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Comprehensive Analysis of Single Nucleotide Polymorphisms in Pro-inflammatory Cytokine Genes as Predictive Biomarkers for Peri-implantitis Susceptibility

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ABSTRACT

Peri-implantitis, an inflammatory condition affecting tissues surrounding dental implants, represents a significant challenge in implant dentistry. This comprehensive review examines the role of single-nucleotide polymorphisms (SNPs) in pro-inflammatory cytokine genes as potential predictive biomarkers for peri-implantitis susceptibility. Current evidence suggests that genetic variations in TNF-α, IL-1, IL-6, RANK/RANKL/OPG, and matrix metalloproteinase genes may influence individual susceptibility to peri-implantitis through altered inflammatory responses and bone metabolism. This review analyzes the strength of evidence across different populations, explores interactions with environmental risk factors, and discusses clinical implications for personalized implant therapy. Despite promising findings, methodological heterogeneity limits definitive conclusions, highlighting the need for larger prospective studies with standardized protocols to validate these genetic markers for clinical use.

Keywords: *Peri-implantitis, Single-nucleotide polymorphisms, Pro-inflammatory cytokines, Genetic susceptibility, Bone metabolism*

INTRODUCTION

Dental implants have revolutionized the field of restorative dentistry, providing patients with functional and aesthetic solutions for tooth replacement. Despite high success rates reported in the literature, implant complications and failures do occur, with peri-implantitis emerging as one of the most significant challenges affecting long-term implant survival (Berglundh et al., 2018). Peri-implantitis represents a pathological condition characterized by inflammation in the peri-implant tissues, accompanied by progressive bone loss beyond initial remodeling (Schwarz et al., 2018).

The etiology of peri-implantitis is multifactorial, involving complex interactions between microbial, host-related, and implant-related factors. While bacterial biofilm plays a crucial role in initiating the inflammatory response, increasing evidence suggests that individual genetic susceptibility significantly

influences disease progression and severity (Derks & Tomasi, 2015). Among the various genetic factors, single-nucleotide polymorphisms (SNPs) in pro-inflammatory cytokine genes have received considerable attention due to their potential impact on immune responses and bone metabolism.

Pro-inflammatory cytokines, including tumor necrosis factor-alpha (TNF-α), interleukins (IL-1, IL-6), and factors involved in bone remodeling such as receptor activator of nuclear factor kappa-B ligand (RANKL), osteoprotegerin (OPG), and matrix metalloproteinases (MMPs), play pivotal roles in the pathogenesis of peri-implantitis (Kadkhodazadeh et al., 2013; Luchian et al., 2022). Genetic variations in these cytokine genes can alter their expression levels and functional properties, potentially modifying individual susceptibility to peri-implantitis (Rakic et al., 2014).

This comprehensive review aims to critically analyze the current evidence regarding SNPs in pro-inflammatory cytokine genes as potential predictive biomarkers for peri-implantitis susceptibility. By synthesizing findings from multiple studies across different populations, we seek to evaluate the strength of association between specific genetic polymorphisms and peri-implantitis risk, explore potential gene-environment interactions, and discuss the clinical implications for personalized implant treatment approaches.

2. Literature Review

Pathogenesis of Peri-implantitis and the Role of Pro-inflammatory Cytokines

2.1 Pathogenesis of Peri-implantitis

Peri-implantitis begins as mucositis, a reversible inflammatory condition limited to the soft tissues surrounding dental implants, which may progress to peri-implantitis with subsequent bone destruction if left untreated (Heitz-Mayfield & Salvi, 2018). The transition from health to disease involves complex interactions between bacterial challenge and host immune response, with several key pathophysiological mechanisms:

1. **Initial bacterial colonization**: Formation of a biofilm on implant surfaces, predominantly composed of gram-negative anaerobic bacteria similar to those found in periodontitis (Fürst et al., 2007).
2. **Host immune response**: Recognition of bacterial components triggering inflammatory cascades, including the production of pro-inflammatory cytokines, chemokines, and other inflammatory mediators by local and infiltrating immune cells (Berglundh et al., 2011).
3. **Tissue destruction**: Persistent inflammation leading to connective tissue breakdown and alveolar bone resorption, primarily through activated osteoclasts (Graves et al., 2011).
4. **Disease progression**: Continued bacterial challenge and dysregulated immune response resulting in progressive bone loss around the implant (Schwarz et al., 2018).

2.2 Pro-inflammatory Cytokines in Peri-implantitis

Pro-inflammatory cytokines serve as key mediators in the pathogenesis of peri-implantitis, orchestrating the inflammatory response and subsequent tissue destruction:

1. **TNF-α**: Initiates and amplifies inflammation, stimulates bone resorption by enhancing osteoclast differentiation and activity, and induces matrix metalloproteinase production leading to connective tissue degradation (Garlet, 2010).
2. **IL-1 family cytokines**: IL-1α and IL-1β promote inflammation, stimulate bone resorption, and induce tissue-destructive enzymes. Elevated levels of IL-1β have been consistently detected in peri-implantitis sites (Faot et al., 2015).
3. **IL-6**: Exhibits pleiotropic effects, including regulation of acute-phase responses, B-cell differentiation, and osteoclast formation, contributing to both inflammation and bone metabolism (Nibali et al., 2012).

4. **RANK/RANKL/OPG axis**: Critical for regulating bone homeostasis, with RANKL promoting osteoclast differentiation and activation, while OPG functions as a decoy receptor, preventing RANKL-RANK interaction and inhibiting bone resorption (Boyce & Xing, 2008).
5. **Matrix metalloproteinases (MMPs)**: Enzymes responsible for degrading extracellular matrix components, contributing to tissue destruction in peri-implantitis. MMPs are upregulated in response to pro-inflammatory cytokines (Sorsa et al., 2006).

Table 1. Summary of Cytokine Gene Polymorphisms Associated with Peri-Implantitis

Gene	SNP (rsID)	Functional Effect	Population	Association	Reference
TNF-α	−308G/A (rs1800629)	transcription	SE Europe	Positive	Rakic et al.
IL-1A	−889C/T (rs1800587)	IL-1α	China	Positive	He et al.
IL-1B	+3954C/T (rs1143634)	IL-1β	China	Positive	He et al.
OPG	rs2073618	Protein change	China	Positive	Zhou et al.

Genetic variations in these cytokine genes can alter their expression levels and functional properties, potentially affecting individual susceptibility to peri-implantitis development and progression (Laine et al., 2006).

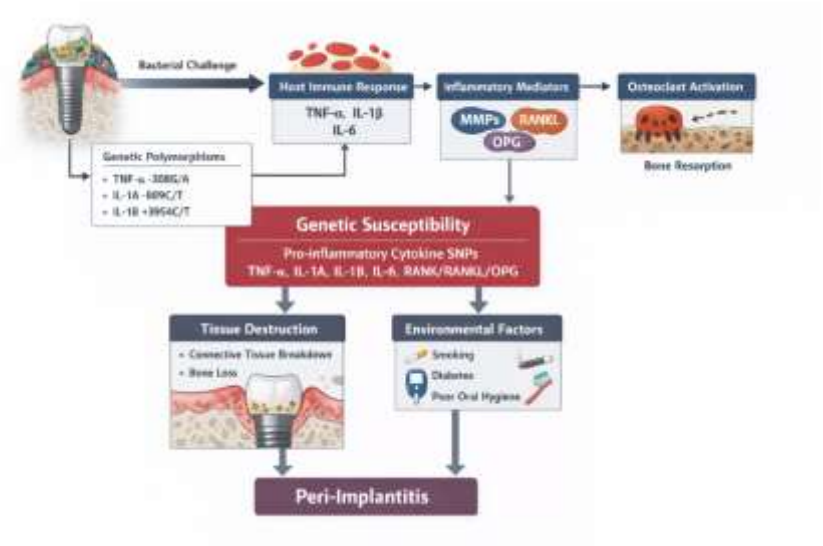

Figure 1. Pathogenic Pathway of Peri-Implantitis

3. Single Nucleotide Polymorphisms in Pro-inflammatory Cytokine Genes

3.1 TNF-α Gene Polymorphisms

TNF-α, encoded by a gene located on chromosome 6p21.3, is a potent pro-inflammatory cytokine that plays a central role in the pathogenesis of peri-implantitis through its effects on inflammation and bone resorption. Several polymorphisms in the TNF-α gene have been investigated in relation to peri-implantitis susceptibility:

3.1.1 TNF-α -308G/A (rs1800629)

The most extensively studied polymorphism in the TNF-α gene is the -308G/A SNP, located in the promoter

region. This polymorphism can influence transcriptional activity, with the A allele associated with increased TNF-α production (Wilson et al., 1997). Studies examining the association between TNF-α -308G/A and peri-implantitis have yielded conflicting results:

- Rakic et al. (2013) reported a significant association between the AG genotype and peri-implantitis in a Southeastern European Caucasian population, with a fivefold increased risk compared to individuals with the GG genotype.
- In contrast, Cury et al. (2009) found no significant association between this polymorphism and peri-implantitis in a Brazilian non-smoking population.
- He et al. (2020), in their study of a Chinese non-smoking population, also found no association between the TNF-α -308G/A polymorphism and the risk of peri-implantitis, consistent with findings from a recent meta-analysis (Liao et al., 2018).

These discrepancies may be attributed to ethnic differences, sample size variations, and heterogeneity in study designs and diagnostic criteria.

3.2 IL-1 Gene Cluster Polymorphisms

The IL-1 gene cluster, located on chromosome 2q13-21, includes genes encoding IL-1α, IL-1β, and IL-1 receptor antagonist (IL-1RN). Polymorphisms in these genes have been extensively studied in relation to periodontal and peri-implant diseases:

3.2.1 IL-1A -889C/T (rs1800587)

This polymorphism in the promoter region of the IL-1A gene can enhance transcriptional activity, with the T allele associated with increased IL-1α production (Dominici et al., 2002). Studies on its association with peri-implantitis have shown:

He et al. (2020) reported that, within a Chinese non-smoking cohort, carriers of the T allele of the *IL-1A* −889C/T polymorphism exhibited a markedly elevated susceptibility to peri-implantitis, with risk estimates ranging from approximately 2.27- to 2.47-fold compared with non-carriers. The same study further demonstrated that individuals homozygous for the TT variant showed significantly poorer periodontal clinical parameters, including increased peri-implant probing depth, higher bleeding on probing scores, elevated gingival and plaque indices, greater calculus accumulation, and more pronounced clinical attachment loss. By contrast, Laine et al. (2006) observed no statistically meaningful relationship between the *IL-1A* −889C/T genetic variant and peri-implantitis among a North European Caucasian population.

3.2.2 IL-1B +3954C/T (rs1143634)

The IL-1B +3954C/T polymorphism, located in exon 5 of the gene, has been shown to influence cytokine expression, with homozygous carriers of the T allele exhibiting elevated production of interleukin-1β (Pociot et al., 1992). Evidence regarding its relationship with peri-implantitis remains mixed. He et al. (2020) observed that, among a Chinese non-smoking population, individuals harboring the T allele of IL-1B +3954C/T had an approximately 1.9- to 1.99-fold higher likelihood of developing peri-implantitis. In addition, Hamdy and Ebrahem (2011) reported that concurrent carriage of the T allele at both IL-1A −889 and IL-1B +3954 was linked to increased peri-implant tissue breakdown in patients presenting with inflammatory peri-implant conditions. Conversely, other investigations have failed to identify a statistically significant association between this genetic variant and peri-implantitis (Lachmann et al., 2007; Melo et al., 2012).

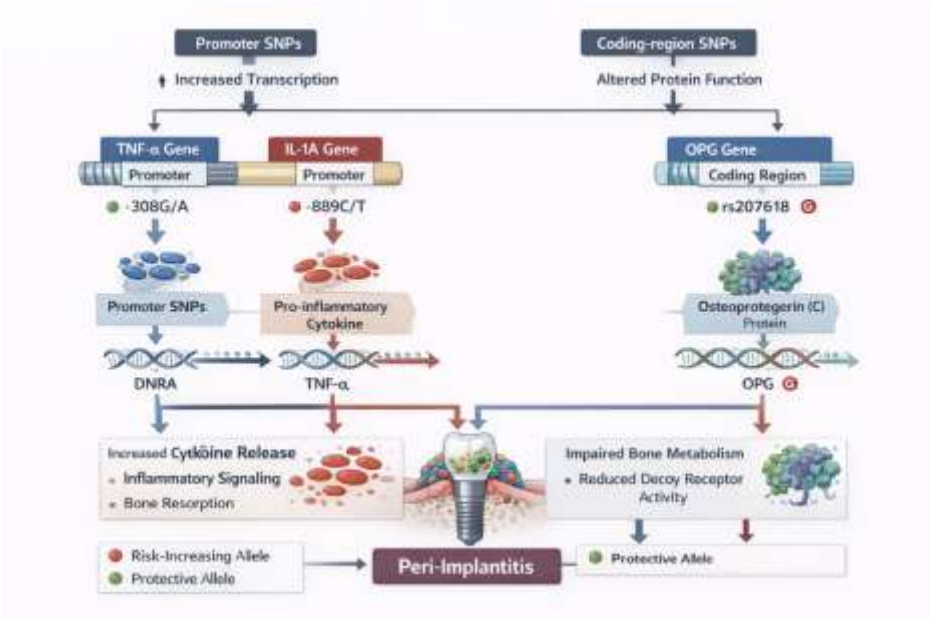

Figure 2. Genetic Polymorphisms and Molecular Mechanisms

3.2.3 IL-1 Composite Genotype

Some studies have investigated the combined effect of polymorphisms in the IL-1 gene cluster, commonly referred to as the IL-1 composite genotype (positive when having at least one copy of the T allele at both IL-1A -889 and IL-1B +3954 loci):

Gruica et al. (2004) found that IL-1 composite genotype-positive individuals had increased risk for peri-implantitis, particularly among smokers, suggesting a gene-environment interaction. In contrast, Laine et al. (2006) and Lachmann et al. (2007) found no significant association between the IL-1 composite genotype and peri-implantitis.

3.3 MMP Gene Polymorphisms

Matrix metalloproteinases (MMPs) are zinc-dependent endopeptidases capable of degrading extracellular matrix components, playing crucial roles in tissue remodeling and destruction during inflammatory processes. Several polymorphisms in MMP genes have been investigated in relation to peri-implantitis:

3.3.1 MMP-1 -1607 1G/2G (rs1799750)

This polymorphism involves the insertion of a guanine (G) at position -1607 in the MMP-1 gene promoter, creating an Ets binding site that enhances transcriptional activity. Studies examining its association with peri-implantitis have shown:

- Leite et al. (2008) reported that the presence of the 2G allele might be linked to implant failure.
- However, Saremi et al. (2024) found no significant association between MMP-1 -1607 1G/2G polymorphism and peri-implantitis in an Iranian population.

3.3.2 MMP-3 -1171 5A/6A (rs35068180)

This polymorphism in the promoter region of the MMP-3 gene involves either five or six consecutive adenines (A), with the 5A allele associated with higher promoter activity and increased MMP-3 expression:

- Saremi et al. (2024) demonstrated a significant difference in the distribution of MMP-3 -1171 5A/6A genotypes between patients with peri-implantitis and healthy controls in an Iranian population.
- Importantly, they found that the presence of the 6A allele in the MMP-3 genotype resulted in a significant decrease in peri-implantitis risk, suggesting a potential protective effect.

3.3.3 MMP-7 -181 A/G (rs11568818)

This polymorphism in the promoter region of the MMP-7 gene can influence gene expression, with the G allele associated with enhanced MMP-7 expression (Kesh et al., 2015):

- Saremi et al. (2024) reported a significant difference in the distribution of MMP-7-181 A/G genotypes between peri-implantitis patients and healthy controls, with the GG genotype more frequent in peri-implantitis patients.

3.3.4 Other MMP Polymorphisms

Additional MMP gene polymorphisms have been investigated in relation to peri-implantitis, including:

- MMP-2 -1306 C/T (rs243865): Saremi et al. (2024) found no significant association between this polymorphism and peri-implantitis in an Iranian population.
- MMP-13 -77 A/G (rs2252070): Similarly, no significant association was observed between this polymorphism and peri-implantitis risk (Saremi et al., 2024).
- MMP-8: Polymorphisms in the MMP-8 gene have been suggested as possible risk factors for peri-implantitis (Chmielewski & Pilloni, 2023), although more research is needed to confirm this association.

3.4 RANK/RANKL/OPG Gene Polymorphisms

The RANK/RANKL/OPG signaling pathway plays a critical role in regulating bone metabolism, with RANKL promoting osteoclast differentiation and activity. At the same time, OPG acts as a decoy receptor, inhibiting RANK-RANKL interaction and osteoclastogenesis. Several polymorphisms in these genes have been examined in relation to peri-implantitis:

3.4.1 RANK rs3826620 (G>T)

This intronic polymorphism in the RANK gene may influence gene expression and function:

- Silva et al. (2020) found no significant association between RANK rs3826620 polymorphism and peri-implantitis or mucositis in a Brazilian population from the Amazon region.

3.4.2 RANKL rs9594738 (C>T)

This intronic polymorphism in the RANKL gene has been investigated in relation to bone mineral density and bone-related disorders:

- Silva et al. (2020) reported no significant association between RANKL rs9594738 polymorphism and peri-implant diseases in a Brazilian population.

3.4.3 OPG rs2073618 (C>G)

This missense variant in exon 1 of the OPG gene leads to amino acid exchange (Lysine to Asparagine) and may affect protein function:

- Zhou et al. (2016) found that the OPG rs2073618 polymorphism may be associated with the risk of peri-implantitis in a Chinese population.
- However, Silva et al. (2020) observed no significant association between this polymorphism and peri-implantitis in a Brazilian population from the Amazon region.

Additional studies have investigated other polymorphisms in these genes:

- Kadkhodazadeh et al. (2012) reported an association between OPG (G1181C) and peri-implantitis in an Iranian population.
- Kadkhodazadeh et al. (2013) also found an association between RANKL rs9533156 polymorphism and peri-implantitis in an Iranian population.

These discrepancies in findings across different studies highlight the complex nature of genetic associations and the potential influence of population-specific factors.

4. Interactions Between Genetic and Environmental Factors

The development and progression of peri-implantitis likely involve complex interactions between genetic susceptibility and various environmental factors. Understanding these interactions is crucial for assessing individual risk and implementing appropriate preventive and therapeutic strategies.

Table 2. Gene–Environment Interactions in Peri-Implantitis

Genetic Variant	Environmental Factor	Effect	Evidence
IL-1 composite	Smoking	↑ Risk	Gruica et al.
TNF-α SNPs	Periodontitis	↑ Risk	Laine et al.
MMP SNPs	Biofilm	↑ Tissue loss	Saremi et al.

4.1 Smoking and Genetic Polymorphisms

Smoking is a well-established risk factor for peri-implantitis, with smokers exhibiting higher prevalence and severity of disease compared to non-smokers (Chrcanovic et al., 2015). Several studies have investigated potential interactions between smoking and genetic polymorphisms in relation to peri-implantitis:

- Gruica et al. (2004) reported a synergistic effect between IL-1 composite genotype and smoking, with genotype-positive smokers showing significantly higher rates of implant complications compared to genotype-negative non-smokers.
- He et al. (2020) conducted their study in a non-smoking population to eliminate the confounding effect of smoking when assessing genetic associations with peri-implantitis.
- Saremi et al. (2024) excluded smokers from their study for similar reasons, recognizing the strong independent effect of smoking on peri-implantitis risk.

These findings suggest that genetic polymorphisms may modulate the impact of smoking on peri-implantitis risk, potentially explaining why some smokers experience more severe disease than others with similar smoking habits.

4.2 History of Periodontitis

A history of periodontitis is another significant risk factor for peri-implantitis, with affected individuals showing higher susceptibility to peri-implant diseases (Sgolastra et al., 2015). The interaction between periodontal history and genetic polymorphisms has been explored:

- He et al. (2020) found that a positive history of periodontitis was significantly more frequent in peri-implantitis patients compared to healthy controls (54.2% vs. 33.3%), suggesting a common susceptibility pattern.
- Several genetic polymorphisms associated with periodontitis, particularly in IL-1 and TNF-α genes, have also been implicated in peri-implantitis susceptibility, indicating shared genetic risk factors (Laine et al., 2006).
- The presence of specific genetic variants may predict increased susceptibility to both conditions, potentially guiding clinical decision-making regarding implant therapy in patients with a history of periodontitis.

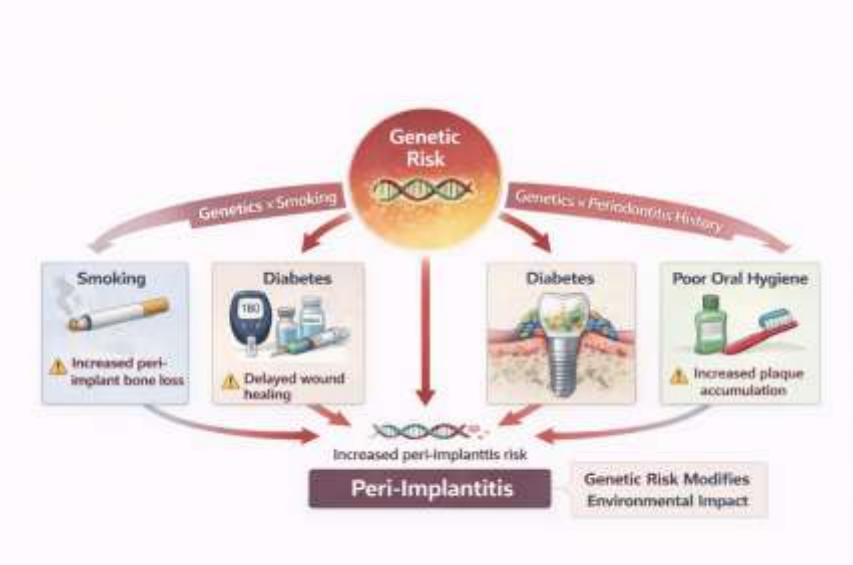

Figure 3. Gene–Environment Interaction Model

4.3 Diabetes and Metabolic Conditions

Diabetes mellitus and other metabolic conditions can influence the host's inflammatory response and wound healing, potentially affecting peri-implant health. Interactions between these conditions and genetic polymorphisms have been investigated:

- Saremi et al. (2024) found that diabetes was significantly associated with both mucositis and peri-implantitis, highlighting its role as a risk factor.
- Studies exploring the combined effect of diabetes and pro-inflammatory cytokine gene polymorphisms on peri-implantitis risk are limited, representing an important area for future research.

4.4 Oral Hygiene and Plaque Control

Bacterial biofilm is a primary etiological factor in peri-implantitis, with poor oral hygiene significantly increasing the risk of disease. The interaction between plaque control and genetic susceptibility has been examined:

- Saremi et al. (2024) reported that the presence of peri-implant biofilm was significantly associated with both mucositis and peri-implantitis, and multivariate analysis showed that absence of biofilm significantly decreased the risk of peri-implant disease.
- He et al. (2020) found that all periodontal variables, including plaque index, were significantly higher in peri-implantitis patients compared to healthy controls.
- The influence of genetic polymorphisms on individual response to bacterial challenge may explain why some patients develop more severe inflammation despite similar plaque levels.

4.5 Other Factors

Additional factors that may interact with genetic polymorphisms to influence peri-implantitis susceptibility include:

- **Alcohol consumption**: Saremi et al. (2024) reported an association between alcohol drinking habits and peri-implantitis.

- **Peri-implant soft tissue phenotype**: He et al. (2020) and Saremi et al. (2024) both found that a thin peri-implant phenotype was associated with increased risk of peri-implantitis, suggesting potential interactions between tissue biotype and genetic factors.
- **Age**: Advanced age has been associated with increased peri-implantitis risk (Saremi et al., 2024), possibly due to cumulative effects of risk factors and age-related changes in immune function and tissue healing capacity.

Understanding these complex interactions between genetic and environmental factors is essential for developing personalized approaches to risk assessment, prevention, and management of peri-implantitis.

5. Clinical Implications and Future Perspectives

5.1 Potential Applications in Clinical Practice

The identification of genetic markers associated with peri-implantitis susceptibility has several potential clinical applications:

5.1.1 Risk Assessment and Patient Selection

Genetic testing for specific polymorphisms could complement conventional risk assessment, helping clinicians identify high-risk individuals before implant placement:

- Patients carrying high-risk genotypes might benefit from more stringent patient selection criteria, alternative treatment options, or enhanced preventive protocols.
- Combining genetic information with clinical risk factors (smoking, history of periodontitis, diabetes) could provide a more comprehensive risk profile than either approach alone.

5.1.2 Personalized Treatment Planning

Knowledge of a patient's genetic susceptibility could inform various aspects of implant treatment planning:

- **Implant type and surface selection**: High-risk patients might benefit from specific implant designs or surface characteristics that minimize biofilm accumulation and promote favorable tissue integration.
- **Loading protocols**: Modified loading protocols might be considered for patients with genetic predisposition to enhanced inflammatory responses or altered bone metabolism.
- **Augmentation procedures**: Genetic information could influence decisions regarding bone and soft tissue augmentation to optimize peri-implant tissue architecture.

5.1.3 Customized Maintenance Protocols

Tailoring supportive care based on genetic risk profiles could enhance long-term implant outcomes:

- Patients with high-risk genotypes might benefit from shorter maintenance intervals, enhanced plaque control measures, or adjunctive therapies.
- More frequent radiographic monitoring might be warranted for patients genetically predisposed to accelerated bone loss.

Table 3. Clinical Implications of Genetic Findings

Genetic Risk Level	Clinical Recommendation
High-risk genotype	Shorter recall intervals
IL-1 positive	Enhanced maintenance
OPG variants	Conservative loading

5.2 Limitations and Challenges

Despite the potential clinical applications, several limitations and challenges must be addressed:

5.2.1 Study Heterogeneity and Conflicting Results

The current literature is characterized by considerable heterogeneity in study designs, populations, sample sizes, and outcome definitions, leading to conflicting results:

- Different diagnostic criteria for peri-implantitis across studies complicate the interpretation and comparison of findings.
- Variations in allele frequencies among different ethnic populations limit the generalizability of results.

5.2.2 Complex Genetic Architecture

Peri-implantitis likely involves multiple genetic variants with small to moderate individual effects, making it challenging to develop clinically useful predictive models:

- Most studies focus on candidate gene approaches examining a limited number of polymorphisms, potentially missing other relevant genetic factors.
- Interactions between multiple genetic variants and environmental factors further complicate the genetic architecture of the disease.

5.2.3 Cost-Effectiveness and Practical Implementation

The clinical utility of genetic testing for peri-implantitis risk assessment depends on its cost-effectiveness and practical implementation:

- Current genetic testing methods may be too costly for routine clinical use, particularly when considering the limited predictive value of individual polymorphisms.
- Interpreting genetic information and translating it into clinical decisions requires specialized knowledge that many practitioners may lack.

5.3 Future Research Directions

Several areas warrant further investigation to advance our understanding of genetic factors in peri-implantitis:

5.3.1 Larger Prospective Studies

Longitudinal studies with larger sample sizes and well-defined diagnostic criteria are needed to establish more robust associations between genetic polymorphisms and peri-implantitis:

- Prospective cohort studies following patients from implant placement through long-term maintenance could provide valuable insights into the predictive value of genetic markers.
- Multi-center collaborations could help achieve adequate sample sizes and enhance the generalizability of findings.

5.3.2 Genome-Wide Association Studies

Expanding beyond candidate gene approaches to genome-wide association studies (GWAS) could identify novel genetic variants associated with peri-implantitis:

- GWAS approaches have successfully identified genetic risk factors for various complex diseases and could provide a more comprehensive view of the genetic architecture of peri-implantitis.
- Integration of GWAS data with functional genomics studies could elucidate the biological mechanisms underlying genetic associations.

5.3.3 Genetic Risk Scores and Predictive Models

Developing and validating genetic risk scores that combine multiple polymorphisms could enhance predictive value:

- Weighted genetic risk scores incorporating the relative effect sizes of multiple variants could

provide more accurate risk prediction than individual polymorphisms.
- Combining genetic information with clinical risk factors in integrated predictive models could further improve risk stratification.

5.3.4 Gene-Environment Interactions

More comprehensive analysis of interactions between genetic polymorphisms and environmental factors is needed:

- Investigating how specific genetic variants modify the effects of smoking, diabetes, or oral hygiene on peri-implantitis risk could enhance our understanding of disease pathogenesis.
- Identifying genetic factors that influence response to preventive and therapeutic interventions could guide personalized treatment approaches.

5.3.5 Epigenetic Studies

Exploring epigenetic modifications that regulate gene expression in peri-implantitis could provide additional insights:

- DNA methylation, histone modifications, and non-coding RNAs may influence cytokine gene expression in response to environmental factors, representing potential biomarkers and therapeutic targets.

6. Conclusion

Single-nucleotide polymorphisms in pro-inflammatory cytokine genes represent promising biomarkers for assessing individual susceptibility to peri-implantitis. Current evidence suggests that genetic variations in TNF-α, IL-1, IL-6, RANK/RANKL/OPG, and matrix metalloproteinase genes may influence the development and progression of peri-implant diseases through their effects on inflammatory responses and bone metabolism. However, conflicting results across studies, methodological heterogeneity, and complex gene-environment interactions present challenges for translating these findings into clinical practice. Future research should focus on larger prospective studies with standardized diagnostic criteria, genome-wide approaches to identify novel genetic markers, and comprehensive analysis of gene-environment interactions. The development and validation of genetic risk scores that combine multiple polymorphisms with clinical risk factors could enhance predictive value and facilitate personalized approaches to implant therapy. As our understanding of the genetic basis of peri-implantitis continues to evolve, integrating genetic information into clinical decision-making has the potential to improve risk assessment, treatment planning, and maintenance strategies, ultimately enhancing long-term implant outcomes. However, careful evaluation of the clinical utility, cost-effectiveness, and ethical implications of genetic testing is essential before widespread implementation in implant dentistry practice.

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