.53	0.308	NS	+3.97	4.82	<0.001	***	0.108	NS
SNB	−0.58	2.95	0.273	NS	+0.28	2.22	0.485	NS	0.324	NS
ANB	−0.33	2.07	0.326	NS	+0.22	1.83	0.493	NS	0.268	NS
SN/Pog	−0.42	3.06	0.443	NS	+0.34	2.13	0.373	NS	0.401	NS
ML/NSL	+1.50	3.73	0.030	*	+0.50	2.54	0.274	NS	0.213	NS
ML/NL	+0.20	3.24	0.730	NS	+0.46	1.90	0.180	NS	0.327	NS
Björk sum	+1.50	3.73	0.030	*	+0.50	2.54	0.272	NS	0.216	NS
N-S-Ar	−0.03	3.29	0.953	NS	−0.01	3.23	0.989	NS	0.974	NS
S-Ar-Go	+1.97	5.38	0.047	*	−0.53	8.06	0.713	NS	0.186	NS
Ar-Go-Me	−0.41	6.19	0.709	NS	+1.06	6.87	0.391	NS	0.237	NS

NS not significant, *RME* rapid maxillary expansion, *ΔT2–T1* positive or negative values indicate increases or decreases, respectively
* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

While some authors reported a mean advancement of 1–2.5° or 1.5 mm [1, 3, 8, 14, 24, 62, 67], others were hard-pressed to find any changes to this effect at all [10–12, 61]. Some authors even reported posterior movement of the maxilla [63]. The methods used to determine maxillary advancement have not been uniform across studies [41, 42]. A common approach has been to combine the SNA angle with a linear parameter like the distance from sella (S) to A-point (A) [3]. This heterogeneity should be kept in mind in interpreting the data in the literature.

Mean inclination of the maxilla (NL/NSL) increased by up to 2.54° in our conventional group but remained almost unchanged in the hybrid group, which is not inconsistent with the literature, considering that this cephalometric parameter has been reported to either decrease or increase or persist during RME [14]. Mean treatment-related increases of NL/NSL are documented in the range of 0.11–0.5° [61, 63, 67]. Whether these changes may be clinically relevant appears questionable. A mean posterior rotation of the mandible, as observable in all our groups and subgroups, has been repeatedly described in the past [1, 3, 11, 16, 25, 26] despite some disagreement about its extent and persistence [7]. Mean treatment-related changes of ML/NSL are documented in the range of 0.19–2.21° [3, 16], which is consistent with our data.

These combined findings of our study—maxillary advancement, maxillary caudal movement, and mandibular posterior rotation—reflect a pattern of three-dimensional geometric change that bears the potential of facilitating treatment of skeletal Class III patients [26]. The most pronounced mean increase of the SNA angle by 2.17° was, interestingly, seen in the hybrid subgroup of skeletal Class III patients, indicating that hybrid RME appliances may indeed be advantageous in these patients, possibly due to skeletal effects related to their direct anchorage in the bony maxilla [47].

Besides cephalometric analysis of cephalograms, another method to investigate the skeletal effects of RME is cone-beam computed tomography (CBCT). Pertinent studies became available following the introduction of CBCT to dentistry—and orthodontics [38]—in the late 1990s [52]. More recently, systematic reviews of CBCT

Tab. 4 Overview of cephalometric results based on skeletal Class III patients. Treatment-related changes observed with the conventional and hybrid appliance types and an intergroup comparison are listed
Tab. 4 Vergleich kephalometrische Parameter—„konventionell“vs. „hybrid“(skelettale Klasse III)

	Conventional subgroup (Class III) (tooth-borne RME appliance)				Hybrid subgroup (Class III) (tooth-/bone-borne RME appliance)				Conventional versus hybrid	
	ΔT2–T1	SD	*p* value		ΔT2–T1	SD	*p* value		*p* value	
Maxilla										
S-Spa	−0.03	5.28	0.981	NS	+3.20	5.48	0.024	*	0.018	*
S-Spp	−0.62	3.01	0.393	NS	+1.21	2.42	0.049	*	0.113	NS
N-Spa	+2.31	3.61	0.015	*	+1.84	3.40	0.035	*	0.692	NS
N-Spp	+1.94	5.19	0.131	NS	+2.89	4.14	0.009	**	0.467	NS
SN-Spa	−1.93	2.57	0.006	**	+1.35	2.89	0.063	NS	0.001	**
NL/NSL	+2.54	3.68	0.010	*	−0.06	1.51	0.878	NS	0.011	*
SNA	−0.52	1.68	0.052	NS	+2.17	1.79	0.001	**	0.980	NS
Mandible										
S-Go	+2.43	5.51	0.079	NS	+2.98	5.07	0.024	*	0.759	NS
N-Me	+4.95	7.79	0.015	*	+4.90	7.11	0.010	*	0.984	NS
N-Pog	+4.46	7.55	0.023	*	+5.50	6.68	0.003	**	0.662	NS
SNB	−2.13	3.07	0.009	**	−0.97	2.09	0.066	NS	0.169	NS
ANB	+0.77	1.95	0.058	NS	+2.77	1.70	<0.001	***	0.002	**
SN/Pog	−1.64	3.26	0.048	*	−0.65	2.16	0.222	NS	0.229	NS
ML/NSL	+2.37	3.17	0.006	**	+1.46	1.93	0.005	**	0.011	NS
ML/NL	−0.17	1.67	0.677	NS	+1.51	1.97	0.005	**	0.011	*
Björk sum	+2.37	3.17	0.006	**	+1.46	1.93	0.005	**	0.310	NS
N-S-Ar	+1.87	3.27	0.027	*	−0.31	2.42	0.595	NS	0.029	*
S-Ar-Go	+0.36	3.35	0.653	NS	+0.36	5.99	0.804	NS	0.624	NS
Ar-Go-Me	+0.16	3.42	0.841	NS	+1.40	5.32	0.222	NS	0.229	NS

NS not significant, *RME* rapid maxillary expansion, *ΔT2–T1* positive or negative values indicate increases or decreases, respectively
* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

studies on RME have become available [5, 9, 21, 27, 37, 39, 57–59]. Given the natural advantages of CBCT, these studies have mainly reported on changes in the transverse plane, but maxillary movements in caudal and anterior directions have also been described [27].

Progress in computer technology has increased the possibilities of analyzing skeletal effects of RME at different levels of detail by finite-element modeling (FEM) [4, 22, 23, 30, 31, 35, 43, 44, 50, 60]. FEM studies can be used to model different appliances and modes of anchorage, followed by evaluating their respective effects on craniofacial structures, although no such modeling is currently documented for mandibles. While three-dimensional changes in maxillary position during RME have also been shown in FEM studies, these results have been ambiguous. In contrast to one study reporting both caudal and forward movement of the maxilla [22], another group confirmed caudal movement but denied advancement [35]. A third FEM study [49]—modeling the same hybrid RME appliance which specifically was also used in the present study [68]—again did demonstrate a mild effect on the antero-caudal position of the maxilla.

To summarize, all groups and subgroups in our study revealed cephalometric changes that were statistically significant in both jaws. Compared to the conventional tooth-borne RME appliances, the hybrid appliances led to more pronounced advancement of the maxilla as inferred from the SNA values measured (which was particularly true in the subgroup of Class III patients) and consistently resulted in caudal movement of the maxilla. Therefore, after duly taking into account all considerations discussed above, the data of the present investigation confirm our study hypothesis.

All results considered, a tooth- and bone-borne RME appliance, also known as hybrid hyrax [68], seems to be advantageous in Class III patients, inducing more pronounced anterior development of the maxillary complex because the force applied is not only supported by teeth but also by a skeletal structure. Several clinical studies and case reports with different treatment protocols have combined this hybrid hyrax with facemasks for maxillary protraction in Class III patients [48, 54–56, 69]. Some of these studies [54–56] demonstrated advancement of the maxillary complex by statistically significant amounts which, due to the extraoral forces from facemasks, were larger than reported in the present study.

Conclusions

Hybrid (combined tooth- and bone-borne) appliances for rapid maxillary expansion might be preferable in the treatment of skeletal Class III patients, since they possibly exert a more pronounced skeletal effect on the sagittal position of the maxilla.

Compliance with ethical standards

All studies on humans described in the present manuscript were carried out with the approval of the responsible ethics committee and in accordance with national law and the Helsinki Declaration of 1975 (in its current, revised form). Informed consent was obtained from all patients included in studies.

Conflict of interest J. Hourfar, G. S. M. Kinzinger, B. Ludwig, J. Spindler, and J. A. Lisson state that there are no conflicts of interest.

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