

## What do 'omic technologies have to offer periodontal clinical practice in the future?

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Title: What do 'omic technologies have to offer periodontal clinical practice in the future?

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Abstract:

**Background & Objective:** Periodontal diseases are the most common chronic inflammatory diseases of humans and a major cause of tooth loss. Inflammatory periodontitis is also a complex multi-factorial disease involving many cell types, cell products and interactions. It is associated with a dysregulated inflammatory response, which fails to resolve, and which also fails to re-establish a beneficial periodontal microbiota. There is a rich history of biomarker research within the field of periodontology, but exemplary improvements in analytical platform technologies offer exciting opportunities for discovery. These include the 'omic technologies, genomics, transcriptomics, proteomics and metabolomics, which provide information on global scales that can match the complexity of the disease. This narrative review focuses on the recent advances made in *in vivo* human periodontal research by use of 'omic technologies.

**Methods:** The Medline database was searched to identify articles currently available on 'omic technologies in regard to periodontal research

**Results:** 144 articles focusing on biomarkers of and 'omic advances in periodontal research were analyzed for their contributions to the understanding of periodontal diseases.

**Conclusion:** The data generated by the use of 'omic technologies have huge potential to inform paradigm shifts in our understanding of periodontal diseases, but data management, analysis and interpretation require a thoughtful and systematic bioinformatics approach, to ensure meaningful conclusions can be made.

## Introduction

Periodontal diseases are the most common chronic inflammatory diseases of humans and a major cause of tooth loss (1). Diagnosis requires training, knowledge and dedicated clinical facilities, creating a need for those in non-specialist and/or non-dental environments (e.g. medical practice) for simple, objective diagnostic tools, to help identify patients with periodontitis. These would help in early diagnosis of disease onset, progression, or indeed resolution following treatment and may reduce both the healthcare and economic burdens arising from periodontitis, estimated as £2.78 billion in the UK in 2008 (2). Moreover, they may positively impact upon systemic inflammatory diseases, where periodontitis is recognised as a risk factor. The identification of biomarkers using 'omic' technologies, such as genomics, transcriptomics, proteomics and metabolomics, could deliver such diagnostic tests.

The official National Institute of Health (NIH, USA) definition of a biomarker is 'a characteristic that is objectively measured and evaluated as an indicator of normal biologic processes, pathogenic processes, or pharmacologic responses to a therapeutic intervention'. Although this could be a physical trait, such as hair colour, for the purpose of this focussed review of *in vivo* biomarkers of human periodontitis only molecular biomarkers, and those determined in a genetic, proteomic or metabolomic profile will be discussed. As Bensalah et al (3) have recently documented, six different types of biomarker can be differentiated. These are:

- early detection of disease;
- diagnosis of presence or absence of disease;
- prognosis of disease outcome and possible patient stratification allowing for personalized medical interventions;

- prediction of treatment outcome;
- identification of patients who will respond well to a particular treatment;
- surrogate end points.

In addition for a biomarker, or a panel of biomarkers, to be successfully employed within the clinical environment, they must also be: objective; reproducible; easy to use; cheaper and; with greater sensitivity, specificity and diagnostic accuracy than existing tests (3-5). These hurdles are made higher still by the need for potential biomarkers to achieve a status akin to the rigorous governance processes through which drugs must pass for licensing; there is, however, currently no such mechanism in place for such evaluations(3).

In the past, the most useful biomarkers have either been found serendipitously or through careful evaluation of candidates generated through hypothesis driven research (6). Many potential biomarkers are developed using pre-clinical *in vitro* models and a few go onto the development of assays used in the evaluation of a small number of patients in the equivalent of phase 1 trials. Proof of biomarker efficacy cannot be established solely by statistics, there needs to be an evaluation akin to structured, phased trial testing (3, 6). Such independent validation and efficacy determination in large community dwelling populations, in the equivalent of phase 2 and 3 trials, is even scarcer than phase 1 studies. Thus to mine the proverbial biomarker iceberg and to leverage these novel biomarker technologies, larger multi-centre multi-omic systems biology trials need to be performed.

Samples available for *in vivo* studies of periodontal diseases include: GCF, plaque, saliva, biopsies, peripheral blood cells and plasma (figure 1). Several excellent reviews discuss these compartments for targeted approaches to biomarker discovery (5, 7-10). In particular Loos & Tjoa (5) undertook a critical review of biomarkers in GCF and found only 8 out of 94, in the literature of the time, fulfilled any of the criteria for biomarker status. These included: alkaline phosphatase (11-17) , beta glucuronidase (15, 18-26) , cathepsin B (27-32) , MMP-8 & -9 (15, 33-45) , dipeptidyl peptidase II & IV (28, 29, 31, 46), neutrophil elastase (15, 24, 26-

29, 39, 47-66). Potential novel biomarkers have been described since using 'omics driven discoveries as are discussed below.

The 'omic technologies include genomics, transcriptomics, proteomics and metabolomics (figure 1) and each is discussed below. It should be noted that, in contrast to genomics, transcriptomics, proteomics and metabolomics assess the temporal expression of genes rather than the static encoding of the genome. Thus they take into account environmental influences, nurture as well as nature. As we progress from genomics, to transcriptomics, proteomics and metabolomics we also progress from what might happen to what actually did happen: with transcriptomics being influenced by translation and activation; proteomics elucidating changes to global protein expression, splice variants of proteins and post-translational modifications; and metabolomics demonstrating end products of reactions. All these technologies and assessments can be applied to both the host and the microbiota in periodontitis. Here, only the host contributions are discussed.

Drawbacks of all the functional genomics technologies include confounding issues such as age, gender, diet, smoking and likely many more. Where dynamic range is a problem the technology may be affected by the 'usual suspects' phenomenon (67) where similar species are found in a variety of unrelated studies and reflect the fact that some situations/treatments affect central signalling or metabolic hubs within cells, for example affecting energy generation. This is a problem that can mask less obvious biological perturbations, but can be overcome with much larger study populations where general "noise" can be removed and small changes can gain statistical significance due to increasing study power.

## Genomics

Genomics is the study of whole genomes, i.e. all the DNA of a single organism. With improvements in sequencing, the dawn of genome-driven individualised medicine has arrived, where changes to multiple genes may be taken into account for diagnosis and

treatment. But with differences in more than 3 million nucleotides (0.1% of the whole genome) evident when comparing 2 individual genomes, it will likely take many years before such differences can be mapped to disease correlations (68, 69). However, for some time, changes in individual genes (gene polymorphisms) have been studied with reference to disease risk, severity and therapeutic outcome. These gene polymorphisms are highly prevalent in the population (70) and the most common type is the single nucleotide polymorphism (SNP) where an individual base pair is affected, by alteration within, insertion into, or deletion from the DNA sequence. Where these changes fall in promoter regions, exons, introns or untranslated regions, will differentially affect gene products (69).

The influence of SNPs on periodontal disease was reviewed in 2006 by Takashiba & Naruishi (69). They highlighted that nearly half of the research in this area has focused upon cytokines, with the rest investigating human leukocyte antigens, immuno-receptors, proteases, structural molecules and other proteins. However, of the 140 papers they used for their review the majority focused on only 6 genes: (Interleukin (IL) 1, Tumour necrosis factor (TNF)  $\alpha$ , Fc $\gamma$  receptors, matrix metalloproteins, cathepsin C and vitamin D receptor), indicating that this field is still in its infancy. IL-1 SNPs were suggested to be more associated with environmental interactions, such as with smoking, than with susceptibility to periodontitis, whereas TNF $\alpha$  showed a lack of association with inflammatory periodontal disease. However, polymorphisms in Fc $\gamma$  receptors tend to be associated with both aggressive and chronic forms of periodontitis. For the other genes mentioned above, limited evidence makes it difficult to relate SNPs to periodontitis. In the past 5 years since the review by Takashiba & Naruishi (69), there have been at least an additional 37 articles published concerning SNPs in cytokines (71-107). These small scale studies of individual SNPs are no longer in a position to contribute anything new to the literature and are of limited value.

Moving into wider ranging analysis, Suzuki et al (108) examined 637 SNPs in 19 healthy and 22 severe periodontitis cases, revealing 5 previously untargeted genes as potential

markers for periodontitis. Using an *ab initio* bioinformatic approach, Covani et al (109) predicted five leader genes from an investigation of 61 genes potentially involved in periodontitis, using published articles as the source of data. These genes were NFkB1, CBL, GRB2, PIK3R1 and RELA, and are predominantly involved receptor-mediated signalling and may reflect the stimulation of the host inflammatory-immune system by bacteria in periodontitis.

Overall the genetic basis of periodontitis accounts for approximately half the population variance in chronic periodontitis (110, 111). There is a need to progress to large scale genome wide association studies (GWAS) and the first of these has been published (111). Comparison of two cohorts of aggressive periodontitis patients independently identified 197 and 244 quality controlled SNPs from 141 and 142 patients respectively, examining 500,568 potential SNPs. However, when the results from both sets were compared only one remained significant, which was subsequently validated in a third set of patients (n=164). The gene identified was *GLT6D1*, which encodes for a glycosyltransferase 6 family protein. These enzymes are single pass transmembrane proteins which contribute to the synthesis of histo-blood related antigens in the golgi. *GLT6D1* was found to be highly expressed in the gingival connective tissues and may influence immune responses. Future studies using greater numbers of patients and controls may yield more associations, however the acquisition of even one unknown gene that may predict periodontal disease is potentially of great value.

### Transcriptomics

The field of transcriptomics involves the study of messenger RNA (mRNA) production by cells under particular conditions. Unlike proteomics and metabolomics (below), this is typically studied in cell populations and thus in periodontal investigations either utilises biopsies of relevant oral tissues or peripheral blood leukocytes rather than oral fluids such as



GCF and saliva, which can be studied using proteomic and metabolomic platforms. There are two major advantages that this technique provides: 1) the ability to amplify the expressed gene products; and 2) the stability and uniformity of the platforms employed in identification of interesting and/or novel species. This is reflected in the far greater number of articles reporting transcriptomic studies than proteomic and metabolomic studies. Over the last 5 years Papapanou and colleagues have analysed whole tissue transcriptomes from the excised papillae of healthy and diseased patients in an attempt to re-classify periodontal disease biologically rather than clinically (112-114). A pilot study however could not differentiate between chronic and aggressive forms of periodontitis (112) but comparison of diseased and healthy papillae from patients with advanced periodontitis did detect differences in gene ontology groups for apoptosis, antimicrobial humoral responses, antigen presentation, regulation of metabolic groups, signal transduction and angiogenesis. The authors commented that the papillae are composed of a variety of cell types, these differences in composition may give rise to different transcriptome profiles and contribute to the heterogeneity of results. However, it was possible to identify genes that have not previously been linked with periodontal diseases, such as CXCL6 (granulocyte chemoattractant protein 6 (112, 115). In their latest paper, Papapanou et al (114) correlated the transcriptomes of chronic periodontitis patients with the subgingival microflora in those patients/sites. This interesting study coupled the two key drivers of periodontal disease expression, the host and microbial factors, to determine whether species of bacteria can cluster the large number of genes differentially expressed in periodontal disease, thus yielding information on how bacterial species might influence host gene expression. Gingival biopsies were also taken by Offenbacher et al (116) to investigate the temporal changes in gene expression during experimental gingivitis. Again, large numbers of genes were differentially expressed and novel gene ontology groups were reported including those of neural process, epithelial defences, angiogenesis and wound healing.

Beikler et al (117) investigated gene expression changes in periodontal tissues before and after treatment using a semi-targeted human inflammation microarray. They concluded that those gene profiles that were altered the most indicated an activation of pathways that regulate tissue damage and repair. Kim et al (118) examined sub-epithelial connective tissues from healthy controls and periodontal patients. They found these tissues also demonstrated transcriptomic increases in the immune response, tissue remodelling and apoptosis genes.

Looking at how periodontitis affects the peripheral blood system, Papapanou et al (119) took monocytes from periodontal patients undergoing treatment and examined mRNA expression using Affymetrix arrays. They found that a third of patients had substantial changes in genes relevant to innate immunity, apoptosis and cell signalling; and concluded that periodontal therapy had a systemic anti-inflammatory effect. Matthews et al (120, 121) have previously reported that neutrophils from periodontitis patients are both hyper-reactive to stimulation by *F.nucleatum* or Fc $\gamma$ -receptors and also show baseline hyperactivity with respect to reactive oxygen species (ROS) production. Following these discoveries, the same group (122) utilised neutrophils from periodontitis patients to determine what genes were affected. They found significant increases in type-1 interferon-stimulated genes and this led to the discovery that patients had significantly greater concentrations of circulating interferon-alpha, which, upon successful periodontal treatment, decreased to the same levels as non-diseased controls. They concluded that periodontitis is a complex disease where increases in interferon-alpha may be one component of a distinct molecular phenotype in neutrophils, triggered potentially by viral priming or autoimmune responses. This latter concept is new to periodontology and may help explain the association between periodontitis and rheumatoid arthritis (123-125).

Advances have been made using transcriptomic approaches but there is a need to bring together the established datasets and also to conduct much larger, wide ranging studies that can take into account possible changes in cell type within periodontal tissues, to pinpoint

genes that may be useful in differentiating between disease types and address the criteria for biomarker research previously stated.

## Proteomics

Proteomics, the study of all the proteins in a given sample, was revolutionised by advances in mass spectrometry in the 1990s. It became possible to identify the constituent protein species within biological samples and now many studies have used an ever expanding and complex array of techniques that are both qualitative and quantitative in their outputs. A feature of many biological/clinical samples is that they exhibit a very wide dynamic range of constituent protein species, for instance in plasma that range is 6 orders of magnitude. Without the advantages that DNA and RNA amplification strategies offer, it is often not possible to examine the entire proteome, and it is frequently necessary to try and remove or separate the most abundant proteins from a sample (e.g. albumin) prior to analysis. However, proteomics does address changes to proteins such as splice variants and post translational modifications. Targeted approaches to look at panels of cytokines, such as using the bead based Luminex platform, allow examination of proteins of low concentration, but such presumptive approaches are not discussed here.

In the study of periodontal diseases many proteomic approaches have been used. Top-down whole protein approaches to identify small molecular weight proteins have investigated the presence of human neutrophil peptides (HNPs) (126-128) in gingival crevicular fluid. However, the use of bottom-up approaches, where proteins are digested to individual peptides prior to identification by tandem mass spectrometry techniques, has yielded many more novel insights into the periodontitis proteome. Kojima et al (129) separated GCF proteins by 2-dimensional electrophoresis (2DE) and then identified proteins of interest by mass spectrometry. The addition of 2DE introduced a way to quantitatively assess protein levels between diseased and healthy subjects, although intra-individual variation swamped

the slight trend for more calprotectin subunits in periodontitis patients. Use of liquid chromatography (LC) mass spectrometry techniques to study periodontitis has recently been reported. Ngo et al (130) examined GCF samples by electrophoresis and LC-MS/MS to identify 66 proteins, which included a large number of serum and cell derived proteins reflecting the dual origin of the fluid. Wu et al (131) compared saliva proteomes from generalised aggressive periodontitis patients and controls using a similar technique. Whole saliva yielded differences in highly abundant proteins, such as albumin and amylase which were increased in the diseased samples, illustrating perhaps the need for prefractionation to dissect deeper down into the proteome. Quantitative LC-MS/MS has been used by Bostanci et al (132) and by Grant et al (133) to investigate GCF profiles from patients with generalized aggressive periodontitis and volunteers undergoing experimental gingivitis, respectively. Both studies, as with Ngo et al (130), found proteins of both serum and tissue origins, and more specifically found changes in common previously uninvestigated proteins, such as neutrophil Plastin-2, an actin bundling protein involved in  $Fc\gamma$ -receptor stimulation. With the inclusion of a quantitative aspect these studies allow for a more detailed investigation, where bioinformatic tools may be able to find composites of proteins that could be used as biomarkers. However, to date these biomarkers have not been validated.

## Metabolomics

Metabolomics is a discipline that studies the quantities of all chemicals except DNA, RNA and proteins within a sample. No one experimental technique can analyse all chemical structures. Thus samples need to be analysed by a battery of techniques and separated by their chemical and physical properties and identified, principally, by nuclear magnetic resonance (NMR) and mass spectrometry. There is a vast number of potential metabolites and targeted approaches have elucidated some changes (22, 134-136), but there are very few articles that report on tackling the global metabolome in periodontal disease. Barnes et

al (137) used gas and liquid chromatographic separations coupled to mass spectrometry to investigate GCF samples from 22 chronic periodontitis patients, stratified for healthy, gingivitis and periodontitis sites. They identified 103 metabolites in comparison to a chemical reference library, finding that levels of metabolites from gingivitis sites fell between healthy and periodontitis sites. At disease sites, in comparison to healthy sites, antioxidant, glutamine and di- and tri-saccharide levels were decreased whereas amino acids (except glutamine), choline, glucose, polyamines, and purine degradation and urea cycle metabolites were increased. This study has expanded our knowledge of the sources of oxidative stress, which is already acknowledged as being of particular importance, in periodontal disease by the potential increase in activity of the xanthine oxidase-reactive oxygen species axis (137). NMR based approaches have not, as yet, been described for human GCF. This may be due to the larger concentrations of samples required.

Lipidomics is a particular subgroup of metabolomics that investigates the role of lipids in cellular function, because they integrate signalling and metabolic processes. The most common technique employs mass spectrometry, particularly using  $MS^n$  where  $n > 1$ . Recently, Gronert et al (138) used a lipidomics approach to identify and quantify diacyl glycerol species in neutrophils from LAP patients, following a transcriptomics analysis that had identified DAG kinase from neutrophils as not being expressed, in comparison to disease free controls. Metabolomics is an area that could and should see intensive research to provide a clearer understanding of periodontitis. It will be able to reveal information about host and host-microflora interactions which may yield specific small molecule targets that have been overlooked by other techniques.

## Systems Biology

Systems biology is the integration of multiple omics platforms and data through the reconstruction of the complex networks involved (139). These complex networks

characterise particular systems, often cells, but in periodontitis it would need to address the whole disease – interactions not of one cell type, but many and also with the micro-organisms present in the disease state. Advances in network inference and analysis in other diseases, such as obesity, diabetes and atherosclerosis, are already highlighting that it may be necessary to target multiple (10-50) genes, in different tissues, simultaneously to treat a disease effectively(140). Such an approach would yield a holistic overview of the disease milieu. The complementary information from the different ‘omic technologies needs to be coordinated and integrated, and several strategies are being progressed in other research areas (141). This still remains a major challenge to the periodontal field and there is still the requirement for fundamental understanding of the mechanisms taking place so that the data can be appropriately modelled. Using holistic approaches will have the advantage that they will address the synergistic qualities of multiple bacterial challenges and multiple cell types present at the diseased lesion. The bacterial challenge in particular should not be overlooked, with so many so called unculturable bacteria being present (142). Microbiome strategies to study the thousands of bacteria present will unite with the ‘omic technologies (143). Nibali et al (144) have already termed the interaction between host genetic factors, such as SNPs, and the oral microbiome as “infectogenomics”.

To conclude, as yet ‘omic technologies have not yielded validated biomarkers for periodontal disease but they are identifying new routes for research to follow in relation to disease pathogenesis. It is unrealistic to think that one biomarker will be found, there is no more “low hanging fruit” (5). Periodontitis is acknowledged as a complex inflammatory disease, initiated by a plaque biofilm and with multiple component causes, and it is therefore much more likely that there is a multiplicity of biomarkers which together can: differentiate between health and disease; between disease onset and progression; improve the prognosis of disease outcomes and possible patient stratification allowing for personalized medical interventions; identify disease resolution/healing; predict treatment outcomes; identify patients who will

respond well to a particular treatment; or provide surrogate end points. The use of use 'omic techniques will play an important role in their discovery.

### Conflict of Interest and Sources of Funding Statement

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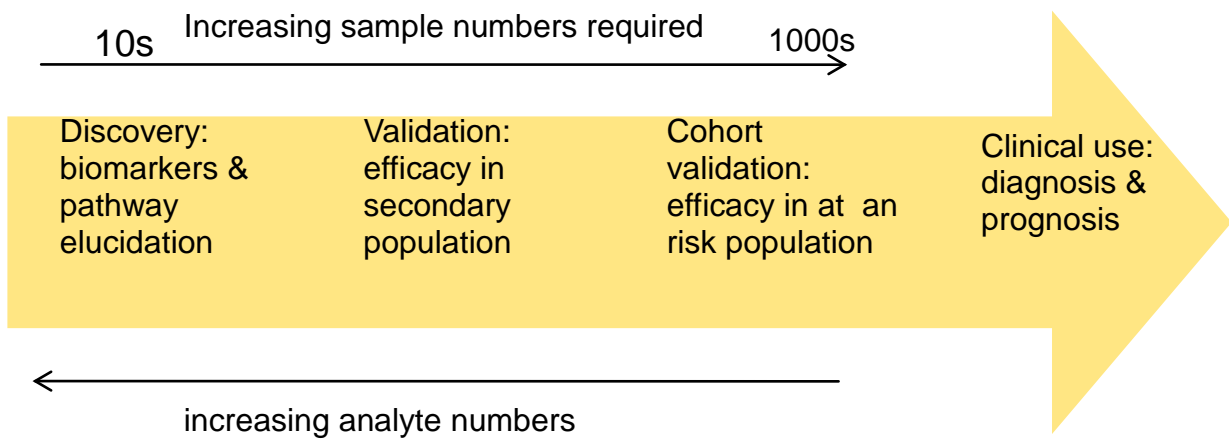


Figure 1. The path through which biomarkers must travel to be useful for the clinician. ‘Omic technologies can be used at all stages but have most impact on the initial stages.

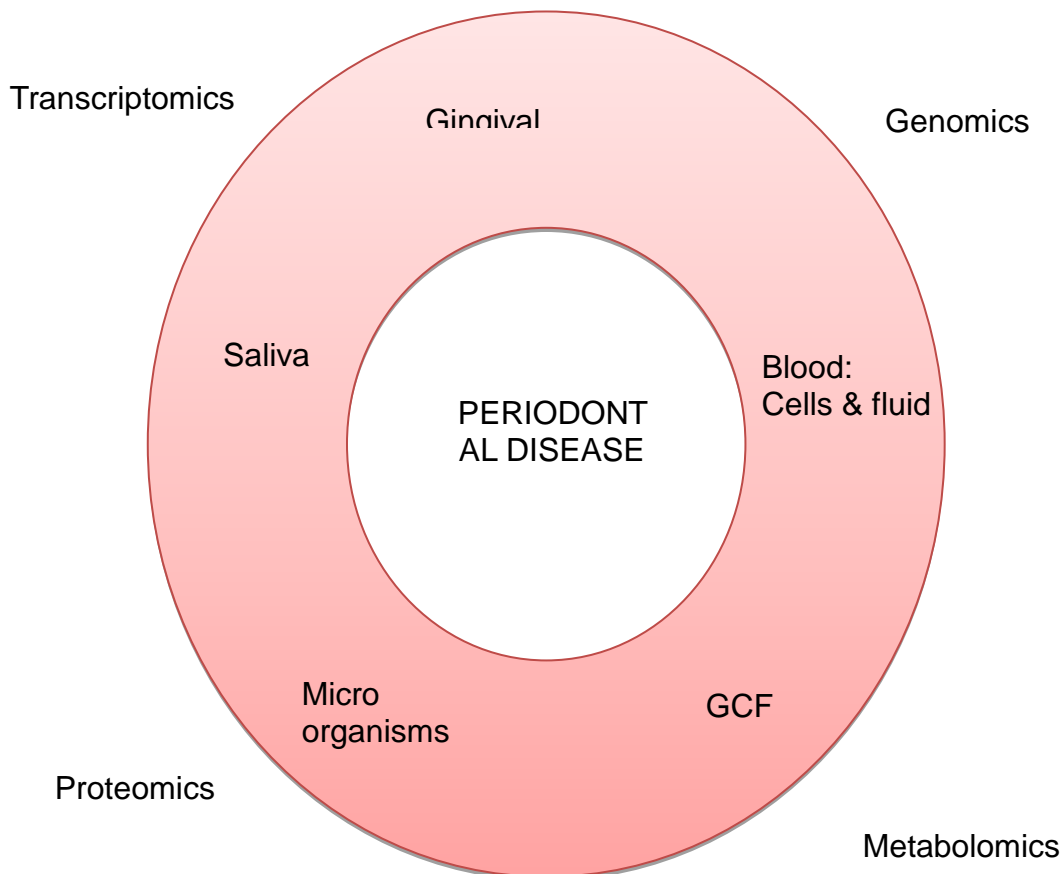


Figure 2. The compartments available for studying periodontal disease using ‘omic technologies

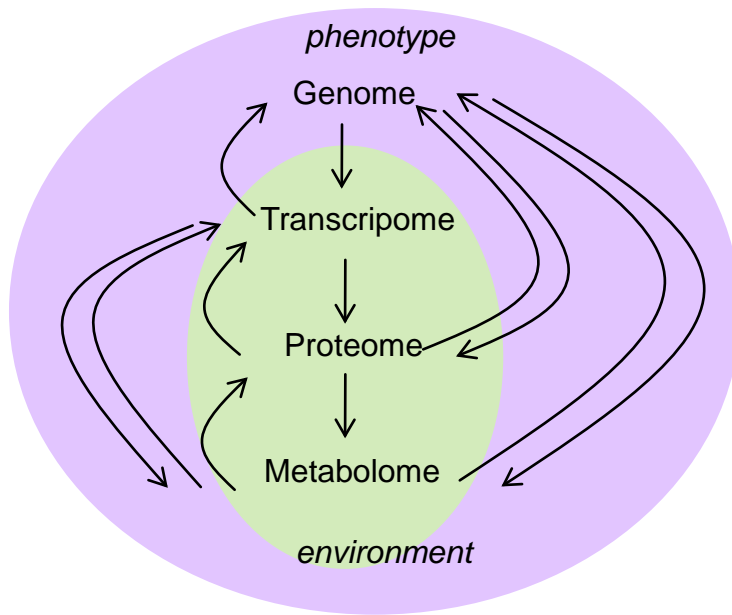


Figure 3. The interplay of the different compartments studied by 'omic technologies.



| Approach        | Study population(s)                                 | Platform of evaluation                            | Number of species investigated | Source of biological samples             | Number of subjects in study                                                                                                        | Conclusion                                                                 | Reference |
|-----------------|-----------------------------------------------------|---------------------------------------------------|--------------------------------|------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------|-----------|
| Genomics        | Severe periodontitis comparison to healthy subjects | TaqMan PCR                                        | 637 SNPs                       | whole peripheral blood                   | n=22 severe periodontitis patients, n=19 controls                                                                                  | GNRH1, PIK3R1, DPP4, FGL2, and CALCR significantly associated with disease | 114       |
|                 | Aggressive periodontitis                            | Affymetrix Gene Chip Human Mapping 500K Array Set | GWAS of 500,000 SNPs           | whole peripheral blood & gingival tissue | n=141, 142, 164 assessment in two cohorts by GWAS and validated in a third cohort (affected teeth 2-6%)                            | GLT6D1 was significantly associated with disease                           | 116       |
| Transcriptomics | Chronic & aggressive periodontitis                  | Affymetrix Human Genome U-133 A arrays            | 22,000 transcripts             | Biopsies of gingival tissue              | n=1 localised chronic periodontitis, n=6 generalised chronic periodontitis n=1 localised aggressive periodontitis, n=6 generalised | Patients were clustered by pathogen presence rather than by disease type   | 117       |

aggressive  
periodontitis

|                                    |                                               |                    |                             |                                                          |                                                                                                                                                                                   |     |
|------------------------------------|-----------------------------------------------|--------------------|-----------------------------|----------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| Chronic & aggressive periodontitis | Affymetrix Human Genome U-133 Plus 2.0 arrays | 47,000 transcripts | Biopsies of gingival tissue | n=90 (63 chronic & 27 aggressive) periodontitis patients | Gene ontology groups increased included apoptosis, antimicrobial humoral response, antigen presentation, regulation of metabolic processes, signal transduction, and angiogenesis | 118 |
| Chronic & aggressive periodontitis | Affymetrix Human Genome U-133 Plus 2.0 arrays | 47,000 transcripts | Biopsies of gingival tissue | n=120 (65 chronic & 55 aggressive) patients              | Commonalities & differences were found between gene expression and bacterial species present                                                                                      | 119 |
| Experimental gingivitis            | Affymetrix Human Genome U-133                 | 47,000 transcripts | Biopsies of gingival tissue | n=14 healthy volunteers                                  | Differences in GO groups: neural processes, epithelial defences,                                                                                                                  | 121 |

|            |                                             |                                                              |                    |                                 |                                                                           |                                                                                              |     |
|------------|---------------------------------------------|--------------------------------------------------------------|--------------------|---------------------------------|---------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|-----|
|            |                                             | Plus 2.0 arrays                                              |                    |                                 |                                                                           | angiogenesis & wound healing                                                                 |     |
|            | Periodontal disease compared with control   | Agilent 2100 Bioanalyzer and a human inflammation microarray | 160 genes          | Biopsies of gingival tissue     | n=12 severe generalized chronic periodontitis, n=11controls               | Activation of pathways regulating tissue damage & repair after treatment                     | 122 |
|            | Refractory periodontitis                    | Affymetrix Human Genome U-133 A arrays                       | 22,000 transcripts | Subepithelial connective tissue | n=7 refractory periodontitis & n=7 periodontally well-maintained patients | Increases in immune response, tissue modelling & apoptosis in disease in refractory patients | 123 |
|            | Periodontitis patients undergoing treatment | Affymetrix Human Genome U-133 Plus 2.0 arrays                | 47,000 transcripts | Peripheral monocytes            | n=15 patients                                                             | Changes in innate immunity, apoptosis & cell signalling were seen                            | 124 |
|            | Periodontitis                               | Affymetrix Human Genome U-133 A arrays                       | 22,000 transcripts | Peripheral neutrophils          | n=19 patients                                                             | Type-1 interferon stimulated genes were increased                                            | 127 |
| Proteomics | Periodontitis in                            | Electrophoresis                                              | Not given          | GCF, serum &                    | n=10 periodontitis patients, n=4                                          | S100A8 and S100A9 represented major                                                          | 134 |

|              |                                                   |                      |                                               |        |                                                     |                                                                                                                                                             |     |
|--------------|---------------------------------------------------|----------------------|-----------------------------------------------|--------|-----------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
|              | comparison to control                             | & MS                 |                                               | saliva | controls                                            | differences between GCF and saliva                                                                                                                          |     |
|              | Periodontitis patients in maintenance phase       | Electrophoresis & MS | 66 proteins identified                        | GCF    | n=12 patients                                       | Identification of serum and cell derived proteins                                                                                                           | 135 |
|              | Aggressive periodontitis in comparison to control | Electrophoresis & MS | Not given                                     | Saliva | n=5 aggressive periodontitis patients, n=5 controls | 6 proteins were increased in saliva of periodontitis subjects, while 5 were decreased                                                                       | 136 |
|              | Generalized aggressive periodontitis              | Quantitative MS      | 154 human, bacterial, fungal & viral proteins | GCF    | n=5 aggressive periodontitis patients, n=5 controls | Human plastin-2 and Microbial proteins increased in disease, Annexin A1 increased in health                                                                 | 137 |
|              | Experimental gingivitis                           | Quantitative MS      | 202 human and bacterial proteins              | GCF    | n=10 healthy volunteers                             | Identification of 186 proteins including serum and cell derived species including plastin-2. Novel structural proteins for cilia and ribbon synapses found. | 138 |
| Metabolomics | Chronic periodontitis                             | MS                   | 103 metabolites identified                    | GCF    | n=22 patients samples collected included diseased   | At diseased sites antioxidant, glutamine, di-&trisaccharide levels                                                                                          | 147 |

|                 |                                    |                                  |                          |             |                                                                          |                                                                                                                                |     |
|-----------------|------------------------------------|----------------------------------|--------------------------|-------------|--------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------|-----|
|                 |                                    |                                  |                          |             | and healthy sites                                                        | decreased; amino acids (except glutamine), choline, glucose, polyamines, purine degradation & urea cycle metabolites increased |     |
|                 | Localised aggressive periodontitis | MS                               | 7 diacylglycerol species | Neutrophils | n=11 localised aggressive periodontitis, n=4 asymptomatic family members | Increased diacylglycerol species in disease compared to control                                                                | 148 |
| Systems Biology | Periodontitis                      | Data mining and cluster analysis | 61 genes                 | In silico   | Not relevant                                                             | 5 leader genes (or hubs) (NFkB1, CBL, GRB2, PIK3R1, RELA) identified                                                           | 152 |

Table 1. Summary of data rich 'omics studies. Abbreviations: MS mass spectrometry; GCF gingival crevicular fluid.