Pharmacogenetics of rheumatoid arthritis: Potential targets from susceptibility genes and present therapies

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Abstract: Rheumatoid arthritis (RA) is a chronic heterogeneous autoimmune disorder of unknown etiology resulting in inflammation in the synovium, cartilage, and bone. Genetic factors play an important role in susceptibility to RA as the heritability of RA is between 50% and 60%, with the human leukocyte antigen (HLA) locus accounting for at least 30% of overall genetic risk. Outside the major histocompatibility complex (MHC) region, six additional risk loci have been identified and validated including PTPN22, STAT4, PADI4, CTLA4, TNEAIP3-OLIG3, and TRAF1/C5. Genetic factors are also important in RA pharmacotherapy due to the gene-dependent activity of enzymes involved in the pharmacokinetics and/or pharmacodynamics of RA medications. Indeed, there is great variability in drug efficacy as well as adverse events associated with any anti-rheumatic therapy and genetics is thought to contribute significantly to this inter-individual variability in response. This review will summarize the genetic factors that have been implicated in the pathogenesis of RA, and how these determinants may factor into the potential pharmacogenetics of this disease. We will also review the therapeutic agents that are currently being utilized or presently being evaluated in the treatment of RA, along with potential pharmacogenetic markers that have been proposed for such medications.

Keywords: rheumatoid arthritis, susceptibility genes, pharmacogenetics

Introduction
Rheumatoid arthritis (RA) is a systemic inflammatory disease that results in inflammation in the synovium, cartilage and bone.1 If RA is not adequately treated in a timely manner, there is significant negative impact to patient health accompanied by a large societal burden. RA typically presents in the sixth decade of life with symmetrical small joint pain and swelling in the hands, feet, and wrists. With disease progression, medium to large size joints such as the shoulder, elbow, knees, and hip become involved. Extra-articular manifestations are common in RA and include features related to vasculitis (eg, rheumatoid nodule, episcleritis, peripheral neuropathy or palpable purpura) and/or lymphocytic infiltrate (eg, sicca symptoms, hypothyroidism, interstitial lung disease, splenomegaly, or lymphadenopathy).

The current therapeutic management of RA includes symptomatic management and early disease modification. Nonsteroidal anti-inflammatory drugs (NSAIDs) and glucocorticoids are first line therapies used for symptomatic relief. However, if oral corticosteroids are instituted, a conscious effort must be made to minimize dosage. In conjunction with the use of NSAIDs, disease-modifying antirheumatic drugs (DMARDs) are promptly initiated in the management of RA. DMARDs attempt to slow down the progression of RA and include: methotrexate (MTX), azathioprine...
(AZA), sulfasalazine (SSZ), hydroxychloroquine (HCQ), and leflunomide (LFA). These agents are either used as monotherapy in a sequential fashion, or more commonly as part of a cocktail with multiple DMARDs. Unless there is a contraindication to MTX, this agent is the DMARD of choice among most rheumatologists. If significant disease activity persists despite an adequate trial of DMARDs, then more targeted biologic therapies such as inhibitors of tumor necrosis factor-α (TNF-α), interleukin-1 (IL-1), IL-6, co-stimulatory molecule, or B-cells are employed. The aforementioned roles of various DMARDs and biologic agents serve only as a antecedent to a more detailed discussion of their potential pharmacogenetic targets, presented in upcoming sections.

The etiology of RA is still not fully elucidated. Theories regarding the pathogenesis of RA must address three key elements of the disease: onset of autoimmunity, chronic inflammation, and subsequent joint destruction. Autoimmunity is manifested by the presence of immunoglobulin G (IgG) antibodies, clinically detectable prior to the onset of RA, which represents the lymphoid phase of the disease. The lymphoid phase is followed by the articular phase which is triggered by poorly understood environmental and biomechanical events in a genetically susceptible host. The environmental factors most frequently associated with RA pathogenesis include smoking and various infectious agents (eg, parvovirus). The persistent inflammation subsequently initiates articular destruction, a process mediated by osteoclasts. The importance of cytokines in the pathogenesis of RA is highlighted by their involvement in every phase of pathogenesis.

In this review, we will summarize the genetic factors and the cytokines that have been implicated in the pathogenesis of RA, and how these determinants may factor into the potential pharmacogenetics of this disease. Moreover, we will review therapeutic agents currently being utilized or presently being evaluated in the treatment of RA, along with potential pharmacogenetic markers that have been proposed for such medications.

Multiple loci are known to contribute to the risk of developing RA. The most compelling evidence to support a genetic basis is the consistent and reproducible association of RA within the major histocompatibility complex (MHC), particularly the human leukocyte antigen (HLA) alleles. This region accounts for at least 30% of overall genetic susceptibility to RA. Within the HLA locus, the strongest association is with alleles of HLA-DRB1, but recent evidence indicates that other HLA genes also contribute to genetic risk. Increasingly genes outside the MHC region on different chromosomes (Figure 1) are being indentified regarding the genetics of RA susceptibility (see also Table 1). To date, the most consistent association outside the MHC region appears to be with a polymorphism in the protein tyrosine phosphatase nonreceptor 22 (PTPN22) gene. Other candidate genes have been identified, but the scope of this review will be limited only to the best studied non-MHC variants.

**MHC locus is associated with RA pathogenesis**

Association with variations in the MHC or HLA locus on chromosome 6 (6p21.3) was identified over three decades ago, and is the primary locus that has been consistently and reproducibly associated with RA susceptibility across all studied populations. The class II molecules of the HLA locus are recognized as the most powerful genetic determinants for RA contributing at least 30% of the total genetic effect. Numerous classes of HLA-DRB1 alleles known to be associated with RA susceptibility comprise the shared epitope (SE) region (Table 2). The HLA-DRB1 alleles of the class II HLA-DRB1 gene encode a conserved sequence of amino acids (ie, QKRAA, QRRAA, or RRRAA) at positions 70 to 74 in the third hypervariable region (HVR3) of the class II DRB1 chain. The aforementioned HLA-DRB1 alleles and their conserved amino acid sequence are collectively referred to as the shared epitope (SE), which distinguishes disease-associated alleles from those that do not confer risk for RA.

As previously mentioned, extensive evidence exists indicating that the HLA-DRB1 SE is strongly associated with susceptibility to RA. While HLA-DRB1 SE alleles confer risk to RA, not all alleles display the same magnitude of association with RA. For example, certain alleles (eg, HLA-DRB1*0401) confer a much stronger degree of risk compared with other alleles (eg, HLA-DRB1*0101). Moreover, certain allelic combinations (eg, HLA-DRB1*0401/*0404) appear to confer a very high risk to RA susceptibility, and even severity of the disease. The strength of association is influenced...
by factors including, but not limited to the: 1) frequency and number of SE alleles; 2) amino acid at position 70 to 74 in the HVR3 region of the class II DRB1 chain; and 3) anti-citrulline-peptide antibody (ACP A) status. The frequency of the SE alleles varies considerably depending on ethnicity. For example, the HLA-DRB1*0401 and *0404 alleles are predominately associated with RA in Caucasian populations, whereas the *0405 and *0101 alleles are associated with RA in Asian and Jewish populations, respectively. In a recent study of French Caucasians, the authors proposed that not only is RA susceptibility conferred by amino acid residues at positions 72 to 74 (ie, RAA), but that the association strength is modulated by amino acid residues at positions 70 and 71 (Table 2). This hypothesis and proposed classification scheme has been subsequently supported by findings in other populations. However, only a single study has investigated the relevance of this new HLA-DRB1 classification in terms of RA susceptibility on both Caucasian and non-Caucasian cohorts.

**Figure 1** Location of validated risk genes for rheumatoid arthritis.

### Table 1 Genetic variants demonstrating strong susceptibility to rheumatoid arthritis

| Gene/Locus       | Number of RA patients | OR    | 95% CI     | P value | Ethnicity | Ref. |
|------------------|-----------------------|-------|------------|---------|-----------|------|
| HLA-DRB1*SE      | 689                   | 3.0   | 2.2–4.2    | 3.0 × 10⁻⁸ | Caucasian | 31   |
|                  | 2,204                 | 1.9   | 1.4–2.8    | <0.05   | Asian     | 9    |
| PTPN22           | 2370                  | 1.6   | 1.4–1.8    | 4.8 × 10⁻¹² | Caucasian | 37   |
| STAT4            | 16,088                | 1.3   | 1.2–1.4    | <0.001  | Caucasian | 49   |
|                  | 16,088                | 1.2   | 1.1–1.3    | <0.001  | Asian     | 49   |
| PADI4            | 5,591                 | 1.1   | 1.0–1.1    | 0.72    | Caucasian | 71   |
|                  | 3,713                 | 1.3   | 1.2–1.4    | <0.0001 | Asian     | 64   |
| CTLA4            | 2370                  | 1.1   | 1.0–1.2    | 0.004   | Caucasian | 37   |
| TNFAIP3-OLIG3    | 3962                  | 1.2   | 1.1–1.3    | 2.6 × 10⁻⁶ | Caucasian | 91   |
| TRAF1/C5         | 1522                  | 1.4   | 1.2–1.5    | 2.8 × 10⁻⁸ | Caucasian | 95   |

**Abbreviations:** HLA-DRB1 SE, major histocompatibility complex, class II, DR beta 1; PTPN22, protein tyrosine phosphatase, non-receptor type 22 (lymphoid); STAT4, signal transducer and activator of transcription 4; PADI4, peptidyl arginine deiminase, type IV; CTLA4, cytotoxic T-lymphocyte-associated protein 4; TNFAIP3-OLIG3, tumor necrosis factor, alpha-induced protein 3/oligodendrocyte transcription factor 3; TRAF1/C5, TNF receptor associated factor/complement component 5.
In that study (n_cases/controls = 759/789), a positive association with RA susceptibility was demonstrated for S_2 allele carriers (odds ratio [OR] = 2.1, 95% confidence interval [CI]: 1.5–3.0; P < 0.0001) and S_P allele carriers (OR = 2.74, 95% CI: 2.0–3.7; P < 0.0001).^{36}

The RA susceptibility associated with the HLA-DRB1 SE appears to be limited to a subset of patients who have ACPA-positive and not ACPA-negative RA.^{12,27–31} For example, in the largest cohort studied to date, the presence of any HLA-DRB1 SE allele was strongly associated with an ACPA-positive phenotype (OR = 3.0, 95% CI: 2.2–4.2; P = 3.0 × 10^{-9}).^{31} That HLA-DRB1 SE confers risk specifically to ACPA and that these antibodies are present in approximately 70% of RA patients^{32} explains, at least in part, an association between these alleles and susceptibility to RA and perhaps more importantly, suggests a difference in the pathology between ACPA-positive and ACPA-negative RA.

In addition to affecting disease susceptibility, the HLA SE appears to be important in onset, progression, and severity of RA. In a large European cohort, the presence of any HLA SE allele was associated with an average 3.6 years earlier diagnosis compared with absence of HLA SE,^{31} a finding replicated in an American cohort.^{33} Moreover, large differences were identified in rates of erosion progression between ACPA-positive and ACPA-negative RA with respect to the HLA SE. The strength of this association appears to be dependent on the number of copies of the SE allele (two copies: OR = 11.8, P < 0.0001; one copy: OR = 4.4, P < 0.0001). This finding combined with the report that ACPA-positive has a more aggressive clinical course than ACPA-negative RA,^{34} strongly implies that this locus not only plays a significant role in RA susceptibility, but also is important in the severity of RA. Thus, in the clinical setting, these determinants (ie, SE alleles or ACPA status) will likely translate into poor therapeutic impacts by virtue of the fact that these subset of patients have a greater burden of inflammatory disease.

**PTPN22 is associated with RA pathogenesis**

The tyrosine phosphatase nonreceptor 22 (PTPN22) gene, located on chromosome 1 (1p13), was the first non-HLA gene associated with RA.^{35} Specifically, the minor allele of a non-synonymous 1858C>T single nucleotide polymorphism (SNP; rs2476601), results in an amino acid change from R620W in the PTPN22 gene.^{35} Outside of the HLA region, this variant exhibits the strongest and most robust association with RA (Table 1). The well studied associations with HLA-DRB1 and PTPN22 explain about 50% of the genetic contribution to RA disease susceptibility.^{36} A meta-analysis of 13 RA studies (n_cases/controls = 2370/1757) revealed a strong association of the T-allele genotype with the development of RA (OR = 1.43, 95% CI: 1.2–1.7; P = 0.0001), but not ACPA-negative (OR = 1.0, 95% CI: 0.8–1.3; P = 0.73) RA;^{37} a finding that strengthens the theory that ACPA-positive and ACPA-negative RA have different pathologies. The greater risk allele frequency present in Caucasian RA populations (OR = 1.7, 95% CI: 1.2–2.2; P < 0.0001)^{35} is consistent with the extensive evidence confirming that the PTPN22 variant is associated with RA in all populations of European or North American descent.^{35,37–41} A lack of association of PTPN22 in Asian and African populations is reflected by the absence or very low frequency of this risk allele in that demographic.^{35}

Similar to the SE, the PTPN22 appears to be important in onset, progression, and severity of RA. In a large European cohort, the presence of any PTPN22 variant was associated with an average 4.2 years earlier diagnosis compared with absence of a variant;^{31} a finding subsequently replicated in another large Caucasian cohort. In contrast to the HLA SE, PTPN22 does not appear to be associated with an erosive phenotype.^{31} This finding combined with the report that ACPA-positive has a more aggressive clinical course than ACPA-negative RA,^{34} suggests that PTPN22 not only plays a significant role in RA susceptibility,
but may also be important in severity of RA; an effect similarly reported for the HLA SE. Likewise, the presence of the PTPN22 variant may influence the outcome of various therapeutic agents in RA. Of course, such speculation requires further confirmation.

PTPN22 which encodes the intracellular protein lymphoid tyrosine phosphatase (LYP), a powerful inhibitor of T-lymphocyte activation, plays a critical role in T-lymphocyte antigen receptor (TCR) signaling pathway. The PNPT22 polymorphism is a gain-of-function variant resulting in greater phosphatase activity which elevates the activation of T-lymphocytes and confers enhanced inhibition of activation. Interestingly, T-lymphocytes expressing the PTPN22 polymorphism produce less IL-2 in response to T-lymphocyte signaling compared to wildtype controls. Such a variant which enhances inhibition of T-lymphocyte activation may result in weaker signaling and failure to effectively remove auto-reactive T-lymphocytes, which could explain, at least in part, its relevance to RA.

STAT4 is associated with RA pathogenesis

The signal transducer and activator of transcription 4 (STAT4) gene, located on chromosome 2 (2q32.2–q32.3) is another non-MHC gene associated with RA pathogenesis. Specifically, a SNP was identified at position 274 (−2358G>A; rs7574865) within the third intron of the STAT4 gene. Four polymorphisms in tight linkage disequilibrium (ie, rs11889341, rs7574865, rs8179673, and rs10181656) form a susceptibility haplotype which is tagged by the T allele (rs7574865), have the strongest reported association with RA. A meta-analysis conducted on 15 studies (n cases/controls = 16,088/16,509) revealed an significant association between RA and the STAT4 variant (rs7574865) in both Caucasians (OR = 1.3, 95% CI: 1.2–1.4; P < 0.001) and Asians (OR = 1.2, 95% CI: 1.1–1.3; P < 0.001). The association of STAT4 variant (rs7574865) with RA was validated in patients from European, North American, and Asian descent. Europeans appear to have the lowest (21.4%) and Asians the highest (32.0%) prevalence of the rs7574865 variant among the populations studied. Stratification of RA patients according to the presence of ACPA antibody revealed a statistically significant association between the rs7574865 variant and RA in both ACPA-positive and ACPA-negative RA patients versus controls. That STAT4 confers risk specifically to ACPA, that these antibodies are present in approximately 70% of RA patients, and that a similar finding has been demonstrated with SE and PTPN22, explains, at least in part, an association between STAT4 and susceptibility to RA and again strongly indicate a difference in the pathology between ACPA-positive and ACPA-negative RA.

The JAK/STAT pathway is the signaling target of a multitude of cytokines that are thought to play biologically significant roles in rheumatoid synovial inflammation. Specifically, STAT4, which encodes STAT4, transmits signals induced by several key cytokines, including IL-12, IL-23, and type 1 interferons (IFNs). Activated STAT4 transcribes specific genes including interferon-γ, and plays a critical role in the development of type 1 helper T (Th1) lymphocyte response thought to drive the chronic autoimmune response. STAT4 has also been implicated in the differentiation of Th17 cells; an effect dependent in part on the activity of IL-23. Thus, the JAK/STAT pathway with its many interactions, including various inflammatory cytokines, may explain, at least in part, the association of the STAT4 gene with chronic inflammatory disorders including RA.

PADI4 is associated with RA pathogenesis

The peptidylarginine deiminase 4 (PADI4) gene, located on chromosome 1 (1p36), is known to be associated with RA, particularly in Asian populations. The strongest association has been demonstrated for a SNP located in intron 3 (341-15A>T) of PADI4, called PADI4_94 (rs2240340) and a recent meta-analysis revealed a significant association between RA and the PADI4_94 SNP in Asian populations (OR = 1.3, 95% CI: 1.2–1.4; P < 0.0001). In contrast, findings in cohorts of European ancestry have been inconsistent. Whereas PADI4_94 was found to be associated with RA in North American and German populations, studies in Spanish, Swedish, and UK populations reported no evidence for association of PADI4 with RA. Analysis of data collected in the largest study performed to date (n cases/controls = 5,591/13,638) gave an overall OR of 1.01 (95% CI: 1.0–1.1; P = 0.72), indicating that PADI4_94 genotype is not associated with RA in European Caucasian descent. This result is supported by a recent meta-analysis which confirmed a lack of association between PADI4_94 genotype and RA in people of European descent (OR = 1.1, 95% CI: 1.0–1.1; P = 0.12). This meta-analysis contrasted two earlier meta-analyses which suggested that the PADI4_94 polymorphism confers susceptibility to RA in those of European descent (OR = 1.1; 95% CI: 1.0–1.2; P = 0.0096), albeit to a lesser degree than in Asian subjects. The discrepancy between studies of Caucasian descent can be explained, at least in part, by previous studies being underpowered to detect an OR of this level, thus producing false-positive results. Therefore, PADI4_94 may be in LD with the true disease associated allele in Asian but
not Caucasian populations. A possible explanation for the difference between RA patients from Asian and European descent may be that PADI4 is associated only with a subgroup of RA patients. Specifically, the association between PADI4 genotype and RA may be restricted to patients with more severe disease. Unlike the HLA-DRB1, PTPN22, and STAT4 genes, there is growing evidence that PADI4 polymorphisms play a role in the development RA in Asian populations independent of ACPA status. This observation suggests that the aforementioned genes may affect RA susceptibility via different but possibility convergent mechanisms. This does not preclude the possibility that PADI4 interacts with and modulates the activity of ACPA-dependent genetic factors such as the HLA SE.

The PADI4 gene encodes the type 4 peptidylarginine deiminase enzyme, which catalyses the post-translational modification of arginine to citrulline, generating citrullinated proteins. The mechanism by which PADI4 genotype may influence RA susceptibility has not yet been elucidated. While the link between synovial intracellular citrullinated proteins and ACPA status emphasizes the role of deimination of synovial proteins in RA, there is no compelling evidence supporting PADI4 genotypes correlating with ACPA levels or ACPA-positive disease in particular. Antibodies to these citrullinated peptides are highly specific for RA and often precede the development of disease, suggesting a critical role in RA pathogenesis. In addition, PADI4 mRNA was detected in hematological cells and pathological synovial tissues, and is significantly overexpressed in the blood of RA patients. Moreover, anti-PAD-4 auto-antibodies were associated with the PADI4 susceptibility haplotype. Collectively, these reports suggest that critical link between the PADI4 gene and the pathogenesis of RA in Asian populations.

**CTLA4 is associated with RA pathogenesis**

The cytotoxic T lymphocyte antigen 4 (CTLA4) gene, which is located on chromosome 2 (2q33), has been investigated frequently in relation to RA. While other polymorphisms within the CTLA4 gene appear to be associated with RA, an G>A SNP in the 3’ untranslated region (CT60; rs3087243) has received a more thorough investigation, especially in European populations. Although previous case-control studies in various populations have suggested a possible association of CTLA4 alleles with RA, the results of these studies are often inconclusive and are sometimes contradictory. A large cohort (n_cases/controls = 2,370/1,757) from the North American Rheumatoid Arthritis Consortium (NARAC) and the Swedish Epidemiological Investigation of Rheumatoid Arthritis (EIRA) collections, provided support for an association of CTLA4 (CT60 allele) with the development of RA, but only in the NARAC cohort (OR = 1.1, 95% CI: 1.0–1.2; P = 0.004). When those results were combined with previously published data for CTLA4, it demonstrated continued evidence of association with RA (OR = 1.1, 95% CI: 1.0–1.2; P = 0.01). These earlier results correlated well with a recent meta-analysis which confirmed an association of CTLA4 gene polymorphism with RA in Caucasians (OR = 0.9, P = 1.8 × 10−7) which also revealed that CTLA4 enhanced the development of ACPA-positive as compared with ACPA-negative RA. Similar to HLA-DRB1 SE and PTPN22, these reports clearly indicate that CTLA4 influences the development of RA only in ACCP-positive patients and is further evidence pointing to a divergence in pathology dependent on ACCP status.

The CTLA4 gene, which encodes the CTLA4 protein, plays an important role in downregulation of T-cell activation. Full activation of T-lymphocytes requires both the recognition of an antigen bound to HLA and a co-stimulatory signal between CD80 or CD86 on the antigen-presenting cell and CD28 on the T-lymphocyte. CTLA4 protein expressed on T-lymphocytes as CTLA4 binds to CD80/CD86, may influence susceptibility to RA by inhibiting this co-stimulatory signal. However, the exact mechanism by which CTLA4 genotype may influence RA susceptibility still remains to be determined.

The importance of CTLA4 to RA pathogenesis is indicated by the development of a soluble fusion protein (ie, abatacept) that consists of the extracellular domain of CTLA-4 linked to the modified Fc (hinge, CH2, and CH3 domains) portion of human immunoglobulin G1 (IgG1). Abatacept inhibits T-lymphocyte activation by binding to CD80 and CD86, thereby blocking interaction with CD28. This interaction provides a co-stimulatory signal necessary for full activation of T-lymphocytes. Abatacept has been shown to be effective in treating RA and is indicated in the treatment of moderate to severe RA and active polyarticular juvenile idiopathic arthritis.

**TNFAIP3-OLIG3 is associated with RA pathogenesis**

This association locus was first identified in a GWAS and has been subsequently confirmed in multiple Caucasian and Asian cohorts. Specifically, a study of 3962 RA patients and 3531 healthy controls demonstrated strong association (OR = 1.2; 95% CI: 1.1–1.3; P = 2.6 × 10−6) with a variant (rs6920220) in an intergenic region of chromosome 6q23 region between oligodendrocyte linear transcription factor 3.
inflammation.

To date, multiple genes known to interact with NFκB signaling have been proposed to be associated with RA susceptibility (eg, CD40, CD244, CDK6, CCL21, PRKCI, TNFRSF14, PIP4K2C, IL-1B, IL-2RB, and IL-2RA). For these genes, replication in large population cohorts is required before validation as true RA risk alleles.

**Gene expression studies in RA**

The cDNA microarray technology enables simultaneous expression of thousands of RNAs transcribed from both known and unknown genes. This technology is helpful for large-scale gene discovery, as it provides diagnostic fingerprints by comparing gene expression patterns in normal and pathological cells in a single experiment. Expression profiling studies in RA cohorts can be categorized in two broad categories: those involved in identifying susceptibility genes and those looking at disease expression in RA. A recent systemic review summarized gene expression studies that was differentially expressed in at least two studies or genes differentially expressed in at least two studies or genes differentially

**Table 3** Genes associated with a differential expression pattern in patients with rheumatoid arthritis

| Gene                                      | Location       |
|-------------------------------------------|----------------|
| Cleavage stimulation factor, 3 pre-RNA, subunit 2 (CSTF2) | Xq22.1         |
| Solute carrier family genes (SLC7A7, SLC25A4) | 14q11.2, 4q35  |
| Colony-stimulating factor 3 receptor (CSF3R) | 1p35–p34.3    |
| Troponin genes (TNNT2, TNNI2, TNNT3) | 1q13.3–32, 11p15.5 |
| Argininosuccinate lyase (ASL) | 7cen–q11.2     |
| Tumor protein p53 (TP53) | 17p13.1         |
| Tyrosine kinase (TXX) | 4p12            |
| Ribosomal protein SA (LAMR1) | 3p22.2          |
| Bone morphogenetic protein 8 (BMP8) | 1p35–p32       |
| Cytokine P450 (CYP3A4) | 7q21.1          |
| Kininogen 1 (KNG1) | 3q27             |
| S100 calcium-binding protein (S100) | 1q21             |
| Protein phosphatase 2 (PPP2R3) | 3q22.1          |
| Matrix metalloproteinase (MMP3) | 11q22.3         |

| Gene                                      | Location       |
|-------------------------------------------|----------------|
| Kininogen 1 (KNG1) | 3q27               |
| Colony-stimulating factor 3 receptor (CSF3R) | 1p35–p34.3    |
| Troponin T type 2 (TNNT2) | 1q32             |
| Protease subunit beta-type 9 (PSMB9) | 6p21.3          |
| EGF receptor pathway substrate 15 (EFS15) | 1p32             |
| Membrane cofactor protein (MCP) | 1q32             |
| Stomatin (EPB72) | 9q34.1            |
| Interferon regulator factor 4 (IRF-4) | 6p25–p23        |
| Neutrophil cytosolic factor 4 (NCF4) | 22q13.1         |
| Interleukin 8 (GM-CSF) | 4q13–q21        |
| Stathmin 1 (STMN1) | 1p36.1           |
| Protein tyrosine phosphatase (PTPRK) | 6p22.2–23.1     |
| AA598840 | 1p34.3            |
| AA487590 | 13q12–q13        |
| Acyl-coenzyme A thioesterase 7 (HBACH) | 1p36.31–p36.11  |

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expressed in at least one study but located within a genetic linkage or association region (Table 3).97

With respect to disease expression, microarray studies of synovial biopsies compared expression of early and long standing rheumatoid arthritis.98 In that study, the authors identified several gene clusters and distinct molecular signatures specifically expressed during early or late RA, suggesting that different mechanisms are in play at various stages of RA.

Pharmacogenetics of RA

There is great variability in drug efficacy as well as adverse events with almost any antirheumatic therapy. Profiling for individual genetic variability holds great promise in treating rheumatic conditions. The identification of such variants has the potential to improve management of patient care by identifying which patients should avoid a specific drug and which patients should be administered a modified dose. A suitable approach in implementing such a strategy could potentially reduce medical costs and improve the overall process and success of drug therapy.99 This section of the paper will serve to highlight the current landscape of genetic targets for RA pharmacotherapy.

NSAIDs

Nonsteroidal anti-inflammatory drugs (NSAIDs) continue to be the mainstay of therapy for symptomatic relief. NSAIDs are primarily metabolized by the polymorphic CYP2C9 enzyme with a minor contribution from the CYP2C8 enzyme. Functionally important SNPs associated with decreased catalytic activities have been identified in both enzymes, especially for CYP2C9, which vary in frequency according to ethnicity.100 The metabolic capacities of the CYP2C9*2 and *3 alleles are approximately 70% and 3% to 11% compared to the wildtype allele, respectively.100 While NSAIDs are usually well tolerated for short periods of time, chronic use can lead to gastrointestinal complications (eg, ulcer formation, perforations, and bleeding), and renal toxicity.101,102 Gene-based dosing for NSAIDs aimed at reducing the occurrence of ADRs is hindered by differing metabolic rates among various NSAIDs and the involvement of additional metabolizing enzymes (eg, CYP2C8). Individuals carrying the gene variants CYP2C8*3 (rs11572080; rs10509681), CYP2C9*2 (rs1799853) or CYP2C9*3 (rs1057910) showed increased risk of developing acute gastrointestinal bleeding with NSAID therapy.103 Specifically, significantly higher frequencies of CYP2C9*1/*3 (34.6% vs 5.8%, OR = 12.9, 95% CI: 2.9–57.9; P < 0.001) and CYP2C9*1/*2 (26.9% vs 15.4%, OR = 3.8, 95% CI: 1.1–13.2; P = 0.036) were identified in bleeding versus control patients.103 However, it is currently unknown whether parent drugs or products of alternative metabolic pathways are responsible for bleeding.

Glucocorticoids

Glucocorticoids, such as prednisone, have been widely used in the treatment of RA by providing rapid symptomatic relief of pain and swelling.104,105 Although glucocorticoids inhibit inflammation, they also induce the expression of macrophage migration inhibitory factor (MIF), which in turn, possesses the unique ability to override the inhibitory effect of glucocorticoids on immune and inflammatory responses.106 The MIF (−173G>C) variant has recently been linked to clinical response in numerous inflammatory conditions.107–111 For example, in juvenile RA patients carrying a MIF (−173C) allele, the number of DMARDs required for the treatment was increased, the duration of corticosteroid treatment was significantly longer, and the number of joints with active arthritis was significantly higher.110 Such a strong predictor of poor treatment outcome in juvenile RA patients would suggest a similar effect in RA patients. A study which investigated this possibility failed to demonstrate a strong association of MIF (−173G>C) with clinical response to glucocorticoids in RA.112 However, due to the small sample size and thus, lack of power, this finding requires replication in larger cohorts. In the future, therapeutic MIF antagonism may therefore provide a specific means of ‘steroid sparing’.

Methotrexate

Methotrexate (MTX) is a very effective therapy in treating RA and is the initial disease modifying agent for the majority of rheumatologists. Thus, the majority of patients with RA would have been evaluated on methotrexate at some point in their course.113 The ADRs associated with MTX range from mild and self-limiting (eg, mucositis, gastrointestinal intolerance) to more severe (eg, hematopoietic suppression, hepatotoxicity, pulmonary toxicity). Both the efficacy and toxicity of MTX is governed by transport (eg, RFC-1, MDR1) and metabolizing enzymes (eg, MTHFR, TYMS, DHFR, ATIC, etc). Variants exist within the genes encoding these enzymes which affect efficacy and/or toxicity of MTX and explains at least in part, the inter-individual variability in response to MTX. Several polymorphisms of genes encoding the MTX signaling pathway have been investigated in relation to efficacy and toxicity (Table 4); however, only the most studied variants will be discussed here in detail. RFC-1 transports folate and MTX into cells and some stud-
ies suggest that a variant in the SLC19A1 gene encoding RFC-1 (rs1051266; SLC19A1 80G>A) may influence MTX efficacy and toxicity in RA;\textsuperscript{114,115} a finding which has not been replicated in subsequent studies.\textsuperscript{116,117} MTHFR, a prominent regulatory enzyme involved in the folate pathway, catalyzes the conversion of 5,10-methylene tetrahydrofolate to 5-methyltetrahydrofolate, which is a substrate for homocysteine remethylation. While seven polymorphisms have been associated with MTX efficacy or toxicity,\textsuperscript{116,121} two nonsynonymous SNPs (rs1801133: 677C>T and rs1801131: 1298A>C) have been extensively studied. The homozygous and heterozygous variants of the MTHFR 677C>T polymorphism decreases enzyme activity by approximately 70% and 40%, respectively.\textsuperscript{122,123} Similarly, the homozygous variant of the MTHFR 1298A>C variant has about 60% of wildtype function.\textsuperscript{124,125} Previous studies suggest that the MTHFR 677C>T variant is not related to MTX efficacy,\textsuperscript{126,127} but rather plays a prominent role in toxicity.\textsuperscript{126,128,129} A recent meta-analysis of eight MTX studies, totaling over 1,400 RA patients for the MTHFR 677C>T analysis, and over 660 for the MTHFR 1298A>C analysis revealed that the MTHFR 677C>T variant (ie, CT or TT genotype) was associated with increased toxicity (OR = 1.71, 95% CI: 1.3–2.2; \textit{P} \leq 0.001).\textsuperscript{116} In contrast, the MTHFR 1298A>C variant was not associated with increased toxicity (OR = 1.12, 95% CI: 0.8–1.6; \textit{P} = 0.626).\textsuperscript{116} Unfortunately, the analysis was limited to these two variants due to a lack of sufficient data for other polymorphisms. Similarly, widely disparate definitions of efficacy among the MTX pharmacogenetic studies combined with insufficient data of MTX polymorphisms prevented meta-analysis of efficacy.\textsuperscript{116}

### Table 4 Candidate gene polymorphisms associated with either efficacy and/or toxicity of MTX pharmacotherapy in rheumatoid arthritis patients

| Gene   | Variant | Function | Effect on MTX therapy | Ref. |
|--------|---------|----------|------------------------|------|
| **Variants affecting transport of MTX** | | | | |
| RFC-1  | 80G>A   | Minimal effect on transport of folate and MTX into cells | AA genotype associated with 3.7-fold greater response (95% CI: 1.7–9.1, \textit{P} < 0.01) | 114 |
|        |         |          | GA/AA genotype associated with increased risk for overall MTX toxicity (OR = 3.574, 95% CI: 1.1–12.0; \textit{P} = 0.039) | 118 |
| MDR1   | 3435C>T | ?        | TT genotype associated with a higher remission probability (OR = 4.65, 95% CI: 1.7–13.0; \textit{P} = 0.003) | 118–120 |
| **Variants affecting intracellular metabolism of MTX** | | | | |
| MTHFR  | 677C>T  | Decreased reduction of 5,10-CH\textsubscript{2}-THF to 5-CH\textsubscript{3}-THF | CT/TT genotype associated with increased ADRs (RR = 2.0, 95% CI: 1.1–3.7) | 126 |
|        |         |          | CT/TT genotype associated with higher rate of MTX toxicity (RR = 1.2, 95% CI: 1.0–1.5; \textit{P} < 0.05) | 128 |
|        |         |          | No effect on efficacy | 126, 127 |
|        | 1298A>C | Decreased reduction of 5,10-CH\textsubscript{2}-THF to 5-CH\textsubscript{3}-THF | AC/CC genotype required lower doses of MTX (RR = 2.2, 95% CI: 1.2–4.1, \textit{P} < 0.05) | 128 |
| TYMS   | 28bp tandem repeat | Decreased conversion of CH\textsubscript{2}-THF to DHF | Alleles with three repeats associated with MTX resistance | 114, 132 |
|        |         |          | Alleles with only two repeats associated with improved response | 114, 132 |
| ATIC   | 347C>G  | Decreased de novo purine synthesis | GG genotype associated with improved response | 130, 114 |
|        |         |          | GG genotype associated with ADRs | 131 |

**Abbreviations:** RFC-1, reduced folate carrier – 1; MDR1, multi-drug resistance – 1; MTHFR, 5,10-methylene tetrahydrofolate reductase (NADPH); TYMS, thymidylate synthetase; ATIC, 5-aminimidazole-4-carboxamide ribonucleotide formyltransferase/IMP cyclohydrolase.
The inter-individual variation in MTX dose required to gain clinical efficacy is highly variable and cannot be currently predicted. Likewise, we are unable to accurately predict which patients will develop ADRs. Given the complexity of the MTX pathway, it is highly probable that multiple genetic variants act in concert to predict MTX efficacy and/or toxicity. Interestingly, the formation of a pharmacogenetic index incorporating the additive effect of multiple genetic variants on MTX efficacy and toxicity may be a possible solution, which may ease the transition of MTX pharmacogenetic testing into the clinic. Indeed, there is evidence to suggest that a low pharmacogenetic index is associated with a good response to MTX, while a higher index score is associated with an increased incidence of ADRs.

Leflunomide

Leflunomide is an immunomodulatory drug that inhibits the rate-limiting intracellular enzyme in the de novo synthesis of pyrimidines, which is crucial for activating lymphocytes. This DMARD is usually an alternative for MTX-intolerant or resistant RA patients. The main molecular target of leflunomide is dihydroorotate dehydrogenase (DHODH), a key enzyme of de novo pyrimidine synthesis. The human DHODH gene sequence is highly conserved and contains only one common missense polymorphism (rs3213422) located in the first exon of the DHODH gene (19C>A; Q7K). The frequency of remission was increased in DHODH 19C allele carriers compared with patients with the DHODH A allele indicating a potential role of the DHODH gene in leflunomide therapy. Consistent with in vitro studies, which demonstrated that CYP1A2 might be involved in leflunomide activation, RA patients with CYP1A2*1F CC genotype had a 9.7-fold higher risk for overall leflunomide-induced toxicity compared to carriers of CYP1A2*1F A allele (OR = 9.7; 95% CI: 2.3–41.4; P = 0.002). It has also been suggested that therapy with leflunomide causes decreased production of mediators such as IL-1β, IL-6, and TNF-α, which are involved in inflammatory process. However, IL-1 β, IL-6, and TNF-α gene variants appear to be insignificant factors influencing the therapy outcome of RA patients with leflunomide.

Azathioprine

The immunosuppressant agent azathioprine (AZA) is a prodrug which is occasionally used in treating RA. However, treatment success is limited as 10% to 28% of patients terminate treatment due to ADRs, specifically myelosuppression. The thiopurine methyltransferase (TPMT) enzyme catalyzes the inactivation of purines, including AZA, and it exhibits genetic polymorphism. Genetic polymorphism of TPMT is evident in all populations studied to date, including Caucasians, Asians, African-Americans, and Africans. TPMT*3A, TPMT*3C, and TPMT*2 are the most prevalent variant alleles comprising approximately 95% of TPMT variant alleles in these populations. Genotyping for the three most studied SNPs (ie, 238G>C, 460A>G, and 719G>A) provides greater than 95% concordance between TPMT genotype and phenotype. Briefly, approximately 90% of individuals inherit high activity, 10% have intermediate activity attributed to heterozygosity, and 0.3% have low or no detectable enzyme activity because they inherit two nonfunctional TPMT alleles. Multiple studies have demonstrated that TPMT-deficient patients and TPMT carriers are at high risk and an intermediate risk for severe hematological toxicity, respectively. Patients with intermediate TPMT activity should receive a reduction of approximately 50% of a normal AZA dose, while AZA should be avoided in patients with low or absent TPMT activity. A genotype-based dosing strategy is less costly, more effective, and is associated with a marked reduction in the number of serious ADRs compared to conventional weight-based dosing strategy. Support amongst rheumatologists for prospective TPMT genotyping continues to grow, due in part, to an accumulation of evidence supporting the use of genetic diagnostic testing.

Sulfasalazine

Sulfasalazine, a mildly potent DMARD used in the treatment of RA, inhibits neutrophil function, reduces immunoglobulin levels, and interferes with T-lymphocyte function via the suppression of NFκB. Polymorphisms within the gene encoding the N-acetyl transferase 2 (NAT2) enzyme affect the rate of acetylation which are thought to affect the efficacy and/or toxicity of sulfasalazine. RA patients lacking the wildtype haplotype (ie, NAT2*4) at NAT2 appear to be more likely to suffer from overall ADRs (relative risk [RR] = 3.31, 95% CI: 1.8–6.2; P = 0.001) and severe ADRs (RR = 24.6, 95% CI: 2.4–254.5; P = 0.015). Although additional studies are warranted, it is possible that, in the future, RA patients can be classified into groups according to NAT2 genotyping: rapid type (homozygote for NAT2*4), intermediate type (heterozygote for NAT2*4 and variant alleles), and slow type (homozygote for variant alleles).

TNF-α inhibitors

Tumor necrosis factor-α (TNF-α) blockade represents a major breakthrough in the treatment of RA. Controlled trials...
with all four anti-TNF-α agents, etanercept (Enbrel®), infliximab (Remicade®), golimumab (Simponi™), and adalimumab (Humira®), presently approved for the treatment of RA, have demonstrated impressive improvement in most response measures, including clinical, laboratory, and radiographic outcomes. Despite the marked improvement of symptoms and radiographic retardation of RA with the use of anti-TNF-α agents, randomized controlled trials reveal that only 60% to 70% of patients with moderate to severe RA achieve a satisfactory response. A lack of clinical and biochemical predictors of efficacy and toxicity of TNF inhibitors in RA patients has focused much attention to the affect of genetic variations on response. Candidate gene polymorphisms that affect response to etanercept or infliximab therapy are listed in Table 5. Although, multiple polymorphisms have been linked to response, the TNF-α gene promoter −308G>A variant (rs1800629) will be the focus of this review.

The functionality and thus relevance of the −308 variant to TNF-α treatment response is reflected by the ability of the TNF-α (−308A) variant to influence the magnitude of the TNF-α secretory response and to affect circulating levels of TNF-α. A recent meta-analysis of nine studies representing a total of 692 RA patients, demonstrated that the probability of successful treatment with anti-TNF-α agents is influenced, at least in part, by the variant in the TNF-α gene promoter region. The frequency of the TNF-α (−308A) variant was 22% in responders and 37% in nonresponders, and the OR was decreased in responders versus nonresponders (OR = 0.4, 95% CI: 0.4−0.7; P = 0.000245), irrespective of the TNF-α inhibitor prescribed. This is strong evidence indicating that the TNF-α (−308A) variant predicts poor response to TNF-α inhibitors. The clinical utility of prospectively genotyping for this variant when initiating anti-TNF-α therapy for RA should now be formally assessed. Moreover, it is conceivable that those with the TNF-α (−308A) variant could either be treated more aggressively with concomitant DMARDs or implement these biologics earlier in the therapeutic regimen. However, larger cohorts involving multiple centres and

| Candidate gene(s) | Sample size | Response criteria | Follow-up time | Genotype/phenotype correlation | Ref. |
|-------------------|-------------|-------------------|----------------|--------------------------------|-----|
| TNF-α (−238G>A)   | 40          | DAS28             | 6 months       | GA genotype is associated with a negative response to INF | 169 |
| TNF-α (−857)      | 70          | ACR20             | 3 months       | CT/TT genotypes are associated with positive response to ETA | 170 |
|                   | 58          | DAS28             | N/A            | CC genotype is associated with positive response to INF | 171 |
| TNFRII 676T>G     | 105         | ACR20             | 12 months      | TG genotype is associated with a negative response to ETN, INF or ADA | 172 |
|                   | 58          | DAS28             | N/A            | TT genotype is associated with positive response in RA | 171 |
| FCGR3A 158F>V     | 91          | ACR20             | 7.5 months     | FF genotype is associated with a positive response to INF | 173 |
| TNF-α (−308G>A) & IL-10 (−1087G>A) combination | 123 | ACR20, DAS28 | 3 months | GG genotype is associated with positive response to ETA | 174 |
| IL-1RN VNTR and TGFB1 915G>C Combination | 123 | ACR20, DAS28 | 3 months | A2/C allele combination is associated with negative response to ETA | 174 |
| HLA-DRB1          | 255         | ACR50             | 12 months      | *0404 & *0101 combination is associated with positive response | 175 |
| IL-10             | 50          | DAS28             | 48 months      | IL-10.R3 is associated with positive response | 176 |
|                   | 50          | DAS28             | 48 months      | IL-10.G13 is associated with moderate or negative response | 176 |
|                   | 50          | DAS28             | 48 months      | IL-10.R2 & G13 combination is associated with moderate or negative response | 176 |
|                   | 50          | DAS28             | 48 months      | IL-10.R3 & G9 combination is associated with positive response | 176 |

**Abbreviations:** ACR, American College of Rheumatology based on perceptual improvement (20, 50, 70, 90%) in disease symptoms; DAS28, disease activity score in 28 joints; IL, interleukin; TNF-α, tumor necrosis factor-α.

Pharmacogenetics of rheumatoid arthritis

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ethnecities are a prerequisite before definite conclusions can be drawn regarding the functional role of the TNF-α-308A variant and response to TNF-α inhibitors.

With respect to expression profiling studies, Lequerre and colleagues set out to identify predictive genes that would determine responsiveness to infliximab in peripheral blood mononuclear cells (PBMCs) by examining 16 responders and 17 nonresponders to infliximab treatment.\textsuperscript{165} Forty-one transcripts discriminated infliximab responders from nonresponders, including CYP3A4, LAMR1, and KNG1. A subset of these transcripts were assessed in two new patients and a sensitivity of 90% and specificity of 70% was achieved for these transcripts.\textsuperscript{165}

### IL-1 antagonists

Although clinical trials of human recombinant IL-1 receptor antagonists in treating RA have been successful, the magnitude of its effect is inferior to that of anti-TNF-α therapy in RA and varies among patients.\textsuperscript{166} The prominent role of IL-1 in the immune response combined with an apparent association between the IL-1 cluster genes and RA susceptibility suggests that this gene may also be related to the likelihood of response to anti-IL-1 therapy in RA patients. Indeed, Camp and colleagues reported that IL-1 gene does influence reduction in swollen joints in RA patients treated with an IL-1 receptor antagonist.\textsuperscript{167} A highly significant association was found between carriage of the rarer allele at IL-1A (+4845) and response to treatment (OR = 4.8; 95% CI: 1.8–12.7; \( P = 0.0009 \)).\textsuperscript{167} Moreover, the response rate in patients carrying this allele was 63.4% compared with 26.3% in noncarriers.\textsuperscript{167} Due to the paucity of pharmacogenetic data on IL-1 receptor antagonists and other biologics (eg, IL-12/23 variants) in RA patients, much more research is warranted to better define the relationship between the IL-1 gene cluster and response to IL-1 receptor antagonists.

### Conclusion

Diagnostic testing using genetic markers is superior compared to testing with traditional biomarkers, such as markers of the inflammatory process (eg, C-reactive protein, cytokines) and markers of disease-associated autoantibodies (eg, rheumatoid factor, ACPA status) as they afford greater predictive power, drastically reduce the need for repeated biochemical testing and are less affected by environmental factors like diet. Whereas, traditional biomarkers are important helping to establish a clinical diagnosis, genetic markers can help identify high-risk individuals reliably and in a timely manner so that they can either be treated before onset of the disease or as soon as possible thereafter. For example, patients at high risk or who fail to respond to conservative therapy are candidates for earlier, more aggressive strategies using single or possibly combination antirheumatic therapy.

RA is a complex disease with considerable genetic heterogeneity. With the advent of GWAS, much progress has been made in the genetics of RA. However, the non-MHC RA risk alleles still account for only 5% of the overall genetic burden of RA, indicating that additional non-MHC risk alleles remain to be discovered.\textsuperscript{168} Likewise, the modest effect size and power of existing studies to detect these effects at genome-wide levels of significance indicates that many more common alleles of modest effect remain to be discovered.\textsuperscript{36} In the future, several steps are paramount in elucidating the genetics of RA in relation to improved patient care. Firstly, as sample sizes increase, coverage across the genome is improved and copy number variations are included, GWAS will reveal these common variants of modest risk, the so-called ‘hidden’ risk alleles. Secondly, in addition to identifying and confirming risk alleles, functional studies will be fundamental to better understand how these variants contribute to RA pathogenesis. Thirdly, it will be important to determine the value of RA risk alleles in providing clinical prediction among healthy individuals, those with early symptoms consistent with RA, and those with established disease. Finally, it will be important to determine whether combinations of risk alleles are able to subset patients into clinically meaningful categories, which would result in superior patient care.

Similar to pathogenesis, the genetics of RA pharmacotherapy is quite complex, with considerable variability in the cost and response to various medications. Likewise, many pharmacogenetic studies are often too small and the results of which can be inconsistent and misleading. The effect sizes are mild to modest, so there is limited clinical predictive value. However, there are some problems inherent to the field of pharmacogenetics. For this field to evolve further in RA, studies employing large genetically diverse cohorts, a standardized study design, and multiple genetic variants in concert, will be a prerequisite to accurately assess the impact of genetic variants on drug efficacy and/or toxicity. A priori knowledge of pharmacogenetic mechanisms associated with RA pharmacotherapy has to potential to identify and therefore stratify patients into clinically important treatment categories (ie, responders vs. nonresponders; tolerant vs intolerant). The incorporation of pharmacogenetics into clinical rheumatology practice (ie, personalized medicine) can certainly be a major
advances in RA pharmacotherapy and a clear enhancement of patient care. However, for this to occur many more well executed and adequately powered studies are required.

It would be remiss to not briefly comment on the influence of epigenetic factors on RA pathogenesis. It has become increasingly evident that the influence of epigenetic processes on the development of rheumatic diseases is probably as strong as the genetic background of a patient. The combinatory nature of these processes forms a complex network of epigenetic modifications with the ability to regulate gene expression through activation or silencing of genes. Indeed, environmental triggers are involved in the development of RA as age, infections, smoking, nutrition, and pollution have been suggested to have an effect on the epigenetic background. Genome-wide analyses of the epigenome (e.g., DNA methylation, histone modifications) will enable the detection of additional genes involved in the pathogenesis of rheumatoid arthritis. In the future, knowledge of the epigenetic processes combined with enhanced genetic information will be essential for the understanding of the differences seen in the clinical picture of patients with rheumatic diseases such as RA.

Disclosures

The authors report no conflicts of interest in this work.

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