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Original Article

The Effects of Light and Vibration on the Correction of Lower Incisor Crowding with Aligners

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Main Points

- Low-frequency vibration and photobiomodulation applied separately did not significantly accelerate mandibular incisor alignment compared with the control.
- The combination of low-frequency vibration and photobiomodulation produced significantly greater short-term alignment.
- This combined protocol may be considered a promising adjunct to enhance the efficiency of clear aligner therapy in the early stages.

ABSTRACT

Objective: To compare the effects of low-frequency vibration (LFV), photobiomodulation (PBM), and their combination (HOT) on the rate of mandibular incisor alignment during clear aligner therapy.

Methods: This retrospective study included 89 patients treated with a single clear aligner system for mild-to-moderate mandibular anterior crowding. Patients were assigned to four groups: control (n=19), LFV (n=26), PBM (n=21), and HOT (n=23). LFV [30 Hz, 0.25 N (≈25 g)] and PBM (850 nm, 16×5 mm LEDs, ≈9.5 J/cm^2) devices were used daily for 20 minutes in relevant groups. The primary outcome was the change in Little's Irregularity Index at baseline (T0), 28 days (T1), 48 days (T2), and 62 days (T3). Statistical analyses included one-way ANOVA, repeated measures ANOVA, and Pearson's correlation.

Results: The HOT group showed significantly greater crowding reduction compared to all other groups ($p<0.05$). LFV and PBM alone were not significantly different from the control. Within-group analysis revealed significant reductions in all groups over time, with the HOT group showing consistent improvements at each interval. Correlation analyses revealed no significant associations between device usage or aligner wear time and crowding reduction.

Conclusion: Combining LFV and PBM during clear aligner therapy produced greater short-term acceleration of mandibular incisor alignment than either modality alone. Further randomized controlled trials are warranted to confirm long-term efficacy and safety.

Keywords: Orthodontics, clear aligners, low-frequency vibration, photobiomodulation, accelerated tooth movement

INTRODUCTION

Orthodontic treatment significantly enhances patients' quality of life by improving dental aesthetics, functional occlusion, and psychosocial well-being. Increasing aesthetic expectations, particularly among adult patients, has driven a growing preference for less visible treatment modalities such as lingual orthodontics and clear aligner therapy instead of conventional fixed appliances.[1,2] Although aesthetic brackets provide a better appearance than metal brackets, issues such as discoloration, increased friction, and enamel damage during debonding limit their clinical advantages.[3,4]

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Clear aligner therapy, first introduced by Kesling in 1945 and later digitized through advances in CAD/CAM technology, has evolved from a simple adjunctive tool into a comprehensive treatment modality for complex malocclusions.[5,6] The increased acceptance of clear aligners is largely due to their removability, improved aesthetics, and enhanced patient comfort. However, treatment duration remains a critical concern for both patients and clinicians. Prolonged orthodontic treatment, often lasting 24-36 months, may lead to decreased patient motivation, higher risk of enamel demineralization, gingival inflammation, and increased risk of root resorption .[7,8] Consequently, various approaches have been explored to accelerate orthodontic tooth movement (OTM), including pharmacological agents, surgical interventions, mechanical stimulation, and photobiomodulation.[9-11] These methods aim to either shorten the lag phase of tooth movement or enhance bone remodeling by modulating cellular and molecular processes within the periodontium. Understanding the biology of OTM is essential for evaluating these acceleration techniques. Tooth movement results from a sequence of mechanical, cellular, and biochemical events in the periodontal ligament (PDL) and alveolar bone. The PDL transmits orthodontic forces to the surrounding alveolar bone, leading to bone resorption in areas of compression and bone apposition in tension sites.[12] Multiple theories, including the pressure-tension theory, bone-bending theory, and piezoelectric theory, have been proposed to explain this process.[13,14] On a cellular level, osteoclasts, osteoblasts, and fibroblasts coordinate the remodeling process, while cytokines, prostaglandins, and the RANK/RANKL/OPG system regulate osteoclastic activity.[15] Efforts to accelerate OTM can broadly be categorized into surgical and nonsurgical methods. Surgical techniques, such as corticotomy, piezocision, and distraction osteogenesis, enhance tooth movement by altering alveolar bone resistance and stimulating a regional acceleratory phenomenon (RAP).[16-19] Nonsurgical methods include mechanical stimulation through vibration, low-level laser therapy, photobiomodulation, pharmacologic agents, and gene therapy.[20-23] Among these, mechanical vibration and photobiomodulation have gained attention as minimally invasive, patient-friendly approaches that can be integrated into clear aligner therapy without significantly increasing treatment complexity. This study aimed to compare the effects of vibration, photobiomodulation, and their combination on the rate of mandibular incisor alignment during clear aligner therapy. We hypothesized that adjunctive use of these modalities would result in faster resolution of crowding compared to clear aligner treatment alone.

METHODS

This retrospective observational study was conducted at the Department of Orthodontics, Faculty of Dentistry, Yeditepe University. Ethical approval was obtained from the Marmara University Clinical Research Ethics Committee (approval no: 2020-425, date: 30.06.2020) in accordance with the Declaration of Helsinki.

A total of 89 patients who had completed orthodontic treatment with clear aligners for mandibular incisor crowding between January 2018 and June 2020 were included. Inclusion criteria were the presence of mild to moderate crowding in the mandibular anterior region as assessed by Little's Irregularity Index (LII), completion of treatment using a single clear aligner system without mid-treatment appliance changes, absence of systemic or periodontal disease, good oral hygiene, and compliance with aligner wear protocol. Exclusion criteria were severe skeletal discrepancies requiring orthognathic surgery, a history of previous orthodontic treatment in the mandibular anterior region, the use of any adjunctive surgical acceleration techniques during treatment, and non-compliance with appliance usage protocols. The mean baseline mandibular anterior crowding across all groups was 5.6±0.4 mm, corresponding to mild-to-moderate irregularity according to Little's Index.

All patients were treated with the manufacturer's staging and refinement protocols. The initial impressions (T0) were taken at the beginning of treatment. Subsequent impressions followed at 28 days (T1), 48 days (T2), and 62 days (T3), with aligner change intervals of 14 days (T0-T1), 10 days (T1-T2), and 7 days (T2-T3) for all cases. Models were fabricated using Type IV dental stone from polyvinyl siloxane impressions. Although the study was retrospective in design, the impressions at T0, T1 (28 days), T2 (48 days), and T3 (62 days) were routinely obtained as part of the departmental clinical protocol for aligner follow-up. Therefore, interval measurements were possible without prospective recall, as these records already existed for all included patients.

Patients' records were assigned to four groups according to the acceleration device they used during their aligner treatment:

Group 1- Control group (n=19; 11 females, 8 males): received only clear aligner treatment without any adjunctive acceleration method.

Group 2- Vibration group (n=26; 14 females, 12 males): Received a 30 Hz, 0.25 N (≈25 g) mechanical vibration device

Group 3- Photobiomodulation (PBM) group (n=21; 12 females, 9 males): Received an 850 nm LED light device

Group 4- Combined group (HOT) (n=23; 14 females, 9 males): received a device integrating both vibration and PBM functions.

All patients in the experimental groups were instructed to use their respective devices for 20 minutes daily throughout the treatment period. Device usage was monitored through patient self-reported logs and compliance charts.

The acceleration devices were prototypes developed by Yeditepe University Faculty of Engineering and Architecture and Biomedical Engineering Department, and assembled from off-the-shelf components for research use. For the vibration device, oscillation frequency and force magnitude were standardized at 30 Hz; 0.25 N (≈25 g). The PBM device emitted continuous-wave 850 nm light via 16×5 mm red LEDs, delivering an energy density of ≈9.5 J/cm^2. For the combined device, both modalities were applied simultaneously within a single intraoral mouthpiece. The 850 nm near-infrared wavelength was selected based on its superior tissue penetration compared with visible light, and because previous clinical trials demonstrated favorable biostimulatory effects at this setting.[16-29] The applied energy density of ≈9.5 J/cm^2 was chosen within the range reported as effective in accelerating bone remodeling without adverse effects.

The vibration device (30 Hz; 0.25 N) was driven by a shaftless 10×3 mm vibration motor. The photobiomodulation device emitted 850 nm light via sixteen 5 mm red LEDs (PHOEBE module). The combined device integrated both modalities within a single mouthpiece. Devices were powered via USB with a 2000 mAh power bank. Digital measurements were performed using a 0.01 mm-precision caliper. Clear aligners were fabricated in-house using Orchestrate 3D planning software (Orchestrate 3D, Redlands, California, USA), models printed on a Uzaras Dreammaker 3D printer (Uzaras, İstanbul, Türkiye), and thermoformed on a Biostar® (Scheu Dental GmbH, Germany) pressure former with 0.75 mm polyethylene terephthalate glycol-modified (PETG) sheets.

Measurements were performed using a digital caliper with 0.01 mm accuracy by a single examiner (M.Ö.). Calibration and intra-examiner reliability were assessed by repeating measurements on 20 randomly selected models at two-week intervals. Method error was calculated using Dahlberg's formula. The primary outcome was the reduction in LII, representing the extent of correction. To evaluate the pace of treatment, we calculated the rate of change (ΔLII per day) between consecutive time intervals (T0-T1, T1-T2, T2-T3). This allowed the assessment of both the magnitude of alignment and the acceleration of tooth movement. Intra-examiner reliability, assessed using the Intraclass Correlation Coefficient (ICC) with 95% confidence intervals, indicated excellent agreement for all time points (Table 1).

Statistical Analysis

Statistical analyses were performed using SPSS Statistics for Windows, Version 26.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics were expressed as mean ± standard deviation. Group differences were assessed using One-Way ANOVA for normally distributed data, followed by Tukey's post-hoc test for pairwise comparisons. Repeated measures ANOVA was applied for within-group changes over time. Pearson's correlation coefficient was used to assess the relationship between device usage and changes in crowding (Table 2). Statistical significance was set at $p<0.05$. For multiple comparisons, Tukey's honestly significant difference (HSD) test was applied. This post-hoc procedure inherently controls for Type I error without the need for additional correction methods.

In the present study, the therapeutic effect achieved through the adjunctive use of photobiomodulation and vibration devices in combination with aligners was considered accelerated when a greater degree of crowding correction was observed within the same aligner replacement interval.

RESULTS

The distribution of age and gender across the four study groups showed no statistically significant differences ($p>0.05$), indicating homogeneity among groups (Table 3).

Table 1 presents the methodological error evaluation for crowding measurements at T0, T1, T2, and T3. The methodological error for LII measurements at T0, T1, T2, and T3 was assessed using Dahlberg's formula and found to be clinically negligible. Intra-examiner reliability was assessed

Table 1. Methodological error evaluation regarding the amount of crowding measurements at T0, T1, T2 and T3 times

Time point	ICC	95% CI (Lower-Upper)	p-value
T0	0.999	0.999-1.000	<0.001
T1	0.998	0.997-0.999	<0.001
T2	0.998	0.997-0.999	<0.001
T3	0.999	0.999-1.000	<0.001

Significance at p<0.05.
ICC: Intraclass Correlation Coefficient; CI, confidence interval.

Table 2. Evaluations of acceleration device and aligner usage

Group	Device usage (min/day) Mean±SD	Aligner wear (h/day) Mean±SD	r (Device vs. crowding change)	p-value
Control	-	21.6±1.6	-	-
LFV	17.9±2.4	21.5±1.5	0.329	0.101
PBM	17.2±2.5	21.6±1.4	0.110	0.636
HOT	18.6±2.1	21.7±1.3	0.419	0.051

Significance at p<0.05.
SD, standard deviation; HOT, combined LFV + PBM; LFV, low-frequency vibration; PBM, photobiomodulation.

using the ICC with 95% confidence intervals, which indicated excellent agreement for all time points (Table 1).

At baseline (T0), no statistically significant differences were observed in the initial crowding scores among the groups (p>0.05). By the end of the treatment period, analysis of crowding reduction revealed significant intergroup differences (p<0.05) (Table 4).

The HOT group demonstrated the greatest mean reduction in crowding from T0 to T3, with a statistically, greater reduction than that observed in the control, vibration, and PBM groups. The vibration group showed a modest reduction in crowding compared to the control group, but the difference was not statistically significant (p>0.05). The PBM group showed results comparable to the vibration group and, importantly, no statistically significant difference when compared to the control group.

Repeated measures ANOVA indicated significant reductions in LII within each group over time (p<0.05). Post-hoc pairwise comparisons (Table 5) showed that the HOT group exhibited significant reductions at each time interval (T0-T1, T1-T2, T2-T3). The vibration and PBM groups showed significant reductions between T0-T1 and T0-T3 whereas changes between consecutive intervals (T1-T2, T2-T3) were less pronounced. The control group showed a significant reduction only between T0-T3.

Post-hoc comparisons demonstrated that the HOT group exhibited significantly greater reductions. HOT vs Control: The largest improvement was observed in the HOT group, with a mean difference of -1.05 mm, which was highly significant (p<0.001). The effect size was large (η^2=0.32, Cohen's d=1.25), indicating strong clinical relevance. HOT vs. low-frequency vibration (LFV): The HOT group also outperformed the LFV group with a mean difference of -0.65 mm (p=0.010). The effect size was moderate to large (η^2=0.18, Cohen's d=0.80). HOT vs PBM: A significant advantage was also found for HOT, when compared with PBM, (-0.53 mm, p=0.025), with a moderate effect size (η^2=0.15, Cohen's d=0.65). LFV vs Control: Although LFV showed better results than Control, with a difference of (-0.40 mm), the difference was not statistically significant (p=0.070), and the effect size was small to moderate effect. PBM vs Control: PBM showed a borderline significant improvement compared to Control (-0.52 mm, p=0.050) with a small to moderate effect size. Overall, the HOT protocol produced the most pronounced acceleration of crowding resolution, with large effect sizes confirming not only statistical

Table 3. Evaluation of the groups in terms of age and gender

	Control	Vibration	PBM	HOT	p-value
Age Mean±SD	23.16±3.55	24.31±2.51	22.57±5.06	23.52±3.19	0.426[1]
Female n (%)	11 (57.9%)	14 (53.8%)	12 (57.1%)	14 (60.9%)	0.969[2]
Male n (%)	8 (42.1%)	12 (46.2%)	9 (42.9%)	9 (39.1%)	

[1]One-Way ANOVA test; [2]Chi-square test.
Significance at p<0.05.
SD, standard deviation; PBM, photobiomodulation.

Table 4. Evaluations of crowding amount measurements

	Control Mean±SD	Vibration Mean±SD	PBM Mean±SD	HOT Mean±SD	p-value
T0	5.66±0.47A,a	5.56±0.39A,a	5.75±0.41A,a	5.65±0.43A,a	0.476
T1	5.49±0.46A,b	5.39±0.39A,b	5.34±0.41A,b	5.16±0.42A,b	0.074
T2	5.31±0.48A,c	5.22±0.41 AB,c	4.95±0.41BC,c	4.68±0.42C,c	0.000*
T3	5.14±0.48A,d	5.06±0.39A,d	4.55±0.41B,d	4.19±0.42C,d	0.000*

One-Way ANOVA test
*Significance at p<0.05.
Uppercase letters in rows indicate intergroup variation, and lowercase letters in columns indicate intertemporal variation.
SD, standard deviation; PBM, photobiomodulation; HOT, combined LFV + PBM; LFV, low-frequency vibration.

Table 5. Post-hoc analysis results (Tukey HSD, effect sizes)

Comparison	Mean difference (mm)	95% CI (Lower-Upper)	p-value	n^2 (Eta squared)	Partial n^2	Cohen's d
HOT vs Control	-1.05	-1.32 - -0.78	<0.001	0.32	0.28	1.25
HOT vs LFV	-0.65	-0.90 - -0.40	0.010	0.18	0.16	0.80
HOT vs PBM	-0.53	-0.78 - -0.28	0.025	0.15	0.14	0.65
LFV vs Control	-0.40	-0.65 - -0.15	0.070	0.09	0.08	0.50
PBM vs Control	-0.52	-0.77 - -0.27	0.050	0.12	0.11	0.60

Significance at p<0.05. Post-hoc test; Tukey HSD. Effect size calculated as n^2.
Values are expressed as mean differences in millimeters (mm).
n^2: Eta squared effect size; Partial n^2: effect size from the model; Cohen's d: standardized mean difference.
HOT, combined LFV + PBM; LFV, low-frequency vibration; PBM, photobiomodulation.

but also clinical significance. LFV and PBM protocols showed some improvements over Control, but their effects were smaller and less consistent. These findings highlight that HOT could be considered the most effective adjunctive modality for enhancing aligner efficiency in resolving lower incisor crowding.

Mean daily usage of the acceleration devices was highest in the HOT group, followed by the vibration and PBM groups. Correlation analyses between device usage time and changes in crowding were not statistically significant in any group.

Clear aligner wear time, recorded via patient compliance charts, did not differ significantly among the groups ($p>0.05$). No significant correlations were found between aligner wear time and crowding reduction in any group.

When evaluating the combined effect of aligner wear time and device usage, usage metrics were comparable among the groups, and combined usage analyses did not yield significant correlations.

DISCUSSION

Over the past decade, LFV and PBM have attracted increasing attention in orthodontics, particularly regarding their potential to accelerate tooth movement and improve patient comfort. The evidence remains inconclusive, with discrepancies mainly attributed to variations in study design, intervention protocols, and outcome measures. The present study adds to this growing body of research by assessing, during the early alignment phase of mandibular incisors treated with clear aligner therapy, LFV, PBM, and a combined HOT approach.

Vibration has been proposed to enhance OTM by modulating the bone remodeling cycle through mechanotransduction and increased PDL fluid flow.[23] However, the effect of LFV (≤30 Hz) remains controversial. Pascoal et al.[24] and Akbari et al.[25] reported that LFV generally failed to significantly accelerate OTM in both aligner and fixed appliance therapies. In contrast, HFV (>90 Hz) has shown more promising effects, particularly in canine retraction and space closure. Our results are consistent with these findings. LFV alone (30 Hz, 0.25 N [≈25 g], 20 min/day) did not significantly outperform the control group over the 62-day period. This parallels the clinical observations of Woodhouse et al.[26] and Lombardo et al.[27] who also failed to detect a statistically significant difference in alignment rate with LFV in clear aligner patients under certain conditions. The modest, non-significant reduction observed in our LFV group might reflect biological limitations of low-frequency stimulation or the short observation period.

PBM, typically delivered via low-level laser therapy (LLLT) or light-emitting diodes (LEDs), acts through photonic stimulation of mitochondrial chromophores, primarily cytochrome c oxidase, leading to increased ATP production, modulation of reactive oxygen species, and altered cellular signaling. These effects can enhance osteoblastic and osteoclastic activity, potentially accelerating bone remodeling.[28] Our PBM-only group, which received 850 nm LED light at 9.5 J/cm^2 for 20 min/day, did not show statistically significant results compared with the control, though a trend toward greater crowding reduction was observed. This aligns with a recent systematic review, indicating that PBM's clinical effectiveness is dose-, wavelength-, and protocol-dependent.[29] Variability in energy density, application intervals, and movement type likely accounts for inconsistent outcomes across studies. For example, Kau et al.[16] reported significant acceleration using similar wavelengths but different usage protocols, while Farhadian et al.[30] observed smaller gains with LED compared to laser sources.

The HOT protocol, integrating both LFV and PBM in a single device, demonstrated significantly greater alignment over 62 days than either modality alone, or control. This suggests a potential synergistic effect, vibration may enhance PDL mechanotransduction and fluid dynamics, while PBM may upregulate cellular metabolism and accelerate the RANK/RANKL/OPG-mediated remodeling cycle. Although clinical evidence for such synergy remains sparse, the biological plausibility is supported by our results and by mechanistic insights from previous *in vitro* and *in vivo* studies.[24,25,28,29]

Although LFV and PBM individually failed to achieve statistical significance, their combination was effective. It is possible that simultaneous mechanical and photonic stimulation engages complementary pathways, compensating for the limitations of each modality. This is particularly relevant in the early alignment of mandibular incisors, where tooth size, morphology, and aligner fit may limit movement efficiency.

The resolution of anterior crowding is often a critical determinant of patient satisfaction in the early stages of treatment. In clear aligner therapy, maintaining tracking accuracy and minimizing refinements are essential for efficiency. Previous aligner-based studies have shown HFV can shorten aligner change intervals,[17] while PBM has demonstrated potential for reducing treatment duration,[16] though not consistently. The superior performance observed in the HOT group suggests that this approach may enable an earlier transition to the finishing stages without increasing adverse effects, consistent with the absence of reported root resorption or discomfort in our cohort.

The short follow-up (62 days) was deliberate, capturing the leveling phase while all patients were in active anterior alignment, but it prevents conclusions about total treatment time. Furthermore, the LFV parameter used (30 Hz) may be suboptimal compared to HFV protocols that have shown clearer benefits. Future studies should include longer follow-up, objective compliance monitoring, and direct comparisons of LFV+PBM versus HFV+PBM.

While surgical methods such as corticotomy, piezocision, and micro-osteoperforations can significantly accelerate OTM,[16-19] their invasiveness, need for anesthesia, and patient reluctance may limit their applicability. Non-invasive methods like HOT may offer a viable alternative, especially for patients unwilling to undergo surgery. Though the absolute acceleration in our study is lower than that of surgical approaches, the favorable safety and comfort profile may make HOT a more acceptable choice for aligner patients.

In aligner-only cohorts, previous studies have reported modest, but clinically significant reductions in LII during the first 6-10 weeks, findings that are consistent with the changes observed in our control group.[21,22] For low-frequency vibration (≈30 Hz), several randomized clinical trials did not demonstrate clinically meaningful acceleration compared with aligners alone,[26,27] and recent systematic reviews also reported mixed or negligible effects.[24,25] Photobiomodulation (PBM), on the other hand, has shown protocol-dependent outcomes; while some early studies suggested accelerated alignment with near-infrared wavelengths,[16] more recent systematic reviews emphasize heterogeneity and dose-response considerations.[28,29] Trials comparing LED and laser sources generally showed smaller effects for LED devices.[30] Against this background, the combined HOT protocol in the present study demonstrated larger between-group differences and effect sizes than aligners alone or either modality used individually (Table 5), supporting a potential synergistic benefit during the early alignment phase.

It is important to distinguish between the amount of correction and the pace of tooth movement. The reduction in LII reflects the absolute amount of alignment achieved, whereas treatment pace is represented by the rate of change in LII per unit of time (ΔLII/day). Previous studies on aligner-only protocols reported average alignment changes of approximately 0.5-0.8 mm per month during the early treatment phase,[21,22] which is consistent with the modest improvements observed in our control group. In contrast, patients in the HOT protocol showed greater reductions in LII within the same time intervals, resulting in higher rates of alignment per day. This indicates that the observed differences are not only in the magnitude of correction but also in the acceleration of the alignment process.

Thus, the HOT protocol not only resulted in a greater absolute reduction in LII but also accelerated the rate of alignment compared with aligners alone. In our control group, the mean reduction in LII corresponded to approximately 0.26 mm per month, which is in line with previously reported aligner-only outcomes of 0.5-0.8 mm per month.[21,22] By contrast, the HOT group demonstrated significantly higher rates of correction per day, indicating a true acceleration of treatment rather than only a larger correction amount.

From a clinical perspective, the combined HOT protocol offers a non-invasive and patient-friendly adjunct to aligner therapy, potentially reducing treatment duration without additional chair time or surgical procedures, thereby increasing the practicality of accelerated orthodontics in daily practice.

CONCLUSION

Within the limitations of this retrospective study, combining low-frequency vibration and photobiomodulation (HOT) during clear aligner therapy resulted in a greater short-term acceleration of mandibular incisor alignment than each modality alone or the control. These findings suggest a potential synergistic mechanism, warranting further randomized trials to confirm efficacy, optimize parameters, and assess long-term safety.

Ethics

Ethics Committee Approval: This retrospective observational study was conducted at the Department of Orthodontics, Faculty of Dentistry, Yeditepe University. Ethical approval was obtained from the Marmara University Clinical Research Ethics Committee (approval no: 2020-425, date: 30.06.2020) in accordance with the Declaration of Helsinki.

Informed Consent: Retrospective observational study.

Footnotes

Author Contributions: Concept - M.Ö., D.N.; Design - M.Ö., D.N.; Data Collection and/or Processing - M.Ö.; Analysis and/or Interpretation - M.Ö.; Literature Search - M.Ö.; Writing - M.Ö.

Conflict of Interest: The authors have no conflicts of interest to declare.

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