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Controlling orthodontic tooth movement with clear aligners

An updated systematic review regarding efficacy and efficiency

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Key words *clear aligners, Invisalign, invisible orthodontics, orthodontics*

Objective: *To update the scientific evidence relating to the efficacy of clear aligner treatment (CAT) in controlling orthodontic tooth movement (OTM).*

Materials and methods: *International medical databases were searched to identify all peer-reviewed papers potentially relevant to the review. The quality of evidence was ranked using the Swedish Council on Technology Assessment in Health Care Tool criteria.*

Results: *Twenty relevant articles were selected and the quality of evidence was high for three studies, moderate for 12 studies and low for five studies. Mesio-distal tooth movement revealed the highest predictability, with a molar distalization up to 2.5 mm and space closure of 7 mm performed with good control. Arch expansion is predictable up to 2 mm on molars. Improvements in Little's and PAR Index were reported in mild to severe malocclusions.*

Conclusion: *The overall quality of available evidence was of moderate/high level. CAT aligns and levels the arches even in severe cases, with efficient control of incisors inclination. Arch expansion and tooth bodily movement are efficiently achievable movements with CAT.*

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Introduction

Orthodontic treatment with clear aligners (CAT) was introduced by Kesling in 1945[1]. Align Technology (San José, CA, USA) revised Kesling's concept and, in 1998, introduced Invisalign aligners.

Since the introduction of Invisalign in 1998, many other aligner companies have started due to the popularity of this technique. However, there was always a great debate involving efficacy and efficiency of this appliance in controlling orthodontic tooth movement (OTM). As stated by Proffit in 2013[2], effectiveness, efficiency and predictability are the three things an orthodontist needs to know about the treatment he or she is providing. Furthermore, Proffit provides a reinterpretation of the hierarchy of studies from Cochrane Collaboration[3], stating that good retrospective or non-random prospective trials should always be considered due to the frequent impossibility of conducting RCTs in orthodontics.

Regarding CAT evidence, in 2015 our research team produced a systematic review of the literature[4], which focused on the three aspects highlighted by Proffit. Results showed heterogeneity of the available evidences regarding different types of OTM, with stronger evidence regarding some features (i.e. aligning and levelling arches) and weaker evidence about others (i.e. torque control).

However, despite the relatively recent publication, the scientific community has been very active in this field, providing us with a significant amount of clinical and scientific evidence in the past few years. Thus, the aim of this study is to update our 2015 systematic review, analysing the available evidence regarding efficiency and efficacy of CAT to provide useful and accurate evidence-based guidelines.

Table 1 Search strategy

Database	Search strategy
Pubmed, PMC, Scopus, Web of Knowledge, Embase, NLM,	((Orthodont* OR Clear) aligner* OR Invisalign) AND (effect* OR effic* OR outcom* OR advant*)
LILACs	((Orthodont$ OR Clear) aligner$ OR Invisalign) AND (effect$ OR effic$ OR outcom$ OR advent$)
Cochrane Central Register of Controlled Clinical trials	(Orthodontic aligner* or clear aligner* or Invisalign) AND (effect* or effic* or outcom* or advant*)

Materials and methods

In February 2017, a systematic search in the medical literature was performed to identify all peer-reviewed papers potentially relevant to the review's questions. The adopted search strategy is illustrated in Table 1 and was used to question the following medical databases: Pubmed, PMC, Scopus, Lilacs, Cochrane Library of Clinical Trials, Scielo, ISI Web of Knowledge. A hand search was thoroughly performed for additional papers in the medical library of Turin University, in the authors' personal libraries and in the references of the selected articles. International patents, abstracts and presentations from international orthodontic meetings were also evaluated.

Table 2 Study selection criteria

Inclusion criteria	Exclusion criteria
Prospective and retrospective original studies on human subjects with permanent dentition (minimum chronological age of 15 years)	Studies on patients with genetic syndromes and severe facial malformations
Studies on orthodontic treatment with clear aligners	Studies with surgical-orthodontic techniques
Studies that included clear descriptions of the materials and applied technique	Case reports
Studies with adequate statistical analysis	Reviews
	Abstracts
	Author debates
	Summary articles
	Studies with fewer than 10 patients
	Studies on animals

Table 3 Results of selected studies

Author	Year	Study design	Population	Intervention	Comparison	Outcomes (statistically significant)
Baldwin et al	2008	RCT	24 pts (18 F, 6 M)	Measurement of tooth tipping adjacent to premolar extraction spaces	Movement of teeth adjacent to premolar extraction sites during space closure with fixed appliances	Tooth tipping Interdental angle 5 17.3
Clements et al	2003	RCT	51 pts; DI between 10 and 20	Description of aligner stiffness evaluated	Pretreatment models, different materials and protocols	PBI 5 0.02 (P 5 .0475
Djeu et al	2005	Retrospective study	96 pts; treatment duration: 1.7 year fixed appliance 1.4 year Invisalign	OGS score of Invisalign appliance treatment outcomes	OGS score of conventional fixed appliance treatment outcomes	OGS score: mean overall score 5 13.14 (braces) OVJ 5 2.65 Buccolingual inclination 5 1.38 Occlusal contacts 5 4.81 Occlusal relations 5 2.21 Buccal posterior crossbite/OGS scores correlation 5 0.2849 Overjet/OGS scores correlation 5 0.3034 (InvisalignH); 0.2975 (braces) Occlusion/OGS scores correlation 5 0.5288 (Invisalign); 0.4497 (braces) OGS passing rate 5 13 (braces)
Drake et al	2012	Prospective study	52 pts: 15 1 week 37 2 weeks; treatment duration: 8 weeks	Examination of influence on tooth movement by material and subject-specific factors	37 Subjects who participated in another study (biweekly control group); CBCT images and data from a similar protocol	OTM first week 5 0.22
Duncan L et al	2016	Retrospective study	61 pts (44 F - 17 M) 3 groups: mild (20) moderate (22) severe (19)	Measurements on pre-treatment casts and cephalometric analysis.	Measurements on post-treatment casts and cephalometric analysis.	Difference T0 vs T1 Mild Ovj: 0,73* Moderate Overbite: 0,74* Overjet: 0,69** Severe Overjet: 1,33* L1-NB (deg): -4,7* L1-NB (mm): -1,55** L1-MPA (deg): -3,95* L1-APog (deg): -4,82** L1-APog (mm): -1,74**

Author	Year	Study design	Population	Intervention	Comparison	Outcomes (statistically significant)
Garino F et al	2016	RCT	30 pts (18 F- 12 M) mean age: 30.5 years 20 cephrx control group from AAO archives	Upper molar distalization with 5 attachments (G1)	Upper molar distalization with 3 attachments (G2)	G1 T0 vs T1 Distalization U7 mesial cusp: 2,3 mm** U7 crown: 1.71 mm** U7 palatal root apex: 1.47 mm** U7 bucco-mesial root apex: 1.68 mm** U6 crown: 2.13 mm** U6 palatal root apex: 1.71 mm** U6 bucco-mesial root apex: 1.75 mm** U1 incisal edge: 2.48 mm* U1 crown: 1.58 mm* Intrusion U7: 1.25 mm** U6: 1.11 mm* U1: 0.91 mm* G2 T0vsT1 Distalization U7 mesial cusp: 1.54 mm** U6 mesial cusp: 1.52 mm* Tipping U6: 2.49°* U1: 4.12°* G1 vs G2 Distalization U6 crown: 1.57 mm* U6 bucco-mesial root apex: 1.95 mm* U1 crown: 2.41 mm* U1 root apex: 3.17 mm* U1 incisal edge: 2.61 mm* Intrusion U7: 1.64 mm* U6: 1.41 mm* G1-G2 vs Control Group Sagittal position U7-U6-U1
Grunheid T et al	2016	Retro-spective study	60 pts 30 pts (22 F - 8 M, mean age: 25 +/- 11.8 years, age range: 13.8 - 64 years) clear aligner treatment (G1) 30 pts (22 F - 8 M, mean age: 26.3 +/- 13.5 years, age range: 12.7 – 56.5 years) fixed appliance treatment (G2)	Clear aligners treatment	Fixed appliance treatment	Canine bucco-lingual inclination G1 vs G2: 2,6°* G2 T0vsT1: -1,9°* Intercanine distance G1 T0vsT1: 0.7 mm* Correlation between intercanine distance and bucco-lingual inclination changes G1, G2 **

Author	Year	Study design	Population	Intervention	Comparison	Outcomes (statistically significant)
Gu J et al	2017	Retro-spective study	96 pts 48 pts (32 F - 16 M, mean age: 26 +/- 9.7 years) Invisalign treatment (G1) 48 pts (30 F - 18 M, mean age: 22.1 +/- 7.9 years) Fixed appliances treatment (G2)	Invisalign treat-ment	Fixed appliance treatment	PAR index G1/G2 MOS G1: 13.35 (min 4, max 48) MOS G2: 19.08 (min 6, max 31) Great improvement G1: 11/48 pts (22,9%) Great improvement G2: 22/48 pts (45,8%)
Hennessy J et al	2016	RCT	40 pts (27 F - 13 M, mean age: 26.4 +/- 7.7 years) 20 pts (14 F - 6 M, mean age: 29.1 +/- 7.5 years) Invisalign treatment (G1) 20 pts (13 F - 7 M, mean age: 23.7 +/- 7 years) Fixed appli-ance treatment (G2)	Invisalign treat-ment	Fixed appliance treatment	-
Houle JP et al	2017	Retro-spective study	64 pts (41 F - 23 M, mean age: 31,2 years, age range: 18-61 years)	Measurements on Clincheck prevision	Measurements on post-treatment casts	Mean differences (mm) T0-T1 (SD, 95% CI) Maxillary Canine tip 0.22 (0.74, 0.03–0.40)* Canine gingival 0.6 (1.02, 0.34–0.85)** First premolar tip 0.58 (1.14, 0.03–0.58)** First premolar gingival 1.09 (1.22, 0.78–1.39)** Second premolar tip 0.75 (1.54, 0.37–1.13)** Second premolar gingival 1.3 (1.61, 0.90–1.7)** First molar tip 0.77 (1.84, 0.31–1.23)** First molar gingival 1.42 (1.9, 0.95–1.90)** Mandibular Canine gingival 0.65 (1.01, 0.39-0.90)** First premolar gingival 0.27 (1.00, 0.02-0.52)* Second premolar gingival 0.38 (1.16, 0.09-0.66)* First molar gingival 0.54 (1.34, 0.21-0.87)*
Kassas et al	2013	Retro-spective study	31 pts (20 F, 11 M); treatment duration: 18 6 5 months	MGS score of pre- and posttreatment models	Cases served as their own controls	MGS scores: Alignment 5 9.16 Buccolingual inclination 5 0.74 Total MGS score 5 9.16

Author	Year	Study design	Population	Intervention	Comparison	Outcomes (statistically significant)
Kravitz et al	2008	Prospective study	31 pts (18 F, 13 M); treatment duration: 7 months	Quantitative measurements for the predicted and achieved canine rotation	Movement predictions made by ClinCheck	No statistically significant outcomes
Kravitz et al	2009	Prospective study	37 pts (23 F, 13 M); mean age: 31 years; treatment duration: 10 aligner mx 12 aligner mdb	Quantitative measurements for the predicted and achieved movements in the anterior region	Movement predictions made by ClinCheck	Canine rotation accuracy 5 32.2% (Mx); 29.1% (Mdb)
Krieger et al	2012	Retrospective study	50 pts (34 F, 16 M); low to moderate Mx and/or Mdb crowding; mean age: 33 6 11.19 years	Superimposition of initial and final casts of Invisalign treatment	Treatment starting point and predicted movement made with ClinCheck	OVB [CI, 21.02, 2.39]
Kuncio et al	2007	Prospective study	22 pts (20 F, 2 M)	Postretention OGS score after Invisalign treatment	Postretention OGS score after fixed appliance treatment	Total alignment Mdb anterior alignment
Li W et al	2015	RCT	152 pts 76 pts (45 F - 27 M, mean age: 35.2 +/- 7.3 years) Invisalign treatment (G1) 76 pts (45 F - 27 M, 32.2 +/- 8.3 years) fixed appliance treatment (G2)	Invisalign treatment	Fixed appliance treatment	OGS Score Differences (SD) G1, T1-T0 Alignment -9,91 (3,56)** Marginal ridges -2,75 (2,13)** Buccolingual inclination -3,55 (1,36)** Overjet -4,77 (2,13)** Interproximal contacts -0,87 (1,46)** Root angulation -4,79 (1,45)** Overall OGS score -30,48 (9,23)** G2, T1-T0 Alignment -10,5 (4,25)** Marginal ridges -3,79 (1,89)** Buccolingual inclination -5,85 (2,68)** Occlusal contacts -3,9 (1,12)** Occlusal relations -2,93 (1,12)** Overjet -5,7 (1,2)** Interproximal contacts -1 (0,68)** Root angulation -4,68 (2,32)** Overall OGS score -38,57 (8,87)** G1 vs G2 T1 Buccolingual inclination** Occlusal contacts**
Pavoni et al	2011	Prospective study	60 pts: 40 self-ligating fixed appliance 20 Invisalign; Class I malocclusion, mild crowding in Mdb arch; treatment duration: 18 6 2 months	Measurements made on the maxillary dental casts at the beginning and at the completion of Invisalign treatment	Outcomes of self-ligating treatment	Invisalign T0/T1 (mm): SPWF 5 0.45 MWF 5 0.5 Self-ligating/Invisalign (mm): CWCDD 5 2.65 FPWFDD 5 3.35 FPWLDD 5 2.30 SPWFDD 5 2.05 SPWLDD 5 1.85 APDD 5 1.35

Author	Year	Study design	Population	Intervention	Comparison	Outcomes (statistically significant)
Ravera S et al	2016	Retro-spective study	20 pts (11 F - 9 M, mean age: 29,7 +/- 6.9 years)	Upper molar distalization	Pre-treatment records	Difference T0-T1 (95% CI) ANB −0.7 (−1.29, −0.11)* 17mcPtV −2.52 (−3.24, −1.79)** 17ccPtV −2.12 (−2.76, −1.48)** 17praPtV −1.50 (−2.07, −0.94)** 17vmraPtV −1.67 (−2.31, −1.03)** 16mcPtV −2.25 (−4.21, −0.29)* 16ccPtV −2.03 (−2.72, −1.35)** 16praPtV −1.84 (−2.86, −0.82)** 16vmraPtV −1.48 (−2.40, −0.57)** 11iePtV −2.23 (−3.76, −0.70)** 11^PP −2.87 (−5.06, −0.69)*
Simon et al	2014	Retro-spective study	30 pts; 11 M; 19 F; age: 13–72 years; mean age: 32.9 years	Superimposition of initial and final digital casts of Invisalign treatment	Treatment starting point and predicted movement made with Clin-Check	T2/Clin T2 (P , .05): Premolar derotation with attachments Premolar derotation without attachments Incisor torque with attachments Incisor torque with PR
Solano-Mendoza B et al	2016	Retro-spective study	109 pts	Measurements on Clincheck prevision for maxillary arch expansion	Measurements on post-treatment casts after maxillary arch expansion	Differences Casts-Clincheck at T2 (95% CI) CGW (−1.39, −0.36)** 2 Pm (−1.28, −0.94)** MGW (−1.58, −1.20)** 1 Pm (−1.64, −1.07)** 2 Pm (−1.20, −0.80)** CCW (−0.68 −0.40)** MCW (−1.82, −1.32)** CDM (0.04, 0.29)* MIM **

* $P < .05$

** $P < .001$

DI, discrepancy index; PBI, papillary bleeding index; OGS, objective rating system; OVJ, overjet; SPWF, second premolar width (fossa); MWF, molar width (fossa); CWCDD, inter-canine width (cusps) mean difference; FPWFDD, first inter-premolar width (fossa) mean difference; FPWLDD, first inter-premolar width (lingual) mean difference; SPWFDD, second inter-premolar width (fossa) mean difference; SPWLDD, second inter-premolar width (lingual) mean difference; APDD, arch perimeter mean difference; OTM, overall tooth movement; OVB, overbite; MGS, model grading system; T2, clinically achieved tooth movement; CBCT, cone beam computed tomography; CLIN T2, tooth movement predicted by ClinCheck; PR, power ridge; L1, lower incisor; G1, Group 1; G2, Group 2; U1, upper incisor; U6, upper first molar; U7, upper second molar; PAR index, Peer Assessment Rating index; MOS, months in treatment; Great improvement, either weighted PAR score reduction of 22 points or more, or weighted PAR score after treatment equal to 0; 17mc, mesial cusp upper second molar; 17cc, central crown upper second molar; 17pra, upper second molar palatal root apex; 17vmra, upper second molar buccal-mesial root apex; 16mc, mesial cusp upper first molar; 16cc, central crown upper first molar; 16pra, upper first molar palatal root apex; 16vmra, upper first molar buccal-mesial root apex; 11ie, upper central incisor incisal edge; PtV, line passing through the Pt Ricketts point, perpendicular to palatal plane; 11^PP, angle between upper central incisor axis and palatal plane; CGW, canine gingival width; 2 Pm, second premolar; MGW, first molar gingival width, 1 Pm, first premolar; CCW, canine cusp width; MCW, first molar cusp width; CDM, canine depth.

The inclusion and exclusion criteria for admittance in the systematic review are reported in Table 2. The reference lists of these articles were perused, and references relating to the articles were followed up.

The selection of papers and duplicate removal was performed independently by two of the authors (GR, SP). Disagreements were solved by discussion between all the authors.

For the purposes of this systematic review, the PICO format was modified in the PICOS one, where "S" stands for study design[5]. (Table 3)

Primary outcomes included the efficacy of CAT in controlling tooth tipping, rotation, intrusion, extrusion and alignment.

According to the CRD (Centre for Reviews and Dissemination, University of York)[3] and to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)[6] statements, evaluation of methodological quality gives an indication of the strength of evidence provided by the study because flaws in the design or in how a study is conducted can result in bias. However, no single approach for assessing methodological soundness is appropriate to all systematic reviews. A grading system described by the Swedish Council on Technology Assessment in Health Care (SBU)[7] and the CRD[3] was used to rate the methodological quality of the articles and to assess the level of evidence for the conclusions of this review (Tables 4 to 6).

Results

The article selection process is illustrated in the PRISMA flow diagram (Fig 1). Twenty relevant publications were identified: 10 studies were retrospective non-randomised[8-17], five

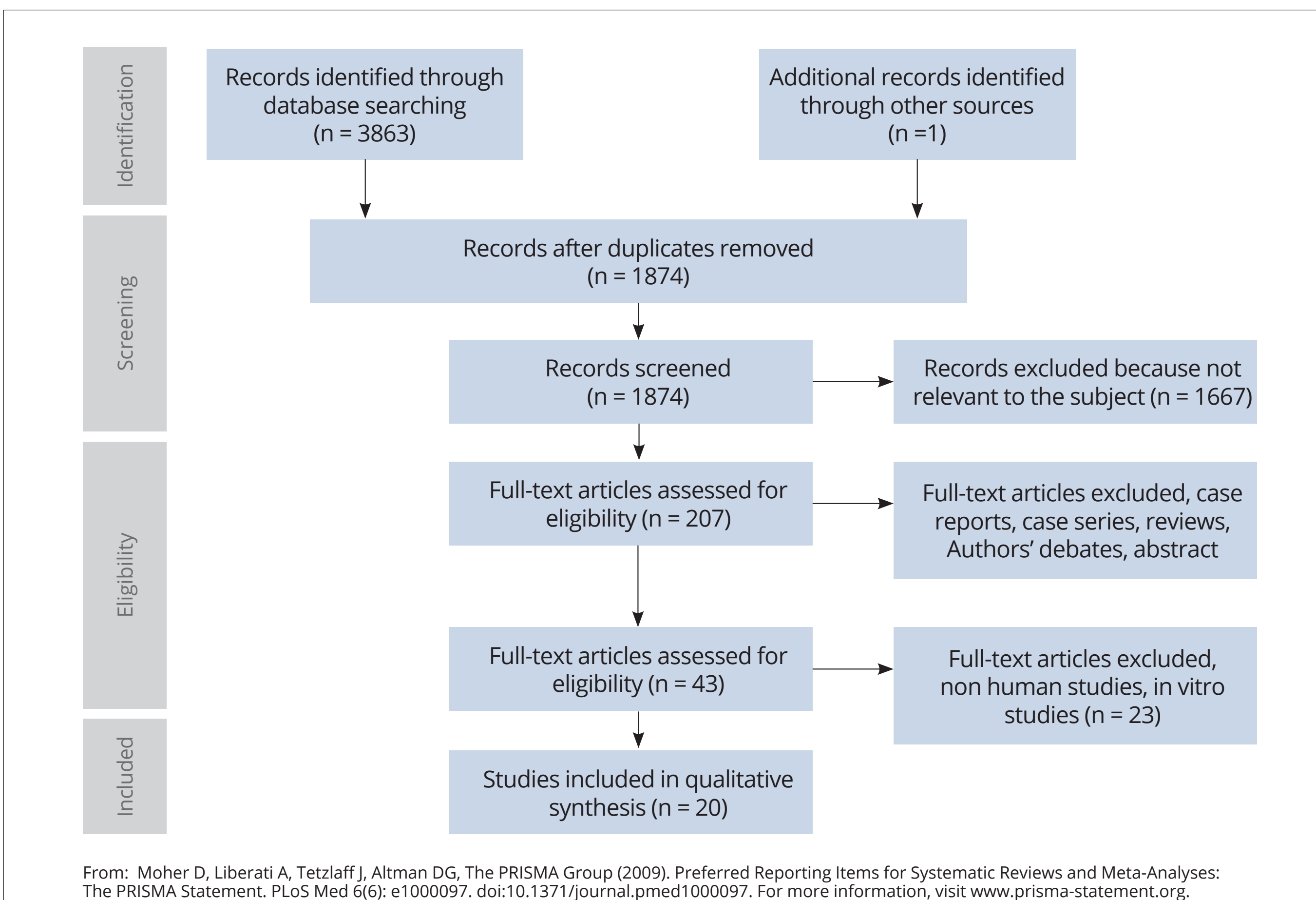

Fig 1 Flow chart according to the PRISMA Statement.

Table 4 SBU criteria for grading assessed studies

Grade A—High value of evidence All criteria should be met: • Randomised clinical study or a prospective study with a well-defined control group • Defined diagnosis and endpoints • Diagnostic reliability tests and reproducibility tests described • Blinded outcome assessment
Grade B—Moderate value of evidence All criteria should be met: • Cohort study or retrospective case series with defined control or reference group • Defined diagnosis and endpoints • Diagnostic reliability tests and reproducibility tests described
Grade C—Low value of evidence • One or more of the conditions below: • Large attrition • Unclear diagnosis and endpoints • Poorly defined patient material

studies were prospective non-randomised[18-22] and five studies were prospective randomised[23-27].

Sample size in individual studies ranged from 20 to 152, with the total being 1116 patients. Age at the start of aligner treatment in the evaluated samples ranged from 13 to 72 years.

The devices used in all the analysed studies were Invisalign aligners (Align Technology, San José, CA, USA).

Quality analysis

Among the selected sample, the value of evidence was high for three studies[20-22], moderate for 12 studies[8,12-19,26,27] and low for five studies[9-11,24,25]. Furthermore, the overall level of evidence of this review was strong. The most recurrent sources of bias were related to the study design, the sample size, and the lack of control group. Furthermore, other sources of bias were the inadequate sequence generation (four studies), the lack of allocation concealment (four studies) and the lack of a proper blinding procedure (five studies) (Tables 4 to 6)

Table 5 Definitions of evidence level

Level	Evidence	Definition
1	Strong	At least two studies assessed with level “A”
2	Moderate	One study with level “A” and at least two studies with level “B”
3	Limited	At least two studies with level “B”
4	Inconclusive	Fewer than two studies with level “B”

Table 6 Evidence levels of studies (as explained in Table 5)

Author, Year	Grade
Baldwin et al, 2008	B
Clements et al, 2003	B
Djeu et al, 2005	B
Drake et al, 2012	B
Duncan et al, 2016	B
Garino et al, 2016	A
Grunheid et al, 2016	B
Gu et al, 2017	B
Hennessy et al, 2016	A
Houle et al, 2017	B
Kassas et al, 2013	C
Kravitz et al, 2008	C
Kravitz et al, 2009	C
Krieger et al 2012	C
Kuncio et al, 2007	B
Li et al, 2015	A
Pavoni et al, 2011	B
Ravera et al, 2016	B
Simon et al, 2014	C
Solano-Mendoza et al, 2016	B

Effects of interventions

Compared with the 2015 review[4], any trial was performed regarding efficiency of rotation, extrusion and intrusion with CAT.

Mesio-distal tipping/bodily movement

In 2008, Baldwin et al[19] analysed the change of interdental angle in radiographs and dental casts, and showed a mean change of 17° ($P < 0.0001$) after CAT.

In 2009 Kravitz et al[25] conducted a study on anterior teeth. It showed a mean accuracy of 41% for mesiodistal tipping, with the highest value of accuracy for maxillary (43%) and mandibular (49%) lateral incisors. Maxillary (35%) and mandibular (27%) canines and maxillary central incisors (39%) showed the lowest accuracy.

A prospective study[27] reported that considering the 2-week period of aligner wear, 4.4 times more OTM occurred during the first week. Even if a bodily protraction movement was programmed on the target tooth, it resulted in uncontrolled tipping.

Simon et al (2014)[11] revealed a high predictability (88%) of the distalization bodily movement of maxillary molars when the use of attachments was planned, with an average movement of 2.6 mm.

In a 2016 multicentre retrospective study, Ravera et al[16] analyzed the effective amount of distalization with CAT in non-growing patients on lateral cephalograms. The average distalization was 2.25 mm for first molar and 2.52 mm for the second molar, when vertical rectangular attachments were planned. Similar results were shown in the study conducted by Garino et al (2016)[20], with a distalization of about 2 mm, accompanied by 1 mm of intrusion.

In their 2015 multicentre RCT[22], Li et al observed no significant differences for root angulation OGS score between extraction patients treated with CAT and with braces.

Anterior bucco-lingual tipping/root torque

Djeu et al (2005)[8], showed better scores for fixed appliances than CAT in relation to bucco-lingual tipping (braces: -2.8 – SD 2.6; CAT: -4.2 – SD 2.73; $P < 0.05$) and similar scores for root angulation. According to Kravitz et al (2009)[25], lingual crown tipping (53%) was more accurate than labial crown tipping (38%), especially for maxillary incisors.

Simon et al (2014)[11] demonstrated no significant differences when maxillary central incisor torque was supported with horizontal ellipsoid attachment (mean accuracy: 51.5%, SD 0.2) or with a different aligner geometry (mean accuracy: 49%, SD 0.2).

In a study based on cone beam computed tomograms (CBCT) analysis, Grunheid et al (2016)[13] showed a significantly high value of buccolingual inclination for mandibular canines with CAT compared with fixed appliance treatment (2.6° of difference).

Duncan et al (2016)[12] analysed cephalometric position of mandibular incisors. In mild to moderate anterior crowding cases, there were no changes in the position or angulation of the mandibular incisors. In severe anterior crowding, mandibular incisors showed a higher buccal inclination (L1-NB: -4,7°; L1-NB: -1.55 mm; L1-APog: -4,82°; L1-APog: -1.74 mm). Hennessy et al (2016)[21] in their RCT reported no differences in mandibular incisors buccal inclination produced by CAT or fixed labial appliances treatment in mild crowding cases.

Posterior bucco-lingual tipping/expansion

Regarding arch expansion with CAT, Pavoni et al (2012)[26] compared post-treatment casts of patients treated with aligners and fixed self-ligating appliances. CAT group showed significant increase, at the fossa points, in second inter-premolar width (0.45 mm) and in inter-molar widths (0.5 mm), with significant differences with respect to the self-ligating group. In 2017, Houle et al[15] reported that expansion with CAT was less accurate going from the anterior to the posterior region. Mean accuracy of upper arch expansion was 72.8% (82.9% at the cusp tips and 62.7% at the gingival margins) and 87.7% for lower arch expansion (98.9% for the cusp tips and 76.4% for the gingival margins). Similar results were found by Solano-Mendoza et al (2016)[17], with a good accuracy ($P = 0.031$) of prediction of molar expansion, with a planned expansion lower than 2 mm.

Grunheid et al (2016)[13] showed a statistically significant increase of mandibular inter-canine distance in patient treated with CAT (0.7 mm).

A 2013 retrospective study[10] demonstrated a significant improvement of the OGS score for buccolingual inclination, with high values in the posterior region (-0.74 – $P < 0.05$).

In 2015, a multicentre RCT[22] compared the OGS score in extraction patients treated with CAT and with braces. Authors observed that CAT was less effective than braces in controlling posterior buccolingual inclination ($P < 0.001$).

Aligning (arch lengthening, lingual constriction, alignment scores)

Clements et al (2003)[18] found improvements in PAR score for anterior alignment of 78% of the analysed sample, while 12% experienced no change and only 10% had worse results. A retrospective study in 2017[14] compared the PAR index score for fixed appliances with Invisalign. The authors described treatment with Invisalign as being quicker than fixed appliances, with an average difference of 30% and final occlusal scores were comparable between the two systems. However, "great improvement" in a malocclusion, which authors meant for great changes in PAR score, appeared to be better with fixed appliances (22.9% with aligners; 45.8% with braces).

Kuncio et al (2007)[23] compared stability after 3 years of retention, total alignment after CAT and after braces treatment. It was registered as statistically significant worsening in OGS (-1.6 – $P < 0.05$).

Krieger et al (2012)[9] showed an improvement of Little's irregularity index between pre- and post-treatment casts in maxillary (-3.8 mm) and mandibular (-5 mm) arches. A significant improvement of the OGS score for alignment (-9 – $P < 0.001$) was also reported by Kassas et al (2013)[10].

A multicentre RCT[22] compared the OGS score in extraction patients treated with CAT and with braces. Authors found similar OGS scores for both treatment for alignment, marginal ridges, occlusal relations, overjet and interproximal contacts, while for occlusal contacts ($P < 0.001$) and buccolingual inclination ($P < 0.001$) CAT was less effective than braces.

Discussion

The aim of this review was to update the available evidence regarding the efficacy and efficiency of CAT. Among the 3846 articles, 20 were selected for the final review process, nine more than in the 2015 paper[4]. The overall quality of evidence was strong, with three studies obtaining grade A[20-22]. Indeed, the quality of evidence improved with this update, however good quality studies are still not available for all the different fields of OTM. Thus, the results of this review are of moderate/high quality, but new studies of higher quality are needed to improve knowledge in areas with less evidence.

Compared with the previous 2015 review[4], no significant data emerged regarding efficiency of rotation, extrusion and intrusion performed with CAT. A key point that needs to be considered in analysing the results from this review is that the aligner material plays a fundamental role in treatment efficiency. Since the selected studies only investigated the Invisalign appliance, results prior to 2013 need to be evaluated carefully, because of changes in the aligners' polymer.

Mesio-distal tipping/bodily movement

It is generally thought that aligners can easily tip crowns, but cannot tip roots because of the lack of control of tooth movement. However, in the past two years, a significant number of studies improved the quantity and quality of evidence regarding this field.

Between 2008 and 2012, relevant studies stated that tipping with a variable degree of control[19,25,27] was the best result achievable with CAT for all teeth except mandibular incisors. However, in 2014, Simon et al[11] stated that maxillary molar distalization was the most predictable movement (88%) to perform with CAT. The authors started to focus on the key role of a correct staging of the planned movement and of the adoption of proper attachments during the whole distalization phase. Thus, a highly significant element of bias in the 2012 study by Drake et al[27] was the staging of 0.5 mm per aligner instead of the 0.25 mm recommended. In 2016, Ravera et al confirmed the results of Simon et al and demonstrated that distalization is efficiently achievable up to 2.5 mm on the first and second maxillary molars, with optimal vertical control of posterior teeth and any loss of anchorage on the anterior teeth[16]. These results were obtained through the combination of staging, vertical rectangular attachments and Class II elastics (1/4" – 4.5 oz) for anchorage reinforcement. The use of attachments and elastics was previously described by expert clinicians[28], however this study represents the first clinical trial on the topic. The need for a determined attachments combination was confirmed in a 2016 RCT by Garino et al[20], which observed significant differences in the amount of distalization when comparing a 5-attachments configuration (second and first molars, second and first premolars, and canine) with a 3-attachments configuration (first molar, second and first premolars), with the first ones being most efficient. The improved efficacy due to the variation in the number of attachments is easily understandable, with the increase of control on two key areas of the aligner: the terminal tooth, which is a hard-to-control zone also with a straight wire appliance[29], and the maxillary canine, which has always represented a challenge for wide-planned movement with aligners. Thus, distalization was confirmed to be a highly predictable bodily movement when performed with the right auxiliaries up to 2.5 mm.

Regarding maxillary canines' bodily movement for space closure (up to 6 mm), Li et al performed a RCT in which they assessed that according to the OGS score, no differences between CAT and fixed appliances were recorded for root inclination at the end of treatment[22]. These results are consistent with the 2010 paper by Djeu et al, even if their study was focused on non-extraction patients[8]. Therefore, even if more clinical trials focussing properly on the efficacy of space closure with CAT are needed, it seems reasonable to state that the improvements in materials, clinical protocols and knowledge of aligners biomechanics resulted in a greater control of bodily movement, which is now achievable with this technique.

Anterior bucco-lingual tipping/root torque

Tipping control in a bucco-lingual direction seems to perform less efficiently than the mesio-distal one. Contrasting evidence emerges from the analysis of the scientific literature of the past 10 years. The study by Simon et al is the only one that refers to “root torque” instead of “buccolingual inclination”. Thus, it could be stated that bucco-lingual tipping and torque control have a mean accuracy rating of 50% of the planned movement, but present a wide variation between 25% and 70%[11,25]. As stated by Simon et al, root torque means expression is independent from the use of attachments or altered geometries in the aligners. However, it could be that less variability, but less maximum efficacy, is observed in mean expression when altered geometries are preferred in respect of attachments[11]. Thus, it seems reasonable to state that altered geometries work well in mild-to-moderate torque corrections, while for wide movements attachments may represent the best choice. Higher quality clinical trials focusing on root torque are needed to obtain better quality evidence.

Despite the results of one study from 2005[18], higher quality trials stated that CAT and fixed appliance achieve similar results when considering buccolingual tipping values on mandibular incisors when treating mild-to-moderate crowding. Duncan et al reported higher buccal inclination in severe crowding (> 6 mm) cases; however, it is not clear if this is due to a lack in efficiency of CAT or to the regular achievement of a treatment prescription[12]. It stated that lingual constriction appears to be more efficient than buccal expansion[25] on incisors; reducing incisors' inclination with the adoption of IPR is a predictable procedure to improve the results of treatment for severe malocclusion.

Posterior buccolingual inclination/expansion

Arch expansion is a predictable movement to perform with CAT (mean accuracy of 70%). Results seem to be achieved with a slight bodily movement in association with a discrete amount of well-controlled tipping[15]. However, for more than 2 mm in the molar area, accuracy decreases significantly[17]. Furthermore, achieved expansion is reported to be significantly lower than that which is obtained with fixed self-ligating appliances[26]. The authors of this study did not state the same planned expansion for CAT and fixed appliances, so it is not possible to know to what extent lower results are related to appliance inefficacy.

Observing evidence regarding anterior and posterior buccolingual inclination and OGS score studies[10,22], which report contrasting results, accuracy and amount of planned expansion are strictly related with an inverse proportionality relationship. Thus, for both bodily expansions and crown up-righting of more than 2 mm on molars and 0.7 mm on canines, the support of auxiliaries, such as inter-arch elastics, is recommended in order to increase predictability and reduce the need for corrections during treatment.

Aligning (arch lengthening, alignment scores)

Two RCTs[18,22] and three retrospective studies[9,10,14] confirmed the efficacy of CAT in aligning and straightening the arches, even when comparing OGS and/or PAR scores of patients treated with CAT or fixed appliances.

Despite some authors being concerned with the greater relapse of CAT cases in respect of fixed appliance, the same authors observed that both the post-treatment and follow-up alignment OGS scores were better in CAT patients[23]. Thus, on the basis of the evidence available on the biology of tooth movement and periodontal perception of orthodontic forces, there is no reason to think that intermittent forces may result in?"lower biological quality" movement then continuous forces[30-32].

Conclusion

Compared with the 2015 review on CAT efficiency:

- The overall available evidence regarding OTM control during CAT increased significantly, with three RCTs at grade A, and an overall quality of evidence of moderate/high level.
- Maxillary molar distalization of 2.5 mm and premolar extraction space closure (7 mm) are the most predictable and controlled movement with CAT.
- The buccolingual inclination of incisors is well controlled in mild-to-moderate malocclusions.
- Arch expansion is a predictable movement up to 2 mm on the molars and 0.7 mm on canines.
- CAT is effective in aligning arches even in severe crowding cases (> 6 mm of crowding) without extractions.
- Auxiliaries such as attachments, elastics, IPR and altered aligner geometries, are mandatory to obtain the prescribed movements.

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