Prevention of white spot lesion formation during treatment with fixed orthodontic appliances

The efficacy of using a fluoride rinse and repeated oral hygiene instructions

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CHAPTER 3

THE EFFECT OF FIXED ORTHODONTIC APPLIANCES AND FLUORIDE MOUTHWASH ON THE ORAL MICROBIOME OF ADOLESCENTS – A RANDOMIZED CONTROLLED CLINICAL TRIAL

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ABSTRACT

While the aesthetic effect of orthodontic treatment is clear, the knowledge on how it influences the oral microbiota and the consequential effects on oral health are limited.

In this randomized controlled clinical trial we investigated the changes introduced in the oral ecosystem, during and after orthodontic treatment with fixed appliances in combination with or without a fluoride mouthwash, of 10-16.8 year old individuals (N = 91). We followed several clinical parameters in time, in combination with microbiome changes using next-generation sequencing of the bacterial 16S rRNA gene.

During the course of our study, the oral microbial community displayed remarkable resilience towards the disturbances it was presented with. The effects of the fluoride mouthwash on the microbial composition were trivial. More pronounced microbial changes were related to gingival health status, orthodontic treatment and time. Periodontal pathogens (e.g. Selenomonas and Porphyromonas) were highest in abundance during the orthodontic treatment, while the health associated Streptococcus, Rothia and Haemophilus gained abundance towards the end and after the orthodontic treatment. Only minor compositional changes remained in the oral microbiome after the end of treatment.

We conclude that, provided proper oral hygiene is maintained, changes in the oral microbiome composition resulting from orthodontic treatment are minimal and do not negatively affect oral health.
INTRODUCTION

The aesthetic effects of orthodontic treatment are often readily visible; in contrast to the effect orthodontic treatment might have on the non-visible part of the oral cavity - the microbiome.

The possible changes in the oral microbiome during orthodontic treatment are likely to be related to, the more easy observable, clinical parameters. For instance, the impaired gingival health status (van Gastel et al., 2008, Gong et al., 2011) and increased plaque formation (Sukontapatipark et al., 2001, Demling et al., 2009) that are associated with the placement of fixed orthodontic appliances. Besides, the latter could lead to the formation of white spot lesions, creating an undesirable aesthetic effect and possibly resulting in a cavity in need of resturction (Mattousch et al., 2007, Ren et al., 2014).

So far, studies aimed to investigate the changes in bacterial taxa during orthodontic treatment, used culturing or targeted molecular approaches, allowing for a limited number of opportunistic pathogenic species to be observed (Choi et al., 2009, Thornberg et al., 2009, Kim et al., 2012, Torlakovic et al., 2013). This implies that the response of the entire microbiome to orthodontic treatment is unclear, as are the possible long-term changes in bacterial composition.

A full understanding of the effects of fixed orthodontic appliances on the oral microbiome and the consequences on clinical parameters, should allow for the preservation of a healthy oral cavity during and after orthodontic treatment, justifying orthodontic treatment.

Our aim was to investigate changes introduced in the oral ecosystem during and after orthodontic treatment in combination with a fluoride mouthwash. To our knowledge, this is the first study to investigate the dynamics of the oral microbiome of adolescents during orthodontic treatment, and the use of a fluoride mouthwash using an open-ended molecular approach.

MATERIALS AND METHODS

Sampling and treatment

A randomized placebo-controlled parallel clinical trial was performed as described by van der Kaaij et al. (van der Kaaij et al., 2015). The study was approved by the Medical Ethical Committee of the VU Medical Centre of the VU University of Amsterdam (VU-METc 2009/026 and Dutch trial register: NTR1817). The randomization allocation list was made in Microsoft Office Excel 2003 (Microsoft, Redmond, WA, USA) using the random number generation function in the analysis toolpack for one variable with a discrete distribution, allocating 50% of the 120 subjects to the test and 50% to the control group. The study was powered on the basis of the primary outcome; the data presented here were secondary outcomes.
All subjects participating in this study were scheduled to receive full fixed orthodontic appliances. Subjects could only be scheduled to receive full fixed orthodontic appliances if they maintained a proper oral hygiene and had no severe gingivitis. The guidelines at the Orthodontic Department at ACTA state that orthodontic appliances will not be placed when the bleeding by probing score is above 2 (1: 0-5% of the sites are bleeding, 2: 6-10% of the sites are bleeding, 3: 11-20% of the sites are bleeding, 4: 21-35% of the sites are bleeding, 5: > 35% of the sites are bleeding), except if immediate orthodontic treatment is indicated, for example, in case of traumatic occlusion.

The inclusion criteria for the study were: 10-18 years of age, good general health, no use of medication and no demineralization in need of restauration present at a buccal surface, in addition to providing their written informed consent. A total of 120 subjects set to receive fixed orthodontic appliances in both jaws were to participate in the study. Roth Ovation Brackets (Dentsply, GAC International, Bohemia, NY, USA) were used and all were bonded following the same procedure and methods, using Transbond XT primer and adhesive (3M uniteit, Monrovia, USA).

In this triple-blind study, the subjects received a randomly assigned mouthwash containing 100 ppm amine fluoride (AmF) and 150 ppm sodium fluoride (SnF$_2$) (Elmex caries protection, Colgate-Palmolive Europe, Therwil, Switzerland) or a placebo, also provided by Colgate-Palmolive Europe. The mouthwash was used from the time of bonding until debonding. The subjects were instructed not to use (extra) fluoride containing products, other than toothpaste, during the course of the study. Their dentist was informed about the study and was asked not to apply extra fluoride during the study period. Furthermore, the subjects received oral hygiene instructions after placement of the fixed appliances and were advised to use interproximal brushes to clean the areas of the tooth adjacent to the bracket underneath the orthodontic wire.

The subjects were instructed not to clean their teeth 24 hr before supragingival plaque samples for microbiome analysis were taken. These samples were obtained at six time-points during this study: T0 (approximately one week before placement of the fixed orthodontic appliances), T1 (six weeks after placement), T2 (twelve weeks after placement), TD (debonding, average of 25 months after placement), TD1 (six weeks after debonding) and TD2 (twelve weeks after debonding). Supragingival plaque was collected from the buccal surface of the upper left premolars using a sterile plastic spatula. In presence of the brackets (visits T1, T2 and TD), which were placed on the middle of the tooth, the plaque was collected between the gingiva and the bracket. Gingival swelling often occurs within one or two months after placement of orthodontic appliances (Zachrisson and Zachrisson, 1972, Ristic et al., 2007, van Gastel et al., 2008). Hence, in cases where the gingival margin reached the bracket, the plaque was collected mesially and/or distally from the bracket. The plaque samples were spun down for 30 s at 16.100 x g and stored at -80°C.
The number of white spot lesions of the subjects was recorded at visits T0, TD, TD1 and TD2, and is described in more detail by van der Kaaij et al. (van der Kaaij et al., 2015). Additionally, a bleeding by probing score was recorded at each visit for each patient. The percentage-based bleeding score was determined by probing each (bonded or to be bonded) tooth mesiobuccally and distobuccally with a periodontal probe (van der Kaaij et al., 2015). For statistical analysis, the bleeding score was dichotomized into a healthy (score 1) and a gingivitis (score 2-5) group.

**DNA isolation and sequencing**

DNA was isolated from the supragingival plaque samples as described by Zaura et al. (Zaura et al., 2009). The V5-V7 regions of the 16S rDNA were used to prepare barcoded amplicon libraries for each sample (Kraneveld et al., 2012). The equimolar pooled samples were sequenced at the Academic Medical Center (Amsterdam, the Netherlands) and Macrogen Inc. (Seoul, Republic of Korea) using the 454 FLX Titanium chemistry (Roche, Basel, Switzerland). The reads are available at NCBI’s Sequence Read Archive under SRP055565.

**Sequencing data analysis**

Quantitative Insights Into Microbial Ecology (QIIME) v1.5.0 was used to analyze the sequence data (Caporaso et al., 2010). The downstream analyses and clustering into OTUs was done according to Koopman et al. (Koopman et al., 2015), with the exception that 1 ambiguous base (N = 1) was allowed. The OTUs were manually aligned against NCBI’s nucleotide (nr/nt) collection using Megablast (Zhang et al., 2000, Morgulis et al., 2008) to obtain species level identification (Table S1).

**Statistical analysis**

The Shannon diversity index and Bray-Curtis similarity index were calculated using PAST v3.0 (Hammer et al., 2001). This program was also used to construct non-metric multidimensional scaling (nmMDS) plots based on the Bray-Curtis coefficient to visualize similarity between the samples. Stress < 0.2 (Kruskal’s stress formula 1) was used as a threshold (Clarke, 1993).

The statistical significance of individual OTUs in relation to clinical parameters was determined using QIIME’s paired t-test and correlation. The OTUs that were significant after FDR correction for multiple comparisons were analyzed further using IBM SPSS Statistics v21 (IBM Corp, Armonk, NY, USA). The Mann-Whitney test was used to determine if there was a statistically significant difference between the mouthwash groups, or gingival health status per visit for the phyla, genera and OTUs. The Wilcoxon Signed Ranks test was used to examine if there was a statistically significant difference between the visits at phylum, genus and OTU level and for the Shannon diversity index.
RESULTS

Study population
A total number of 120 subjects participated in the study. Contribution of 22 subjects to this study was discontinued because they declined further participation, moved or failed to show up. For 7 of the subjects, no supragingival plaque samples could be obtained because they brushed their teeth prior to sampling or the quality of the reads after sequencing was poor. From the 91 remaining subjects, one or more supragingival plaque samples were obtained. The number of microbiological samples obtained per visit was: T0; n = 76, T1; n = 73, T2; n = 68, TD; n = 44, TD1; n = 43 and TD2; n = 45. The number of subjects per mouthwash group per visit and the gender ratio per visit are described in Table S2. At the time of bonding, the average age of the subjects was 13.3 years old (SD 1.4, range 10-16.8). There was no significant difference in gingival bleeding between the group receiving the fluoride mouthwash and the group receiving the placebo at the baseline visit (van der Kaaij et al., 2015).

Sequencing output
Of the processed sequencing reads, 78% passed quality control and 75% (2607737 reads) remained after the removal of chimeric reads. For 31 of the samples the number of reads was too low (8-769 reads per sample, average 227 reads); these were excluded from further analyses. The remaining 349 samples had an average of 7164 reads per sample (SD 5131, range 835-28432). The reads clustered into 461 OTUs. The subsampling threshold was set at 800 reads and the remaining subset, containing an average of 49 OTUs per sample (SD 14, range 11-94), was used for further analysis.

The reads were classified into 15 phyla and, when averaged over all time-points, dominated by Firmicutes (27%), Actinobacteria (22%), Proteobacteria (22%), Bacteroidetes (16%), Fusobacteria (11%) and Candidate division TM7 (1%). At a lower taxonomic level, the reads were classified into 149 genera, dominated by Streptococcus (12%), Neisseria (11%), Corynebacterium (9%), Veillonella (7%), Leptotrichia (7%) and Actinomyces (6%).

Mouthwash effect
Non-metric multidimensional scaling plots were made by mouthwash group per visit. These plots did not show any separation of the microbial profiles based on mouthwash (fig. 1). There were no statistically significant differences in Shannon diversity index at any of the visits. To assess the stability of the microbiome composition in time, the Bray-Curtis similarity index between visit T0 and the subsequent visits was calculated per individual and tested for each mouthwash group. The difference in similarity did not reach statistical significance at any of the time-points.
There was no significant difference in relative abundance of any bacterial phylum between the two mouthwash groups at any visit.

Figure 1. Non-metric multidimensional scaling plots based on the three-dimensional Bray-Curtis similarity index by mouthwash. The plots are constructed per visit. The subjects receiving the fluoride mouthwash are symbolized by ●, the subjects receiving the placebo mouthwash are indicated by ○. Mouthwashes were administered between visits T0 and TD. The stress for each individual plot is (a) 0.1543, (b) 0.1465, (c) 0.1256, (d) 0.1402, (e) 0.1495 and (f) 0.1531.
At genus level, within the placebo group, *Fusobacterium* decreased significantly in abundance from visit T0 to T1 ($p = 0.049$) and from T1 to T2 ($p = 0.002$). Between visits T2 and TD, the level of abundance became significantly higher again ($p = 0.038$) (fig. S1). In the fluoride mouthwash group, there was no significant difference in abundance of *Fusobacterium* between any of the visits.

At the OTU level, the abundance of OTU381 (*Kingella*) was higher ($p = 0.028$) in the placebo group compared to the fluoride group at visit T1 (fig. S2).

**Gingival health**

The gingival health status of the subjects was determined by probing. To assess the relation between gingival health and the supragingival plaque microbiome, we dichotomized the group into subjects with healthy gingiva and with gingivitis. The highest prevalence of gingivitis was recorded at visit TD (fig. 2). Non-metric multidimensional scaling plots based on the OTU profiles of each subject per time-point showed that gingivitis-microbiome profiles were less scattered, especially at visits T0, T1 and T2, in space compared to the healthy-gingiva microbiome profiles (fig. 3).

![Figure 2. Count of subjects with healthy gingiva and with gingivitis per visit.](image)

At the phylum level, the proportion of Bacteroidetes was higher in the individuals with gingivitis compared to those with healthy gingiva at visits T0 ($p = 0.012$) and T1 ($p = 0.035$) (fig. S3a). The abundance of Candidate division TM7 was significantly elevated in individuals with gingivitis at visits T0 ($p = 0.001$), T1 ($p = 0.029$), T2 ($p = 0.032$) and TD2 ($p = 0.037$) (fig. S3b). The proportion of the phylum Fusobacteria was higher in the subjects with gingivitis at visits T1 ($p = 0.031$) and TD2 ($p = 0.024$) (fig. S3c).
At genus level, the relative abundance of the genus *Selenomonas* was significantly higher in the gingivitis group compared to the healthy group at visits T0 ($p = 0.022$), T1 ($p = 0.041$) and TD2 ($p = 0.012$) (fig. S4a). The same applied to *Porphyromonas* at visits T0, T1 and
T2 ($p = 0.036$, $p = 0.010$ and $p = 0.033$, respectively) (fig. S4b) and *Johnsonella* at visits T0 ($p = 0.004$), T1 ($p = 0.013$) and TD2 ($p = 0.042$) (fig. S4c). In contrast, the genus *Derxia* was significantly higher in the healthy group at visits T0 and T1 ($p = 0.046$ and $p = 0.028$, respectively) (fig. S4d). The same was observed for the genera *Haemophilus* at visit T0 ($p = 0.021$) and visit TD2 ($p = 0.024$) (fig. S4e) and *Rothia* at visit T0 ($p = 0.004$) (fig. S4f).

In agreement with the genus *Rothia*, OTU65 (*Rothia*) was significantly more abundant in the healthy subjects compared to those with gingivitis at visit T0 ($p = 0.011$) (fig. S5a). The difference in abundance in OTU351 (*Streptococcus*) between the two groups was significant at visit T1 ($p = 0.023$) where the OTU was higher in number in the healthy group (fig. S5b). On the other hand, OTU424 (*Johnsonella*) was more abundant in the gingivitis group compared to the healthy group at visits T0 ($p = 0.032$), T1 ($p = 0.039$) and TD ($p = 0.044$) (fig. S5c). The OTUs 55, 171 and 355, all three classified as Candidate division TM7, were higher in the gingivitis group at visit T0 ($p = 0.005$, 0.006 and 0.005, respectively). OTU355 was also higher at T1 ($p = 0.011$), while OTU55 was higher at visit T2 ($p = 0.011$) in the gingivitis group (fig. S5d-f). The OTU302 (*Selenomonas*) was significantly higher in the gingivitis group compared to the healthy group at T0 ($p = 0.038$), T1 ($p = 0.045$) and TD2 ($p = 0.010$) (fig. S5g) as was OTU398 (*Fusobacterium*) at TD2 ($p = 0.012$) (fig. S5h).

**Time**

Next, we assessed the changes in microbiome of the study population in time. An nmMDS plot on OTU level was constructed of the individuals (N = 19) whose samples were available from all six time-points. However, no discernable effects of time on the microbiome profiles were found (fig. 4). The microbiome diversity became higher between visit T0 and T1 ($p = 0.003$) and became lower between visits TD and TD1 ($p = 0.003$) (fig. 5).

The abundance of the phylum Actinobacteria decreased between visit T0 and T1 ($p = 0.043$), while the same phylum increased at visits TD1 and TD2 compared to the baseline ($p = 0.002$, $p = 0.006$, respectively) (fig. S6a). The phylum Firmicutes had increased in abundance at visits T1 ($p = 0.005$), TD ($p = 0.021$) and TD2 ($p = 0.035$) over visit T0 (fig. S6b). Compared to visit T0, the abundance of Bacteroidetes had decreased in both post-debonding visits: TD1 ($p = 0.015$) and TD2 ($p = 0.025$) (fig. S6c). Between visits T0 and TD1, the abundance of Candidate division TM7 decreased ($p = 0.031$) (fig. S6d), while Fusobacteria decreased from T0 to T2 ($p = 0.001$) and TD1 ($p = 0.001$) (fig. S6e). The abundance of Proteobacteria was significantly lower at visit TD compared to the baseline ($p = 0.001$) (fig. S6f).

Several genera showed significant differences in abundance between the visits (fig. 6). *Streptococcus* became significantly more abundant at visits T1 ($p = 0.036$), TD ($p = 0.025$), TD1 ($p < 0.001$) and TD2 ($p = 0.001$) compared to the baseline. An increase in abundance from visit TD to TD1 ($p = 0.048$) was observed as well (fig. S7a). The abundance of *Neisseria* became higher at visit T2 compared to T0 ($p = 0.008$), while at visits TD and TD1 the abundance became lower compared to visit T0 ($p = 0.006$, and $p = 0.029$, respectively).
Moreover, the abundance of *Neisseria* increased significantly at visit T2 compared to visit T1 \((p = 0.011)\), yet it was significantly lower again at visit TD \((p = 0.018)\) (fig. S7b). *Actinomyces* had increased significantly at the last three visits when compared to visit T0 (TD: \(p = 0.004\), TD1: \(p < 0.001\) and TD2: \(p < 0.001\)) (fig. S7c). Both *Veillonella* (fig. S7d) and *Porphyromonas* (fig. S7e) were only at visit TD significantly more abundant when compared to visit T0.
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T0 ($p = 0.033$ and $p = 0.011$, respectively). Additionally, the abundance of *Porphyromonas* decreased significantly between T2 and TD ($p = 0.017$). For *Leptotrichia*, the abundance became significantly lower at TD1 ($p < 0.001$) and TD2 ($p = 0.037$) compared to the baseline (fig. S7f). The abundance of *Campylobacter* had decreased at the last three visits compared to visit T0 (TD: $p = 0.033$, TD1: $p < 0.001$ and TD2: $p < 0.001$) (fig. S7g). At both visits T1 and TD, *Prevotella* had increased in abundance compared to visit T0 ($p = 0.004$ and $p = 0.001$, respectively), while at TD1 the abundance had become significantly smaller again ($p = 0.010$) (fig. S7h). For the genus *Haemophilus*, the only significant increase in abundance was between visits TD and TD1 ($p = 0.033$) (fig. S7i). For the genus *Selenomonas* a decrease in time was observed (fig. S7j). The abundance of the genus *Fusobacterium* was significantly lower at T2 and TD1 compared to the baseline ($p < 0.001$ and $p = 0.043$, respectively) (fig. S7k). The abundance of *Rothia* was higher in the last three visits compared to the baseline (TD: $p = 0.009$, TD1: $p < 0.001$, TD2: $p < 0.001$) (fig. S7l).

At the OTU level, the abundance of OTU28 (*Actinomyces*) was higher at TD1 ($p < 0.001$) and TD2 ($p = 0.001$) compared to visit T0 (fig. S8a). When compared to visit T0, the abundance of OTU65 (*Rothia*) was higher in the last three visits (TD: $p = 0.009$, TD1: $p < 0.001$, and TD2: $p < 0.001$) (fig. S8b). In addition, both OTU28 and OTU65 were elevated significantly between visits TD and TD1 ($p = 0.049$ and $p = 0.002$, respectively). The abundance of OTU351 (*Streptococcus*) became higher between visits TD and TD1 ($p = 0.033$) and was significantly higher compared to visit T0 at visit TD1 ($p < 0.001$) and visit TD2 ($p = 0.002$) (fig. S8c). In comparison to the baseline, the abundance of OTU398 (*Fusobacterium*) was lower at visit T2 ($p < 0.001$) and at visit TD1 ($p = 0.043$) (fig. S8d). The abundance of OTU143 (*Leptotrichia*) decreased significantly between visits TD and TD1 ($p = 0.003$). Moreover, at visit TD1, the abundance of OTU143 was significantly smaller compared to visit T0 ($p = 0.007$) (fig. S8e). The abundance of OTU151 (*Campylobacter*) was lower at visit TD compared to visit T2 ($p = 0.032$) and at TD1 the abundance was lower compared to visit TD ($p = 0.001$). At both visits TD1 and TD2, the abundance of OTU151 was significantly lower compared to visit T0 ($p < 0.001$ and $p < 0.001$, respectively) (fig. S8f). When compared to visit T0, the abundance of OTU302 (*Selenomonas*) had increased at visits T1 ($p = 0.002$), T2 ($p < 0.001$) and TD ($p = 0.029$), while the abundance had decreased at visit TD1 ($p = 0.003$) (fig. S8g).

DISCUSSION

The results of our study indicate that the fluoride mouthwash had little effect on the adolescent oral microbiome composition during fixed orthodontic appliance treatment. More pronounced were the microbial changes observed in relation to gingival health status and orthodontic treatment. Yet, the resilience of these adolescent oral communities was noteworthy in regard to the interference caused by the orthodontic treatment, fluoride
mouthwash and the physiological changes of puberty itself. There was no observable shift in the composition of the total community in time (fig. 4). A remaining change in abundance was observed for a few genera (fig. 6) and, interestingly, most genera that did increase in abundance in time were associated with a healthy oral cavity.

In this study, an amine fluoride (AmF) combined with stannous fluoride (SnF$_2$) mouthwash was used to reduce the amount of demineralization, since fluoride is a well-established anti-caries agent (van Loveren et al., 2009) and caries is an infectious bacterial disease. Compliance is regarded as a drawback in studies aiming to observe the effect of a mouthwash. Nonetheless, van der Kaaij et al. (van der Kaaij et al., 2015) observed that the use of an AmF/SnF$_2$ mouthwash inhibited formation of white spot lesions during this study. Likewise, Øgaard et al. (Øgaard et al., 2006) observed that there was no difference in white spot lesions before and after orthodontic treatment of patients using an AmF/SnF$_2$ mouthwash. Madléna et al. (Madleña et al., 2012) observed a decrease in plaque index, gingival index and bleeding on probing within one month in orthodontic patients using AmF/SnF$_2$ toothpaste, regardless if the toothpaste was combined with an AmF/SnF$_2$ mouthrinse. Gerardu et al. (Gerardu et al., 2006, van Loveren et al., 2009) did observe dental plaque shifting towards less acidogenic plaque, yet there was no significant difference in bacterial composition after the use of AmF/SnF$_2$ products compared to fluoride-free periods. This is similar to our findings, as we did not observe a clear effect of the fluoride mouthwash on the microbial composition. Although it is suggested that fluoride has antibacterial properties, its main effect appears to be on the demineralization and remineralization processes in the oral cavity (van Loveren, 2001, ten Cate, 2009, Rosin-Grget et al., 2013, ten Cate, 2013).

We did observe that the abundance of several bacterial taxa was associated with the gingival health status of the subjects. Gingivitis during orthodontic treatment is presumably related to plaque accumulation caused by the newly created retention sites and consequently impaired oral hygiene (Ren et al., 2014). Yet, it is not only the orthodontic treatment that is related to the onset of gingivitis in these subjects, for ‘puberty itself’ is also associated with increased gingivitis (Morishita et al., 1988, Mombelli et al., 1990, Nakagawa et al., 1994). Generally, orthodontic treatment takes place during adolescence, as was the case in our study. During this period, the human body experiences many (e.g. behavioral and hormonal) changes (Vetter-O’Hagen and Spear, 2012).

The exact reason why gingivitis becomes prevalent in this age-group is unclear but hormonal changes are likely to play a part. Our study did not include a control group of adolescents that did not receive orthodontic treatment. Therefore it is difficult to discern which microbial changes are related to the orthodontic treatment, and which ones to the onset of puberty. Thus far, most studies regarding the (changes in the) oral microbiome during adolescence or orthodontic treatment have focused on a limited number of bacteria, due to the nature of their techniques.
The use of an open-ended molecular approach allowed us to detect Candidate division TM7 (and OTUs 55, 171, 355) (fig. S3b and fig. S5d-f). Next-generation sequencing has demonstrated that these bacteria, of which only recently a member was grown as a pure laboratory culture (Soro et al., 2014), are widespread in the human oral cavity (He et al., 2015). Crielaard et al. (Crielaard et al., 2011) reported that Candidate division TM7 increased with advancing age, in a study regarding children aged 3-18 years. Duran-Pinedo et al. (Duran-Pinedo et al., 2014) presumed a role for Candidate division TM7 in periodontitis. We found Candidate division TM7 to be associated with gingivitis, in accordance with Huang et al. (Huang et al., 2011).

Interestingly, we observed the presence of the genus Derxia (fig. S4d), although low in abundance in our study population, to be related to a healthy state of the gingiva. Members of this genus are known to fix nitrogen in different environmental habitats (John et al., 2011, Chen et al., 2013). Recently Derxia has been observed as a member of the human (and canine) oral cavity (Hu et al., 2013, Sturgeon et al., 2013, Jiang et al., 2014), yet its role in this particular environment remains to be elucidated.

Well-known inhabitants of the oral cavity are members of the genus Prevotella; often associated with an unhealthy state of the periodontium (Nadkarni et al., 2012). Moreover, an increase of Prevotella intermedia has been associated with orthodontic treatment (Ristic et al., 2007, van Gastel et al., 2011, Kim et al., 2012). In addition, van Gastel et al. (van Gastel et al., 2011) observed a decrease of P. intermedia after the removal of the orthodontic appliances. This coincides with our finding of the abundance of the genus Prevotella (fig. S7h). Hence, there appears to be an association between orthodontic treatment and the prevalence of Prevotella, although Choi et al. (Choi et al., 2009) did not find a significant decrease of Prevotella after orthodontic treatment was ended. This discrepancy might be due to difference in sampling sites or detection techniques.

In this study, we found that the genus Actinomyces increased with time (fig. S7c), while OTU28 (Actinomyces naeslundii) increased mainly after debonding (fig. S8a). According to Delaney et al. (Delaney et al., 1986) the levels of A. naeslundii are higher in prepubertal subjects compared to postpubertal subjects. Gusberti et al. (Gusberti et al., 1990) observed that the levels of the species Actinomyces odontolyticus elevate during puberty. Tanner et al. (Tanner et al., 2012) found Actinomyces sp. to be associated with gingivitis, whereas Tsuruda et al. (Tsuruda et al., 1995) observed a relation between Actinomyces species and healthy pubertal children. These diverse findings indicate that the role of Actinomyces in the oral microbiome cannot be determined on genus level, yet it does not explain the contradictory findings of the study by Delaney et al. (Delaney et al., 1986) and our own results. Although sampling site and used technique might again be of influence.

The genus Veillonella had previously been shown to increase during adolescence (Moore et al., 1993, Crielard et al., 2011). In this study population however, the abundance of Veillonella remained stable throughout time (fig. S7d). In addition, the abundance of Veillonella
was not significantly different between the two mouthwash groups or between the healthy and gingivitis groups.

Both the genus *Campylobacter* (fig. S7g) and OTU151 (*Campylobacter gracilis*) (fig. S8f) decreased with time. A similar pattern of decrease has been observed for *Campylobacter rectus* (Choi et al., 2009, Thornberg et al., 2009, Kim et al., 2012). This decrease could be explained primarily by the reduction of retention sites due to the alignment of the teeth and secondly by the removal of the orthodontic fixed appliances, causing an additional loss of retention sites.

A similar decrease in time was observed for the genera *Porphyromonas* (fig. S7e) and *Selenomonas* (fig. S7j). Additionally, we found that *Porphyromonas* (fig. S4b), *Selenomonas* (fig. S4a) and OTU302 (*Selenomonas*) (fig. S5g) were associated with gingivitis. Members of both these genera are among the main periodontal pathogens (Huang et al., 2011, Mysak et al., 2014). Therefore their decrease in time might be considered desirable. Why they decrease in time, if it is e.g. the reduction in retention sites through alignment of the teeth or hormonal changes in the host, remains unclear.

*Neisseria* became lower in abundance during the advancement of the visits (fig. S7b), in agreement with Moore et al. (Moore et al., 1993), who found this genus to be more associated with prepubertal children than older children. Thus far, most studies investigating the oral microbiome during orthodontic treatment or puberty did not target members of the genus *Neisseria*. Nonetheless, Tanner et al. (Tanner et al., 2012) found *Neisseria elongata* to be associated with reduced gingivitis in orthodontic patients. They made the same observation for *Fusobacterium periodonticum*.

Tsuruda et al. (Tsuruda et al., 1995) found *Fusobacterium* sp. to be more abundant in pubertal children with gingivitis compared to healthy children. *Fusobacterium nucleatum* is regarded as a bridging organism in the formation of dental biofilms (Wright et al., 2013). This might explain our observation that the genus *Fusobacterium* decreases during the orthodontic treatment, yet increases again in time (fig. S7k). The additional retention sites created by the brackets leave *Fusobacterium* superfluous in the formation of biofilms. On the other hand, Wojcicki et al. (Wojcicki et al., 1987) found that *Fusobacterium* sp. was lower in their circumpubertal group compared to a younger and older test group, suggesting that the presence of *Fusobacterium* sp. is influenced by the physiological maturity of the host.

In contrast to *Fusobacterium*, the abundance of the genus *Streptococcus* (fig. S7a) and OTU351 (*Streptococcus*) (fig. S8c) showed an increase in time without decreasing first. Increase in *Streptococcus* abundance in puberty has been observed before (Moore et al., 1993), although we cannot identify this member of the genus *Streptococcus* on species level, we speculate that it is associated with a healthy state of the gingiva.

*Haemophilus* (fig. S4e), *Rothia* (fig. S4f) and OTU65 (*Rothia*) (fig. S5a) were associated with a healthy state of the gingiva as well. Their increase after debonding appeared to
coincide with the decrease in gingivitis after debonding (fig. 2). Members of these two genera were usually not included as target microorganisms in studies of the oral microbiome during puberty or orthodontic treatment. Although the role of *Haemophilus* in health and disease of the oral cavity remains somewhat ambiguous, *Rothia* is generally associated with health (Zaura *et al.*, 2009, Fujinaka *et al.*, 2013).

In conclusion, the effects of the fluoride mouthwash on the adolescent microbiome were indiscernible and promoted neither health nor disease associated bacterial growth. Yet, van der Kaaij *et al.* (van der Kaaij *et al.*, 2015) did observe fewer demineralizations in subjects using the fluoride mouthwash compared to those using the placebo. Thus, the use of a fluoride mouthwash during orthodontic treatment might be beneficial for the health status of the oral cavity.

Nevertheless, we did observe changes in the abundance of various bacteria. In general, the bacteria that were associated with periodontal pathogenesis decreased in abundance in time, while the abundance of the health related bacteria increased, suggesting that orthodontic treatment during puberty does not have a lasting negative effect on the gingival health status. Still, the lack of an age-related control group not receiving orthodontic treatment precludes us from making a clear distinction between microbial changes instigated by puberty and the effects on the oral ecology caused by orthodontic treatment with fixed appliances. A future study including such a control group would be necessary to determine which microbial changes are truly caused by the presence of orthodontic appliances, allowing for the maintenance of a healthy oral microbiome during orthodontic treatment.
REFERENCES


CHAPTER 3


Orthodontic treatment and the oral microbiome


SUPPLEMENTARY MATERIAL

**Figure S1.** Difference in abundance of the genus *Fusobacterium* between mouthwash groups per visit. The read count is displayed on the y-axis. Mouthwashes were administered between visits T0 and TD. Statistical significance ($p < 0.05$) was determined using the Mann-Whitney test between the two groups per visit, or the Wilcoxon Signed Ranks test within the same group between different visits. The boxes represent the median and interquartile range (IQR), the whiskers represent the minimum and maximum values. Outliers more than 1.5x IQR are depicted by ○, and more than 3x IQR by *.

**Figure S2.** Difference in abundance of OTU381 (*Kingella*) between mouthwash groups per visit. The read count is displayed on the y-axis. Mouthwashes were administered between visits T0 and TD. Statistical significance ($p < 0.05$) was determined using the Mann-Whitney test between the two groups per visit, or the Wilcoxon Signed Ranks test within the same group between different visits. The boxes represent the median and IQR, the whiskers represent the minimum and maximum values. Outliers more than 1.5x IQR are depicted by ○, and more than 3x IQR by *.
Figure S3. Difference in abundance of the phyla Bacteroidetes (a), TM7 (b) and Fusobacterium (c) based on gingival health status per visit. The read count is displayed on the y-axis. Statistical significance (p < 0.05) was determined using the Mann-Whitney test. The boxes represent the median and IQR, the whiskers represent the minimum and maximum values. Outliers more than 1.5x IQR are depicted by o, and more than 3x IQR by *.
Orthodontic treatment and the oral microbiome

Figure S4. Difference in abundance of the genera *Selenomonas* (a), *Porphyromonas* (b), *Johnsonella* (c), *Derxia* (d), *Haemophilus* (e) and *Rothia* (f) based on gingival health status per visit. The read count is displayed on the y-axis. Statistical significance ($p < 0.05$) was determined using the Mann-Whitney test. The boxes represent the median and IQR, the whiskers represent the minimum and maximum values. Outliers more than 1.5x IQR are depicted by ○, and more than 3x IQR by *. 

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$p = 0.036$ $p = 0.010$ $p = 0.033$

$p = 0.042$ $p = 0.013$ $p = 0.004$

$p = 0.046$ $p = 0.028$ $p = 0.004$

$p = 0.021$ $p = 0.024$ $p = 0.004$
Figure S5. Difference in OTU abundance based on gingival health status per visit. The read count is displayed on the y-axis. Statistical significance ($p < 0.05$) was determined using the Mann-Whitney test. The boxes represent the median and IQR, the whiskers represent the minimum and maximum values. Outliers more than 1.5x IQR are depicted by o, and more than 3x IQR by *.
Figure S6. Difference in phylum abundance between visits for Actinobacteria (a), Firmicutes (b), Bacteroidetes (c), TM7 (d), Fusobacteria (e) and Proteobacteria (f). The read count is displayed on the y-axis. Statistical significance ($p < 0.05$) was determined using the Wilcoxon Signed Ranks test. The boxes represent the median and IQR, the whiskers represent the minimum and maximum values. Outliers more than 1.5x IQR are depicted by ◦, and more than 3x IQR by *.
Figure S7. Difference in genus abundance between visits. The read count is displayed on the y-axis. Statistical significance ($p < 0.05$) was determined using the Wilcoxon Signed Ranks test. The boxes represent the median and IQR, the whiskers represent the minimum and maximum values. Outliers more than 1.5x IQR are depicted by $\circ$, and more than 3x IQR by $\ast$. 
Figure S7. (continued) Difference in genus abundance between visits. The read count is displayed on the y-axis. Statistical significance ($p < 0.05$) was determined using the Wilcoxon Signed Ranks test. The boxes represent the median and IQR, the whiskers represent the minimum and maximum values. Outliers more than 1.5x IQR are depicted by ○, and more than 3x IQR by *.
Figure S8. Difference in OTU abundance between visits. The read count is displayed on the y-axis. Statistical significance ($p < 0.05$) was determined using the Wilcoxon Signed Ranks test. The boxes represent the median and IQR, the whiskers represent the minimum and maximum values. Outliers more than 1.5x IQR are depicted by ○, and more than 3x IQR by *.
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The BLAST results were retrieved on 13 November 2014. Sequences were aligned against the Nucleotide collection (nr/nt) using Megablast. Uncultured or environmental samples were excluded from the search results.
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