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1 **Polymicrobial oral biofilm models: simplifying the complex**

2

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18 **Key words:** Biofilms, dental plaque, oral microbiology, host-pathogen interactions

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1 **Abstract**

2 Over the past century, numerous studies have used oral biofilm models to investigate
3 growth kinetics, biofilm formation, structure and composition, antimicrobial
4 susceptibility and host-pathogen interactions. *In vivo* animal models provide useful
5 models of some oral diseases; however, these are expensive and carry vast ethical
6 implications. Oral biofilms grown or maintained *in vitro* offer a useful platform for
7 certain studies and have the advantages of low cost of establishing such models, as
8 well being easy to reproduce and manipulate. In addition, a wide range of variables
9 can be monitored and adjusted to mimic the dynamic environmental changes at
10 different sites in the oral cavity, such as pH, temperature, salivary and gingival
11 crevicular fluid flow rates, or microbial composition. This review provides a detailed
12 insight for early-career oral science researchers into how biofilm models used in oral
13 research have progressed and improved over the years, their advantages and
14 disadvantages, and how such systems have contributed to our current understanding
15 of oral disease pathogenesis and aetiology.

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1 Introduction

2 Polymicrobial oral biofilms consist of many bacterial and fungal species.
3 Approximately 700 bacterial species or phylotypes (1) and more than 100 fungal
4 species (2) have been identified in the oral cavity. It is estimated that overall species
5 numbers may well exceed 1000, although many of these are uncultivated (3). There
6 is significant diversity in the oral microbiome, varying greatly from person to person.
7 For example, only 100-200 microbial species are thought to be found in the oral cavity
8 of any given individual (4). Despite this diversity, the concept of microbial “complexes”
9 of microorganisms has emerged, which demonstrates a shift in biofilm colonisation
10 from health to disease, such as in the development of periodontal diseases (5, 6). Our
11 understanding of how dental plaque composition relates to oral health and disease
12 have also changed over time. For example, hypotheses such as the “non-specific
13 plaque hypothesis” (7) “specific plaque hypothesis” (8), “ecological plaque hypothesis”
14 (9) and “keystone pathogen hypothesis” (10) were all developed over the past 50
15 years. Throughout time, these hypotheses have set the foundations of future oral
16 microbiological research, ultimately contributing to our current understanding of the
17 complex nature behind microbial disease onset and progression in the oral cavity.
18 Recently, OMICs approaches (e.g., genomics, transcriptomics, proteomics and
19 metabolomics) have enhanced our understanding of microbial interactions in the oral
20 cavity, and it is now possible to identify all microbial species that colonise our mouths
21 (3, 11). The OMICs platforms provide the power to investigate complex systems in
22 unprecedented detail, and these have been used to examine biofilms in human
23 diseases and in animal models of disease. Nonetheless, *in vitro* biofilm models provide
24 useful systems for oral microbiologists and immunologists. In the following sections
25 we will discuss how oral biofilm models have advanced over the past century and

1 appraise their value in understanding the pathophysiology of oral disease throughout
2 each era.

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4

5 **The initial discoveries in oral microbiology – “*the pioneers*”**

6 Over three centuries ago, Antoni van Leeuwenhoek was the first to observe that
7 bacteria resided in the oral cavity. His descriptions of the ‘white matter between teeth’
8 (now known as ‘dental plaque’) and hand-drawn pictures of plaque observed through
9 a homemade light microscope were later found to likely represent *Streptococcus*
10 chains, rod-shaped *Actinomyces* and *Fusobacteria*, and spiralling forms of
11 spirochetes. However, it would not be until the late 19th and early 20th century that
12 scientific research would begin to truly increase our knowledge of the microorganisms
13 that colonise the oral cavity. In 1952, Pigman et al (12) proposed that Magitot was the
14 first to conceive the early ideas for *in vitro* oral microbiology work as far back as 1878,
15 which involved the simple process of incubating extracted teeth in culture media. At a
16 similar time, Black and Miller postulated that accumulation of bacteria in dental plaque
17 facilitated pathogenicity (13, 14), which has now been superseded by modern-day
18 hypotheses e.g., the ecological plaque and keystone pathogen hypothesis. This early
19 work collectively resulted in the identification of cariogenic *Streptococcus* species,
20 including *Streptococcus mutans*, which was named by Clarke in 1924 and later found
21 to play an aetiological role in experimental caries in 1960 by Fitzgerald and Keyes
22 (15). These studies led to an increase in the number of researchers investigating oral
23 bacterial interactions *in vitro*.

24

25

1 **A foundation for *in vitro* plaque research - “*the early colonisers*”**

2 Following further confirmation of the causal link between cariogenic streptococci and
3 dental caries during the 1960s (16-18), oral microbiologists took a reductionist
4 approach and turned to assessing the nutritional requirements, culture conditions and
5 plaque forming-capabilities of *S. mutans* and other cariogenic bacteria (19-24).
6 However, most of this work was limited to the use of bacterial culture in planktonic
7 suspension, which we now know does not reflect the true conditions observed in the
8 oral cavity. Such investigations on *S. mutans* led to the development of the “specific
9 plaque hypothesis” by Loesche (8), who proposed that *S. mutans* along with other
10 *Streptococcus* and *Lactobacillus* species were specific pathogens responsible for
11 dental caries. As with most microbial-induced diseases, the search was then on for
12 identifying a ‘gold-standard’ active compound that could target specific pathogens in
13 the oral cavity. In 1970, Gjermo et al (25) was one of the first to assess the
14 antimicrobial effects of multiple compounds on plaque samples formed *in vivo* and *in*
15 *vitro*. One of the compounds tested, chlorhexidine gluconate (CHX), is now the main
16 component of many commercial mouthwashes. Other studies subsequently showed
17 that CHX was a broad-spectrum anti-septic against most oral microorganisms (26, 27).
18 Unfortunately, due to limitations in microbiological techniques, much of the work at the
19 time was restricted to utilising undefined plaque samples with unknown composition,
20 meaning reproducibility was low, or largely unachievable. An improvement in culture-
21 based methods in the 1970s, including the development of anaerobic jars and
22 cabinets, expanded the breadth of *in vitro* research. The ability to grow strict
23 anaerobes led to the identification of pathogens associated with PD. Consequently, a
24 range of anaerobic bacteria such as *Bacteroides gingivalis* (now known as
25 *Porphyromonas gingivalis*) were isolated from PD lesions (28). Research throughout

1 this period concentrated on producing robust methods for isolating and cultivating
2 anaerobic bacteria from plaque (29, 30). As a result, the “non-specific plaque
3 hypothesis” and “specific plaque hypothesis” were adjusted to take into account
4 specific anaerobic pathogens associated with PD (7, 31).

5

6 An advancement in microscopic techniques also meant that *in vitro* oral research
7 began to flourish throughout the 1970s. The first scanning electron microscope (SEM)
8 and transmission electron microscope (TEM) were made commercially available
9 during this time, meaning that the morphology and architecture of individual colonies
10 and cell aggregates in plaque could be imaged. Publications by Sudo and colleagues
11 (32, 33) described the development of a model to assess continuous culture of saliva
12 samples on substrates of glass beads coated with hydroxyapatite (HA) to mimic the
13 tooth surface. SEM images provided evidence of bacterial colonization on the HA-
14 coated beads with distinct cell-cell interactions between different bacterial species
15 (33). Others followed suit with multiple studies reporting the use of SEM and TEM
16 technology to image plaque formed both *in vivo* and *in vitro* (34-36). It was arguably
17 the combination of culture-based methods and microscopy at the time that helped us
18 to understand the complex polymicrobial interactions between different species in
19 plaque. Accordingly, it was at a similar time that the phrase “biofilm” was initially coined
20 by Costerton in 1978 (37), a term that is now synonymous with oral microbiology.

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1 **Bridging the gap with chemostat models – “*the intermediate***
2 ***colonisers*”**

3 Multiple research groups reacted to this new way of considering oral microbial plaque
4 and started to utilise continuous cultures to generate “biofilms” under appropriate
5 controlled conditions (e.g., under shear force and constant flow). This technique, which
6 utilises a chemostat flow system, allows for the growth of planktonic cultures and
7 biofilms through a regular supply of fresh medium, continuously pumped through the
8 system, with spent growth medium being removed at a similar rate (Figure 1A). The
9 idea of the chemostat was first described in 1950 as a method to culture a bacterial
10 population at a reduced growth rate (38, 39). Continuous culture models were
11 revolutionary for oral biofilm research although most early work using the technology
12 was restricted to planktonic mono- or mixed-cultures. Throughout the 1970s, the
13 metabolic and enzymatic activity of cariogenic microorganisms were assessed
14 following growth in chemostat systems pumped with different carbohydrates such as
15 sucrose, fructose and glucose (33, 40-42). However, it was undoubtedly the
16 pioneering work of Marsh who instigated the use of the chemostat in oral microbiology,
17 driving the field forward during the 1980s. His early chemostat work was limited and
18 was used to measure the growth rate of 1-2 bacterial species or undefined plaque
19 samples in nutrient-excess or limited media (43, 44). However, later in the decade,
20 defined mixed-species containing a more complex consortium of anaerobic
21 microorganisms such as *Fusobacteria*, *Actinomyces*, *Veillonella*, *Neisseria* and
22 *Bacteroides* species were introduced into chemostat systems under standardised
23 conditions. Whilst reductionist in nature, these studies were some of the first to piece
24 together interactions between different species which relatively reflected *in vivo*
25 plaque, and subsequently led to the formulation of the “ecological plaque hypothesis”

1 (9). Of note at the time, the works of McKee et al (45), McDermid et al (46) and
2 Bradshaw et al (47) all demonstrated that mixed-species cultures were influenced by
3 carbohydrate availability, and subsequent shifts in pH. In these studies, cultures were
4 pulsed with carbohydrate-rich media resulting in the generation of an acidic
5 environment (following carbohydrate fermentation by cariogenic microorganisms),
6 before the pH was adjusted back to neutral. This technique ultimately replicates the
7 environment of the oral cavity after a consumption of a carbohydrate-rich meal, but
8 also accounts for the return to a relatively neutral pH between meals. Additionally, as
9 the pH at certain oral sites may be slightly alkaline (48, 49), chemostats provided an
10 excellent platform for growing mixed-species biofilms in a highly controlled manner, in
11 environments that closely mimic different sites of the oral cavity.

12

13 By the late 1980s and early 1990s, chemostat systems were utilised for biofilm growth,
14 as well as assessing the impact of nutrient availability on plaque composition and in
15 antimicrobial susceptibility biofilm testing (50-53). These flow-through models allowed
16 for minimum inhibitory concentration (MIC) testing of anti-microbials such as triclosan,
17 CHX, xylitol and fluoride against mixed-species biofilms. An advantage being that the
18 compounds could be pulsed through the system using MIC or sub-MIC levels, or
19 dosed appropriately to give a constant final concentration. This meant that the effects
20 of such compounds could be assessed either directly on bacterial species, or
21 indirectly, if inhibition of one species impacting on the growth of another, thus altering
22 the homeostasis of the biofilm. In 1991, Marsh and colleagues (54) showed that *S.*
23 *mutans*, *Lactobacillus casei* and *Veillonella dispar* (carbohydrate-fermenting, acid-
24 tolerant bacterial species) predominate a mixed-species biofilm in environments of
25 carbohydrate excess, and subsequent acidic pH, whilst treatment with sodium fluoride

1 reduced the acid production, stabilising the biofilm and allowing other bacterial species
2 to flourish. Similar mechanisms were proposed for pathogens associated with PD, with
3 Bradshaw and colleagues demonstrating that anaerobic bacteria such as
4 *Fusobacterium nucleatum* and *P. gingivalis* could only survive aerobic environments
5 when grown in communities containing oxygen-consuming bacteria (55-57). It was
6 around this time that Marsh proposed the “ecological plaque hypothesis”, which
7 assumed that an imbalance in the composition of the oral biofilm due to environmental
8 factors (carbohydrate accessibility and pH in dental caries), and nutrient availability
9 (oxygen levels and redox potential in PD) can result in the enrichment of disease-
10 associated pathogens (9). Although chemostats do have evident disadvantages e.g.,
11 high risk of contamination and low throughput, the use of such systems provided an
12 opportunity to mimic *in vivo* environments with higher accuracy than previously
13 developed models.

14
15 Throughout the 1990s, the concept of chemostat flow was utilised and adapted for
16 other continuous culture systems. A constant depth film fermenter (CDFF) used the
17 principle of chemostat flow to reproducibly grow a large mass of biofilm with defined
18 thickness for imaging, antimicrobial testing and inter-species transfer of drug
19 resistance genes (58-61). Flow cells, which are slides containing suitable substrata
20 such as HA, were also introduced into chemostat systems to assess biofilm formation
21 and allow for microscopic imaging of the biofilm development. In 1994, Herles and
22 colleagues (62) utilised a chemostat-flow cell system to study the effects of different
23 anti-plaque agents on biofilms formed on flow cells. Their work qualitatively showed
24 that multi-species biofilms formed *in vitro* were susceptible to triclosan-containing
25 mouth-rinse, whilst untreated biofilms remained largely viable. Interestingly, at a

1 similar time, Singleton et al (63) combined flow cell technology with fluorescence
2 microscopy to map spatial distribution of bacterial species within plaque using
3 mathematical modelling. Others have used flow-cell systems in conjunction with
4 fluorescence microscopy for imaging interactions between organisms (64-66). Cook,
5 Costerton & Lamont (64) were the first to show that *Streptococcus gordonii* forms an
6 attachment substratum on saliva-coated flow-cell coverslips for *P. gingivalis* using
7 confocal laser scanning electron microscopy (CLSM). Thus, fluorescence microscopy
8 highlighted key microbial interactions like never before.

9

10 **Maturation of modern-day models – “*the late colonisers*”**

11 ***Microbiological models – from plaque to plate***

12 Static biofilm models became important systems in the field of oral microbiology during
13 the 1990s. These models exploited a relatively simple method of producing biofilms to
14 perform high-throughput antimicrobial susceptibility testing and phenotypic screening
15 of mutant libraries to assess the importance of certain genes in biofilm formation (67-
16 69). Oral biofilms were grown on either plastic, glass, HA coated-substrates, directly
17 in the bottom of different sized microtiter plates, or on inverted pegs placed into specific
18 media with inoculum (Figure 1B). The latter method known as the Calgary Biofilm
19 Device (CBD) or minimum biofilm eradication concentration (MBEC) assay was first
20 described by Ceri et al in 1999 (70). The CBD method remains used to this day,
21 particularly for antimicrobial testing on undefined plaque samples cultured *in vitro* on
22 inverted pegs (71-73). One major advantage of these static models is that multi-
23 species biofilms can be grown in large quantities, an improvement of chemostat flow
24 systems which were restricted to producing no more than a few biofilms at any given
25 time. In the present day, modern high-throughput techniques for oral biofilm cultivation

1 have been developed, e.g., microfluidics for miniaturising biofilm culture and
2 characterisation (74-76) and impedance-based technology for real time monitoring of
3 biofilm growth (77) (Figure 1C). However, these new techniques are expensive and
4 therefore batch methods for growing biofilms in microtiter plates are arguably the
5 preferred choice for the majority of research groups given the cost attached to
6 generating such models. Additionally, these high-throughput approaches serve as
7 ideal models employed by industry, which seek robust, minimalistic biofilm platforms
8 that can be used as definitive test-beds for standardised biofilm testing (78, 79).
9 Advantages and disadvantages of the continuous flow models, static biofilm systems
10 and current high-throughput modern-day options utilising new technology are
11 discussed in greater depth in Table 1.

12

13 From the turn of the millennium, many research groups began to utilise high-
14 throughput static systems to develop their own multi-species biofilms from a defined
15 number of microorganisms (Table 2). The increase in commercially available real-time
16 quantitative polymerase chain reaction (RT-qPCR) machines in the early 2000s made
17 this possible, meaning oral biofilm models could be grown to precise composition.
18 Previously, compositional analysis was largely restricted to using selective and
19 differential media for identification of different microbial species grown in multi-species
20 biofilms. Currently, the use of genus- or species-specific primers in conjunction with
21 microscopic technology means that biofilms can be repeatedly grown with
22 reproducible composition and architecture (Figure 2A) (80). In addition, it is now
23 possible to discriminate between viable or dead microbial species in biofilms using
24 RT-qPCR methods. In 2011, Loozen et al (81) described a protocol using a DNA
25 intercalating substance called propidium monoazide to identify the proportion of dead

1 *S. mutans*, *Prevotella intermedia* and *Aggregatibacter actinomycetemcomitans* cells
2 in heat-killed mono-cultures. Since development, this method has become an
3 important tool in assessing the effectiveness of antimicrobials and other actives on
4 oral biofilms (82, 83)

5

6 ***Immunology based models – the host-biofilm interface***

7 In the last two decades, oral immunologists have started to utilise these defined multi-
8 species biofilms to identify mechanisms involved in oral disease pathogenesis and
9 aetiology. As such, co-culture mammalian cell-biofilm models are now frequently used
10 in oral health and disease research (Figure 2B). Co-culture models have been
11 described using primary and immortalised cell lines (e.g., immune cells including T
12 cells, B cells, neutrophils and monocytes, primary human oral or gingival epithelial
13 cells and immortalised cell lines such as OKF4, OKF6/TERT2 or TR146) and multi-
14 layered tissues (e.g., in-house 3D tissue models containing keratinocytes and
15 fibroblasts or commercially available organotypic tissue). Results from multiple
16 research groups have shown that cell viability and immune response in orally relevant
17 cell lines or tissues can vary depending on biofilm complexity, composition and viability
18 (84-86). These studies have demonstrated that commensal and pathogenic microbial
19 species differentially modulate the epithelial immune response. For example, oral
20 epithelial cells challenged with biofilms containing only commensal, health-associated
21 microorganisms result in a minimal pro-inflammatory response, whilst biofilms
22 comprised of disease-associated pathogens can induce an elevated pro-inflammatory
23 gene- and protein- signature and induce cytotoxicity. It was *in vitro* co-culture research
24 that showed planktonic *P. gingivalis* can invade oral epithelial cells and impair cytokine
25 production (87-89). For example, interleukin-8 (IL-8) production is diminished by a

1 serine phosphatase and degraded by the cysteine proteases called gingipains
2 produced by *P. gingivalis* (90, 91). Others have shown that oral epithelial cells co-
3 cultured with *P. gingivalis*-containing biofilms result in reduced IL-8 protein detection
4 in spent cell supernatants (85, 92). Cytokine degradation may explain the “local
5 chemokine paralysis” by which *P. gingivalis* delays the recruitment of neutrophils to
6 the gingival tissue, impairing the mucosal defence to the pathogen *in vivo*, and
7 ultimately evading the immune system (87). The plethora of oral biofilm and cell co-
8 culture models now available means that it is possible to investigate the mechanistic
9 pathways that oral pathogens (and commensals) utilise to facilitate inflammation in a
10 highly controlled manner *in vitro*. Despite their simplicity, these *in vitro* studies provide
11 a strong foundation for on-going *in vivo* research.

12

13 ***Imaging biofilms – Spying on the community***

14 Microscopy techniques have advanced in recent years; light, fluorescent and electron
15 microscopic technology are now common methodologies for imaging oral biofilms in
16 most laboratories (Figure 2C). In addition, these methods, in particularly fluorescent
17 microscopy, have been adapted for more unique investigations in oral biofilm
18 research. For example, an interesting technique described by Schlafer et al (93)
19 utilising a ratiometric pH-sensitive dye called C-SNARF-4 has been applied to oral
20 biofilms to monitor changes in pH in the biofilm landscape. A five-species early dental
21 plaque biofilm containing four *Streptococcus* species and *A. naeslundii* was grown in
22 the presence and absence of artificial saliva containing 0.4% glucose, and pH
23 gradients in the extracellular matrix monitored fluorescently. Regions within the biofilm
24 with higher cell density correlated with lower pH values (93).

1 Fluorescent *in situ* hybridization (FISH), a technique allowing for sensitive identification
2 of target microorganisms within complex microbial communities, has been used in
3 imaging of oral biofilms, sampled directly from volunteers, or grown *in vitro*. Thurnheer,
4 Gmur and Guggenheim (2004) were the first to combine FISH and CLSM to stain six
5 species of bacteria and fungi within *in vitro*-grown oral biofilms (94). All six microbial
6 species were identified using fluorescently labelled 16S or 18S rRNA-targeted
7 oligonucleotides, with biofilms containing *S. oralis*, *Streptococcus sobrinus*, *Veillonella*
8 *dispar*, *F. nucleatum*, *Actinomyces naeslundii* and *Candida albicans* visualised from
9 two experiments (e.g., two independent triple-hybridisations using three different
10 fluorescent probes). Other publications have used similar methods to show localisation
11 of different bacterial species in mixed-species biofilms using multiple independent
12 hybridisations (80, 95). A publication by Kommerein et al (2017) effectively showed
13 the development of a robust four-species biofilm model with highly reproducible
14 biomass and architecture as assessed by FISH (80). It is now possible to use
15 additional combinations of fluorophores to identify tens of bacterial species in dental
16 plaque. A publication by Valm (96) elegantly described an “proof of concept” imaging
17 technique which combines fluorescent labelling coupled with spectral image
18 acquisition and analysis to identify 15 different oral taxa in dispersed dental plaque.
19 The technology, which is known as Combinatorial Labelling and Spectral Imaging
20 (CLASI-FISH), has scope to distinguish between 120 different fluorescently-labelled
21 microorganisms in a single image (97). In 2016, Mark-Welch et al (98) used CLASI-
22 FISH to visualise the “biogeography of the human oral microbiome” in intact dental
23 plaque. The study utilised a nine- and ten-probe set of fluorescently labelled probes to
24 demonstrate that oral biofilms formed unique ‘hedgehog-like’ structures predominated
25 by *Corynebacterium* filaments that provide a “scaffold” for other microorganisms such

1 as *Streptococcus* and *Porphyromonas* species. To date, no studies have investigated
2 the feasibility of identifying over 100 microorganisms in dental plaque using CLASI-
3 FISH, nor have any studies applied the technology to oral biofilms grown *in vitro*.
4 However, it would be of great importance to assess whether microbial interactions in
5 laboratory-grown polymicrobial biofilms recapitulate such complex spatial
6 organisations in plaque formed *in vivo*.

7

8 **Spreading into other technologies – “*biofilm dissemination*”**

9 Throughout the last 20 years, the use of high throughput technologies has become
10 routine to support biological discoveries and drive hypotheses. OMICs approaches
11 have enabled researchers to view the genomics, transcripts, metabolites and proteins
12 of oral biofilm models in a “holistic” manner.

13

14 Microbiome analysis by shotgun sequencing or 16S amplicon sequencing has become
15 one of the most widely used technologies and bioinformatic techniques in the
16 microbiologist’s toolbox. Within the last 10 years there has been an increase in
17 microbiome studies due to the cost of the sequencing technologies decreasing and
18 the availability of analysis pipelines and packages increasing (99-101). The
19 microbiome has been studied in caries, PD, denture stomatitis, peri-implantitis among
20 several other oral diseases (102-105). These studies have allowed for the greater in-
21 depth characterisation of distinct microbial community shifts within the oral cavity, also
22 accounting for uncultivated organisms. Large-scale molecular techniques such as
23 microbiome sequencing have allowed for the identification of species, as well as
24 species-species interactions and environment-species interactions previously
25 undeterminable with conventional techniques. In periodontitis, such techniques have

1 uncovered unique characteristics exhibited by the sub-gingival plaque biofilm in health
2 and disease. For example, Abusleme *et al.*, (106) highlighted that in contrast to
3 infections occurring in other sites of the body where diversity has been shown to
4 decrease during active disease, in periodontitis, the diversity of sub-gingival plaque
5 significantly increases in relation to health. Similarly, analysis of the sub gingival
6 plaque microbiome has revealed that disease associated organisms may extend far
7 beyond the previously identified 'Red-complex'. Of note, organisms such as *Filifactor*
8 *alocis* and *Prevotella denticola* have been consistently found to be higher in diseased
9 sites (107-109). Together, such analysis has led to the re-evaluation of individual
10 pathogens driving a disease state, and it is now hypothesised that "ecotypes" and/or
11 whole microbial communities may drive dysbiosis and pathogenesis (110, 111).

12

13 The sequencing of messenger RNA for studying transcriptomics is a powerful tool to
14 gain insight into how an organism is reacting to and adapted to its environment. This
15 can give us clues and hypotheses about how microorganisms interact in a complex
16 biofilm environment. For example, the use of RNA-Seq has helped in our
17 understanding of species-species adhesion and virulence mechanisms between *C.*
18 *albicans* and *P. gingivalis* (112), and synergistic relationships in *C. albicans* and *S.*
19 *mutans* biofilms (113). Transcriptomic studies have also been indispensable in
20 understanding disease pathogenesis, drug resistance mechanisms and community
21 dynamics with regard to oral biofilm research in recent years (114, 115). In a study by
22 Frias-Lopez et al (114), it was shown that incorporation of periodontal pathogens (e.g.,
23 *P. gingivalis*) into biofilms containing commensal species can alter patterns in gene
24 expression in the healthy oral community.

25

1 Similarly, Mass Spectrometry (MS) and Nuclear Magnetic Resonance (NMR) have
2 allowed for snapshot profiling of metabolic and protein expression for the identification
3 of signatures in oral biofilms. Metabolomics enables the identification and relative
4 quantification of all the metabolites in a biological system. Metabolomic pathways and
5 biofilm regulatory mechanisms are discernible with these technologies (116). They
6 offer the potential to identify signatures associated with disease progression. This was
7 highlighted in a 2015 pilot study which validated the use of metabolomics by Gas
8 Chromatography–MS in identifying metabolic profiles between cariogenic and
9 disease-free oral biofilms (117). Advancements have also been made in oral microbial
10 studies which allow for the correlation of the metabolome with shifts in the oral
11 microbiome (110). These studies further our understanding of bacterial communities
12 with different ecological states with more specialised function, which the authors of the
13 2017 study (110) suggest could highlight specific metabolic function of communities
14 which could indicate dysbiosis. In the coming years, it is likely that the use of OMICs
15 approaches in investigating microbial-host interactions will continue to grow. It is
16 important that these techniques should be utilised in conjunction with laboratory
17 science, in order to identify mechanistic pathways by which oral pathogens facilitate
18 disease onset and progression.

19

20 **Conclusion**

21 We have highlighted in this review how our understanding of oral microbiology at any
22 given time has resulted in relevant robust biofilm models, often simple to start with, but
23 developing complexity over time. On the contrary, *in vitro* biofilm models have also
24 enhanced our knowledge of the simple and complex microbial interactions in the oral
25 cavity. Recent OMICs analyses imply that no oral biofilm model is ideal, and that it is

1 simply impossible to replicate exact microbial-microbial or microbial-host interactions
2 *in vitro*. Nonetheless, understanding how a few organisms interact together in biofilms,
3 and with host immunity, aids our view of microbial and host dynamic interactions. We
4 should not lose sight of the importance of hypothesis-driven research when creating
5 or using these models, and not simply rely on 'big data' to shape our ideas and become
6 more speculative in our outlook. As with all approaches, OMICs techniques are not
7 devoid of disadvantages. Whilst offering powerful platforms to investigate a large
8 number of variables simultaneously, issues persist over poor reproducibility and
9 statistical bias. As such, there remains a requirement for such approaches to be
10 supplemented with accessible and reproducible *in vitro* assays. In the future,
11 combining results from OMICs studies, *in vivo* animal models, and *in vitro* biofilm
12 research will undoubtedly continue to enhance our knowledge of oral disease
13 aetiology and pathogenesis, consequently impacting clinical practice and disease
14 treatment.

15

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1 **Figures and Tables**

2 **Figure 1 – Models used to grow oral biofilms.** Early work focused on the use of
3 continuous flow systems such as the chemostat model which offered the advantage
4 of a regular supply of fresh medium whilst maintaining a constant media volume (A).
5 However, such models were hindered by low-throughput, leading to the development
6 of high-throughput static biofilm models (B). Since development, static biofilms have
7 become the most ubiquitously used models in oral research and encompass the
8 conventional model; where biofilms are grown in microtiter plates, and the Calgary
9 device; where biofilms are grown on pegs attached to the surface of lids. As the field
10 of biofilm research continues to grow, novel systems have been employed to
11 incorporate the advantages of continuous flow and static models. One such model is
12 the microfluidic device, which uses microchannels to combine continuous media flow
13 with high-throughput screening potential (C). Image created by Biorender.

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1 **Figure 2 - Different methodologies used to investigate oral biofilms.** There are
2 three main outputs used to generate data from biofilm models described in this review;
3 microbiological, immunological and microscopic methods. Modern investigations seek
4 to analyse the composition of *in vitro*-grown polymicrobial biofilms using quantitative
5 PCR and species- or genus- specific primer sets, whilst omics approaches have been
6 used to investigate the unique transcriptome profiles of microorganisms associated
7 with health and disease (A). Co-culture systems are now commonplace in oral biofilm
8 research. These involve the simultaneous incubation of biofilms with immune cell
9 types such as gingival epithelial cells to assess host-pathogen interactions and better
10 understand the underlying pathologies of oral disease (B). Microscopic techniques
11 include the use of simple light microscopy to observe general organism topography
12 within biofilms, fluorescent microscopy (e.g. FISH) to highlight organism viability and
13 scanning electron microscopy (SEM) to visualise distinct cell-cell aggregates
14 encapsulated within a biofilm (C). Image created by Biorender.

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Model	Description	Advantages	Disadvantages
Continuous flow models			
Chemostat	A bioreactor system with a continuous inflow of fresh media and sterile air, waste media is removed at the same rate to maintain a constant culture volume. Biofilms form within the culture chamber.	Suitable for growth of large biofilms. Continuous flow of fresh media. Allows for control of the external environment which can influence biofilm growth.	Low through-put. Requires specialised equipment. Large quantity of material lost if contaminated. No direct access to biofilms. Prone to contamination.
Flow-cell	Slides containing suitable substrata which allow biofilms to form within small channels under a constant flow of media. Spent media is removed	Allows for direct visualisation of biofilm growth stages. Optimised for microscopy. Compatible with a range of substrata. Continuous flow of fresh media.	Low through-put. Requires specialised equipment. No direct access to biofilms. Prone to contamination.
Constant depth film fermenter	Coupons are suspended from the lid via a suitable coupon holder. Fresh media is pumped through the reactor, with continuous mixing. Biofilms form on the surface of coupons.	Commercially available. Continuous flow of fresh media. Allows for direct access to biofilms. Can alter shear stress.	Low through-put. Requires specialised equipment. Expensive. Prone to contamination.
Static models			

Microtiter plate	Media containing bacteria is placed into microtiter plate. Biofilms form on the bottom of wells, or on suitable substrates placed in each well. Media can be replaced through pipetting.	High through-put. Inexpensive. No specialised equipment required. Microtiter plates with varying well sizes can be used to better suit the desired assay.	Biofilms not grown under continuous flow. Prone to sedimentation. Multiple plates required for continuous timepoint assays. Labour intensive.
Calgary device	Media containing bacteria is placed into 96-well microtiter plates. Pegs suspended from lids are placed into wells, allowing for biofilm formation on their surface.	High through-put Allows for easy manipulation of culture media. Requires active attachment of bacteria as opposed to sedimentation.	More expensive than simple microtiter plates. Multiple plates required for continuous timepoint assays. Prone to contamination. Labour intensive.
Modern technologies			
Microfluidics (e.g., BioFlux microfluidic devices)	Small microfluidic chips contain channels etched into a suitable substrate (glass, silicon, plastic) which are connected through inlets and outlets. Media is pumped through channels, allowing for micro-biofilm formation.	High through-put. Can be designed to mimic specific environments. Suitable for antimicrobial susceptibility testing. Allows for analysis of different stages of biofilm growth.	Expensive. Requires specialised equipment for preparation and analysis. Clogging may occur in micro-channels.

<p>Impedance-based technology (e.g., XCELLigence real-time monitoring system)</p>	<p>Media containing bacteria is placed into microtitre E-plates with gold electrodes on the plate floor. Electron impedance is used to monitor several factors such as biofilm growth and cell morphology. Cell index values directly related to biofilm maturation.</p>	<p>High through-put. Allows for real-time monitoring of biofilm growth. Suitable for antimicrobial susceptibility testing. Can allow for direct access to the biofilm.</p>	<p>Expensive. Requires specialised equipment for preparation and analysis. Prone to sedimentation. Gold electrodes can be fragile and easily damaged.</p>
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2 **Table 1 – Advantages and disadvantages of current oral biofilm methodologies.** A table showing the current methodologies
3 used by research groups for growth of oral biofilm models including continuous flow systems, static models and current modern
4 options utilising new technology. A description of the models, advantages and disadvantages are highlighted for each methodology.

Authors	Biofilm	Bacterial/fungal strains	Substratum	Media	Reference
Guggenheim et al., 2001 *	Supra-gingival biofilm	<i>Streptococcus oralis</i> , <i>Streptococcus sobrinus</i> , <i>Veillonella dispar</i> , <i>Actinomyces naeslundii</i> & <i>Fusobacterium nucleatum</i>	Saliva-coated hydroxyapatite disc	Human saliva, human serum and modified universal fluid medium	(118)
Guggenheim et al., 2009 * and Ammann et al., 2012	Sub/Supra-gingival biofilm	<i>Streptococcus intermedius</i> , <i>Streptococcus oralis</i> , <i>Campylobacter rectus</i> , <i>Fusobacterium nucleatum spp. vincentii</i> , <i>Veillonella dispar</i> , <i>Actinomyces naeslundii</i> , <i>Porphyromonas gingivalis</i> , <i>Prevotella intermedia</i> , <i>Tannerella forsythia</i> & <i>Treponema lecithinolyticum</i> or <i>Treponema denticola</i>	Saliva-coated hydroxyapatite disc	Human saliva, human serum and modified universal fluid medium	(95, 119)
Peyyala et al 2013 *	Health, gingivitis, periodontitis biofilms	<i>Streptococcus gordonii</i> , <i>Streptococcus oralis</i> & <i>Streptococcus sanguinis</i> (health), <i>Streptococcus gordonii</i> , <i>Actinomyces naeslundii</i> & <i>Fusobacterium nucleatum</i> (gingivitis), <i>Streptococcus gordonii</i> , <i>Fusobacterium nucleatum</i> & <i>Porphyromonas gingivalis</i> (periodontitis)	Rigid gas permeable hard contact lenses	Supplemented brain heart infusion broth	(84)
Frias-Lopez and Pinedo, 2012	Health, periodontitis biofilms	<i>Actinomyces naeslundii</i> , <i>Lactobacillus casei</i> , <i>Streptococcus mitis</i> , <i>Veillonella parvula</i> & <i>Fusobacterium nucleatum</i> (health)	Saliva-coated hydroxyapatite disc	Mucin growth medium	(114)

		including <i>Porphyromonas gingivalis</i> & <i>Aggregatibacter actinomycetemcomitans</i> (periodontitis)			
Falsetta et al 2014	Caries biofilm	<i>Streptococcus mutans</i> & <i>Candida albicans</i>	Saliva-coated hydroxyapatite disc	Human Saliva	(120)
Millhouse et al 2014	Periodontitis biofilm	<i>Streptococcus mitis</i> , <i>Fusobacterium nucleatum</i> , <i>Porphyromonas gingivalis</i> & <i>Aggregatibacter actinomycetemcomitans</i>	Thermanox™ coverslips	Artificial Saliva	(121)
Muhammad et al 2014	Endodontic biofilm	<i>Enterococcus faecalis</i> , <i>Streptococcus salivarius</i> , <i>Porphyromonas gingivalis</i> & <i>Prevotella intermedia</i>	Extracted tooth	Schaedler anaerobic broth	(122)
Cavalcanti et al 2016	Peri-implantitis biofilm	<i>Candida albicans</i> , <i>Streptococcus mutans</i> , <i>Streptococcus oralis</i> , <i>Veillonella dispar</i> , <i>Actinomyces naeslundii</i> & <i>Fusobacterium nucleatum</i>	Titanium coated discs	Modified universal fluid medium with glucose	(123)
Sherry et al 2016	Denture stomatitis biofilm	<i>Candida albicans</i> , <i>Streptococcus intermedius</i> , <i>Streptococcus mitis</i> , <i>Streptococcus oralis</i> , <i>Aggregatibacter actinomycetemcomitans</i> , <i>Actinomyces naeslundii</i> , <i>Veillonella dispar</i> , <i>Fusobacterium nucleatum</i> , <i>Fusobacterium nucleatum spp. vincentii</i> , <i>Porphyromonas gingivalis</i> & <i>Prevotella intermedia</i>	Polymethylmet hacrylate discs	Artificial Saliva	(83)

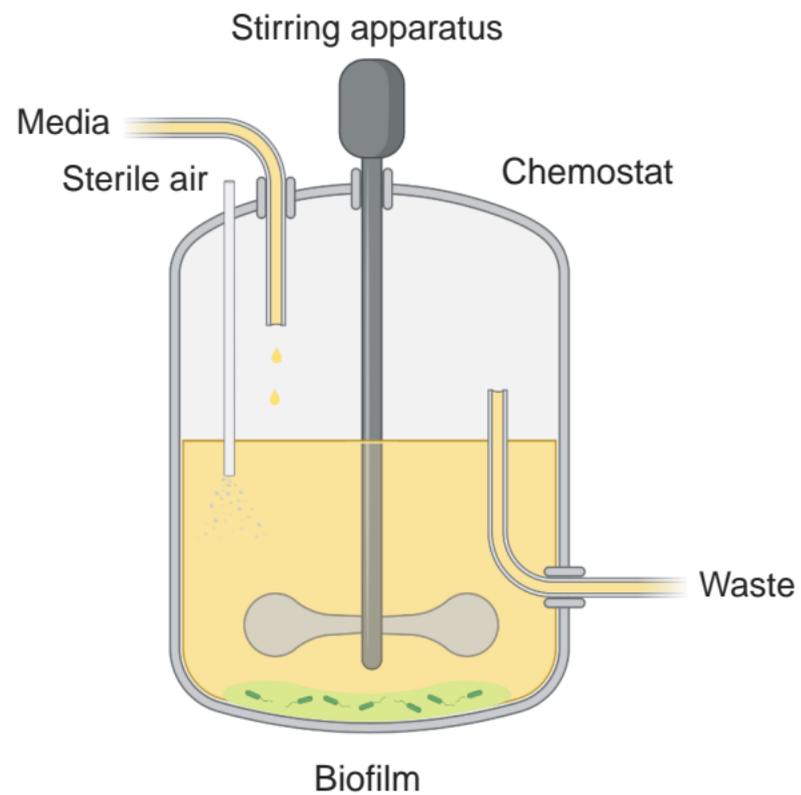
Thurnheer & Belibasakis, 2016	Peri-implantitis biofilm	<i>Streptococcus oralis</i> , <i>Streptococcus anginosus</i> , <i>Actinomyces oris</i> , <i>Fusobacterium nucleatum</i> , <i>Veillonella dispar</i> , <i>Campylobacter rectus</i> , <i>Prevotella intermedia</i> , <i>Porphyromonas gingivalis</i> , <i>Tannerella forsythia</i> , <i>Treponema denticola</i> , <i>Staphylococcus aureus</i> & <i>Staphylococcus epidermidis</i>	Saliva-coated hydroxyapatite or titanium discs	Human saliva, human serum and modified universal fluid medium	(124)
Kommerein et al., 2017	Peri-implantitis biofilm	<i>Streptococcus oralis</i> , <i>Actinomyces naeslundii</i> , <i>Veillonella dispar</i> , <i>Porphyromonas gingivalis</i>	96-well glass bottom plate	Supplemented brain heart infusion broth	(80)
Zhou et al., 2018	Caries biofilm	<i>Streptococcus mutans</i> , <i>Lactobacillus casei</i> , <i>Veillonella dispar</i> , <i>Actinomyces naeslundii</i> & <i>Fusobacterium nucleatum</i>	Thermanox™ coverslips	Artificial Saliva	(125)
Ramage et al., 2019 *	Denture Stomatitis	<i>Streptococcus mitis</i> , <i>Streptococcus intermedius</i> , <i>Streptococcus oralis</i> , <i>Candida albicans</i> , <i>Actinomyces naeslundii</i> , <i>Veillonella dispar</i> , <i>Rothia dentocariosa</i> , <i>Lactobacillus casei</i> & <i>Lactobacillus zeae</i>	Polymethylmet hacrylate discs	Artificial Saliva	(126)

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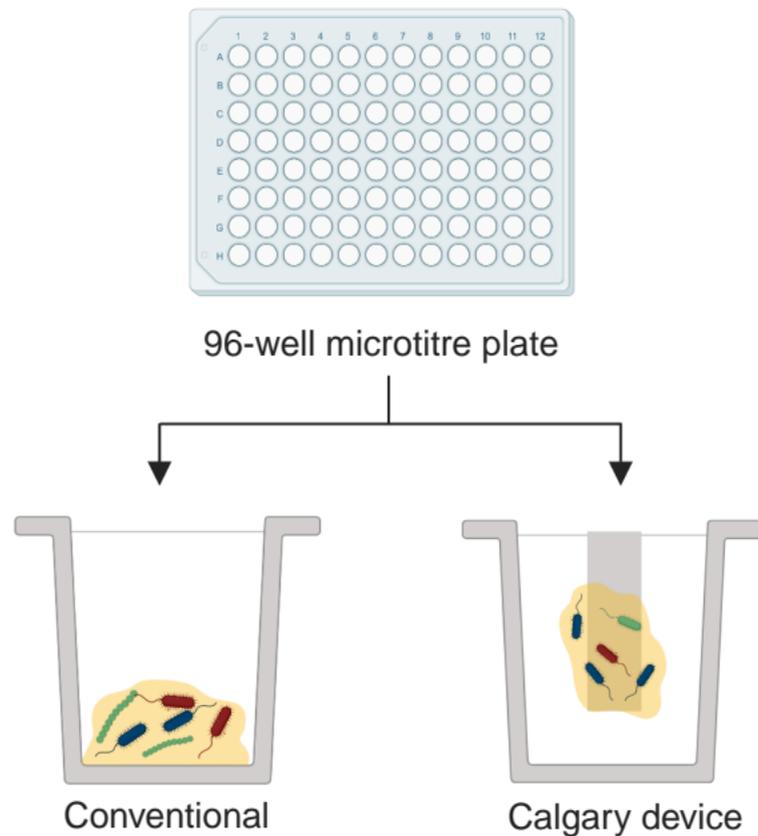
2 **Table 2 – The multi-species oral biofilm static models developed over the last 20 years.** A table showing the range of oral
3 biofilm static models developed by multiple research groups. Each model contains bacterial and fungal species associated with
4 different health and disease states in the oral cavity. Asterisks denote models of major importance (*). In 2001, Guggenheim et al
5 (118) was one of the first to describe the validation of a supra-gingival static biofilm model. Prior models to this work predominantly

1 utilised continuous culture systems such as chemostats or flow cells. The “Zurich” biofilm model was adapted by the same group
2 (95) and made more complex including a total of 9- species associated with health and periodontitis. Using a combination of
3 microbiological and microscopic techniques, the authors were able to comprehensively characterise the composition and
4 architectural features of the biofilm, in addition to assessing the inflammatory outputs in a co-culture system with gingival cells. A
5 number of studies have used the “Zurich” biofilm as a template for their own models. The Ebersole group (84) developed biofilm
6 models for co-culture experiments, to study the host-pathogen response to biofilms containing a consortium of microorganisms
7 associated with oral health and disease. The ensuing studies from the group have enhanced our understanding of the host
8 response to commensal and pathogenic biofilms. A recent publication by Ramage et al (126) developed a complex denture plaque
9 model using the dominant microbial genera from a microbiome study (104). Future models may serve to utilise OMICs approaches
10 such as microbiome analyses to develop new biofilm models incorporating microorganisms newly associated with oral diseases
11 such as denture stomatitis, periodontitis or endodontic infections.

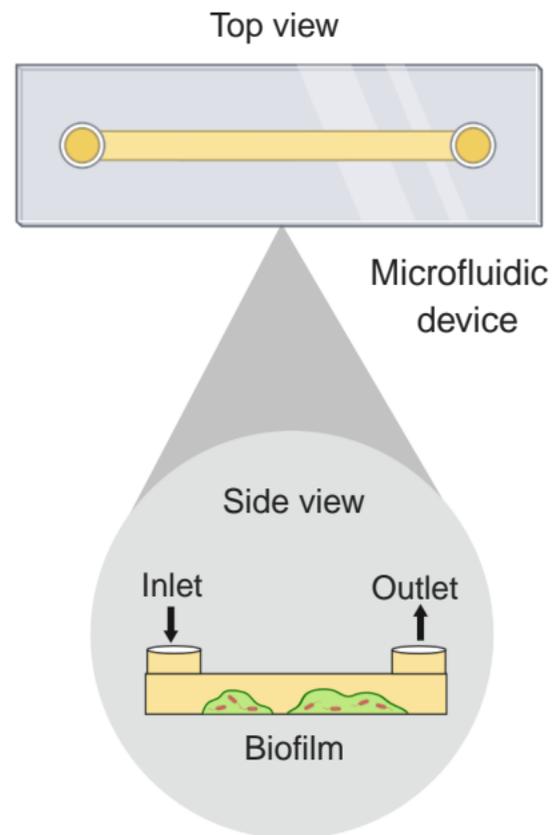
A Continuous flow models



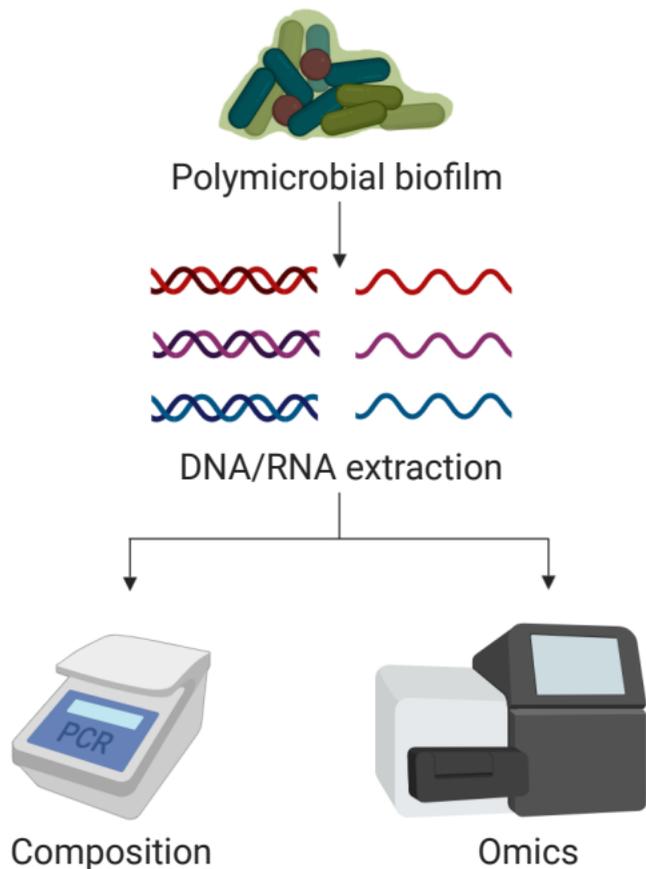
B Static biofilm models



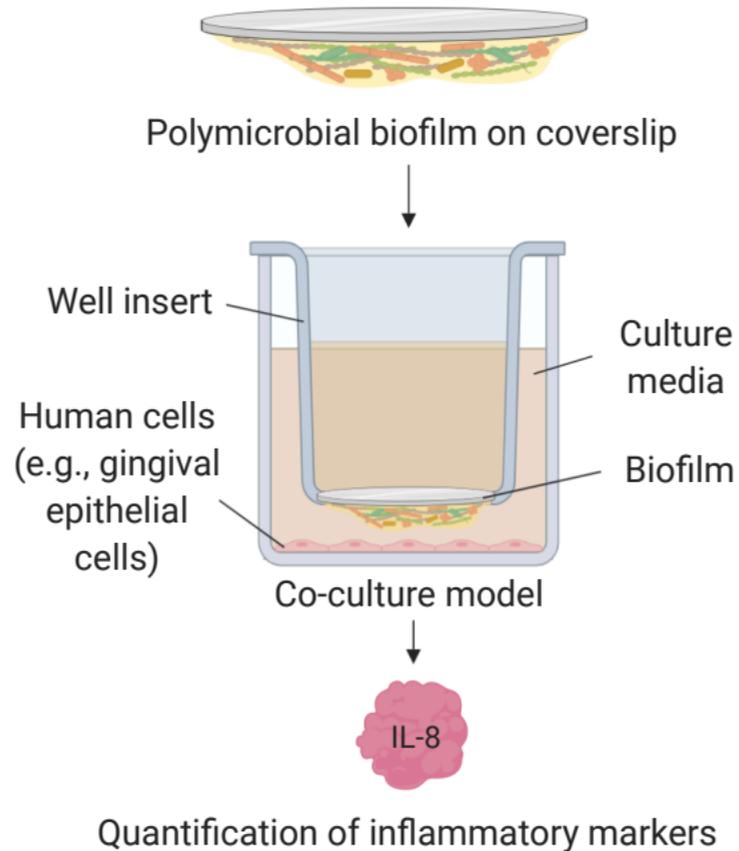
C Modern technologies



A Microbiological methods



B Immunological methods



C Microscopic methods

