Review Article
Update: Cytokine Dysregulation in Chronic Nonbacterial Osteomyelitis (CNO)

Sigrun R. Hofmann,1 Angela Roesen-Wolff,1 Gabriele Hahn,2 and Christian M. Hedrich1,3

1 Department of Pediatrics, University Hospital Carl Gustav Carus, Fetscherstraße 74, 01307 Dresden, Germany
2 Department of Pediatric Radiology, University Hospital Carl Gustav Carus, 01307 Dresden, Germany
3 Division of Rheumatology, Department of Medicine, Beth Israel Deaconess Medical Center, Harvard Medical School, Boston, MA 02215, USA

Correspondence should be addressed to Sigrun R. Hofmann, sigrun.hofmann@uniklinikum-dresden.de

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Chronic nonbacterial osteomyelitis (CNO) with its most severe form chronic recurring multifocal osteomyelitis (CRMO) is a non-bacterial osteitis of yet unknown origin. Secondary to the absence of both high-titer autoantibodies and autoreactive T lymphocytes, and the association with other autoimmune diseases, it was recently reclassified as an autoinflammatory disorder of the musculoskeletal system. Since its etiology is largely unknown, the diagnosis is based on clinical criteria, and treatment is empiric and not always successful. In this paper, we summarize recent advances in the understanding of possible etiopathogenetic mechanisms in CNO.

1. Introduction
Chronic nonbacterial osteomyelitis (CNO) (OMIM number 259680) is an autoinflammatory, noninfectious disorder that affects the skeletal system and has first been described in 1972 [1]. An association with further autoimmune and autoinflammatory disorders such as pustolusis palmoplantaris [2], chronic inflammatory bowel disease (IBD), psoriasis, c-ANCA positive vasculitis, Takayasu’s arteritis, and deficiency of IL-1 receptor antagonist (DIRA) has been discussed [3–5]. CNO covers a wide clinical spectrum from non- or oligosymptomatic monofocal bony lesions to its most severe form chronic recurring multifocal osteomyelitis (CRMO). Generally, any skeletal site can be affected. However, metaphyses of long bones are predominantly involved [6] with a predilection for the lower extremities (distal femur, proximal tibia, distal tibia, and distal fibula [7]), followed by the clavicle and spine. A symmetric involvement is common. Systemic symptoms occur in a subset of patients and include low-grade fevers and malaise. Even though Scully et al. (2008) [7] reported a predominance in females (up to 85%), larger studies did not confirm this.

However, little is known about the pathophysiology of CNO. Most research articles focus on clinical aspects of CNO, and only few reports discuss putative pathomechanisms underlying this autoinflammatory disorder.

2. Classification, Clinical Picture, Diagnosis, and Treatment
Autoinflammatory diseases are rare disorders, characterized by recurrent episodes of fever and inflammation, and mostly affect joints, serosal surfaces, eyes and skin in the absence of high-titer autoantibodies, autoreactive T lymphocytes [11], and underlying infection [7]. In 2006, Mcgonagle and McDermott [12] suggested a clinical continuum with autoimmune disorders on the one, and autoinflammatory diseases on the other end of the spectrum. Disorders located towards the middle of the continuum exhibit features of both autoinflammatory as well as autoimmune diseases. According to this definition, CNO has been classified as an autoinflammatory disorder. In CNO the diagnosis relies on clinical symptoms, systemic inflammation, and elevated
acute phase proteins during attacks. In very few cases, underlying mutations in the relevant genes can be detected (Majeed syndrome, see below). CNO needs to be differentiated from infectious osteomyelitis, including mycobacterial infections, and malignant neoplasms.

Laboratory and histopathological findings are nonspecific, with mildly elevated acute phase markers, and plasmacellular, granulocytic, and monocytic infiltrations respectively [13]. However in a substantial number of patients, systemic inflammatory signs (such as low-grade fever and malaise and elevated acute phase proteins) cannot be found, even during attacks. In these cases, the diagnosis of CNO can be made, combining clinical findings (localized bone pain, swelling, and warmth in the affected areas) and laboratory tests (including testing for mycobacteria) with radiographic techniques. The presence of osteolytic lesions with surrounding sclerosis in X-ray imaging, supplemented by computerized tomography (CT) and/or magnetic resonance imaging (MRI), is usually helpful (Figure 1). Silent asymptomatic lesions frequently appear on nuclear scans.

Even though CNO has been treated with azithromycin [14] in the past, it does generally not respond to antibiotics. Treatment involves anti-inflammatory agents, including NSAIDs [13, 15, 16] and corticosteroids. In treatment resistant cases, bisphosphonates [17] and biologicals, usually infliximab or etanercept (blocking tumor necrosis factor-α) [18] have been applied successfully, suggesting an involvement of TNF-α in the pathophysiology of CNO.

Individual clinical courses of CNO are generally unpredictable. Most cases are self-limiting and eventually resolve without major sequelae. However, a subset of patients exhibit severe and prolonged disease courses and are at risk of developing bone deformities that can be caused by premature closure of the epiphyses, and kyphoscoliosis as a result of vertebral involvement [4, 6, 19]. Disease onset at a young age and high numbers [20] of inflammatory bone lesions at disease onset seem to be predictive of poor outcomes [4, 19].

3. Putative Pathomechanisms

Imbalances in cytokine expression can cause a disruption of immune homeostasis, resulting in increased or reduced inflammatory responses that in turn may cause susceptibility to infections or autoimmune disorders. Cytokine dysregulation can be caused on various levels, including (1) impaired transcription that can be caused by genomic variation and (2) epigenetic modifications. Genomic variations, including single-nucleotide polymorphisms (SNPs), can influence gene expression by variable transcription factor binding or variation in genome organization [21]. Epigenetic modifications alter chromatin accessibility for transcription factors and/or RNA polymerases [21, 22]. Posttranslational histone modifications influence the transcriptional activity of genes and serve as markers of epigenetic changes. Histone hypermethylation as repressing histone modification mediates dense packing of nucleosomes in transcriptionally silent, so-called “heterochromatic” regions. Activating histone modifications, such as histone acetylation and phosphorylation, mediate “open” or “euchromatic” chromatine conformation that is accessible for transcriptional regulatory factors and RNA polymerases [8].

3.1. Genetic Susceptibility Studies. Genetic studies suggested a predisposing locus for CNO on chromosome 18q21.3-18q22 [23]. However, convincing evidence for the involvement of this locus in the pathophysiology of CNO is still lacking. Several observations suggest the contribution of genetic factors to the etiology of CNO.

Ferguson et al. [24, 25] described homozygous mutations in the LPIN2 gene, causing a syndromic autosomal recessive
form of CNO known as Majeed syndrome. The Majeed syndrome's classical triad includes early-onset CRMO, congenital dyserythropoietic anemia and a neutrophilic dermatosis. It is an extremely rare disease and has only been identified in three unrelated Arabic families [14, 26]. Bone lesions in Majeed syndrome occur within the first two years of life, and the course is more aggressive than in CNO, with more relapses. LPIN2 was mapped to chromosome 18p and found to be expressed in almost all tissues [25]. Little is known about the function of LPIN2. It shares a lipin domain with the human ortholog of murine lipin1, which plays a role in fat metabolism. Because of the dyserythropoiesis in Majeed syndrome, it has been proposed that LPIN2 could also play a role in mitosis, and that an impaired function may lead to abnormal mitosis in rapidly dividing cells, including the red blood cell lineage in the bone marrow [25]. It has further been hypothesised that mutations in LPIN2 may play an etiologic role in psoriasis, since it localizes to a genomic region identified as a psoriasis susceptibility locus. Furthermore, all carriers of disease causing homozygous LPIN2 mutations exhibit inflammatory dermatoses [25].

Mutations in the pstpip2 gene have been described in the murine form of CNO [27]. To date, there are two murine CNO models, both carrying mutations in the pstpip2 gene: (1) cmo mice [26–29] and (2) Lupo mice [30]. Cmo (chronic multifocal osteomyelitis) mice have been reported to develop a phenotype that is similar to severe cases of human CNO with multiple sites of inflammation. However, most CNO patients present with less severe mono- or oligo-focal disease which does not completely resemble the disease in cmo mice that develop multifocal (systemic) inflammatory symptoms. The disease is inherited in an autosomal recessive manner, and the cmo locus has been mapped to the murine chromosome 18 [27]. Within the refined region was the gene pstpip2, which shares significant sequence homology to human PSTPIP1. Expression patterns of murine Pstpip2, also called MAYP (macrophage actin-associated tyrosine-phosphorylated protein), are discussed controversially. While Pstpip2 mRNA is ubiquitously expressed [31], Western blot analysis revealed narrow protein expression patterns, with the highest Pstpip2 expression in myeloid cells [32]. Pstpip2 plays a role in cytoskeletal reorganization, and localizes to the cytosol as an F-actin associated phosphoprotein that interacts with PEST-type protein tyrosine phosphatases (PTP PEST) [31, 32]. The association with PEST family PTPs inhibits tyrosine phosphorylation of wildtype PSTPIP1 [33]. Mutations in the PSTPIP1 gene have been documented to cause the autoinflammatory PAPA syndrome (pyogenic arthritis, pyoderma gangrenosum, and acne). The PSTPIP1 protein binds to pyrin, a regulator that inhibits the NLRP3 inflammasome. Interestingly, Veillette et al. [33] and Wise et al. [34] demonstrated that the PSTPIP1 mutations found in the autoinflammatory PAPA syndrome are in the putative coi-coil domain of PSTPIP1, abolishing the capacity of PSTPIP1 to bind PEST family PTPs. This alteration results in enhanced PSTPIP1 tyrosine phosphorylation and is accompanied by augmented binding of PSTPIP1 to pyrin via an SH3 domain [10], resulting in constitutive activation of NLRP3, production of IL-1β, and inflammation [33] (Figure 2). Some similarities in the phenotypes of cmo mice and (human) PAPA patients may suggest an involvement of the same or similar immunologic pathways. However, the absence of the SH3 domain in Pstpip2 suggests that it does not bind pyrin directly [27]. However, “classical” CNO patients do not develop the characteristic pustulotic or pyogenic dermatitis that is seen in PAPA patients.

Even though cmo mice serve as an interesting model for bone inflammation, none of the reported CNO patients [35] carry mutation in the PSTPIP1 and PSTPIP2 genes, except for several known polymorphisms.

The recent report of a condition, presenting with neonatal onset sterile multifocal osteomyelitis, periostosis, and pustulosis, that is caused by a deficiency of IL-1 receptor antagonist (DIRA), is of special interest [5]. Because of similar clinical, radiological and histological features of CNO and DIRA, both disorders might share common or similar autoinflammatory processes. However, in a recent study [36] a heterozygous missense mutation c.281G>T (p.Cys94Phe) could only be found in one patient with CNO. In the other patients, only frequent polymorphisms were found.

Another hint towards the understanding of genetic contributors to the pathophysiologic of CNO may be the clinical similarities of CNO patients and patients with hypophosphatasia [37, 38]. Hypophosphatasia is a rare defect of bone metabolism that is caused by a number of mutations in the gene encoding for the tissue-nonspecific alkaline phosphatase (TNSALP) on chromosome 1p36.1. The mode of inheritance is mostly autosomal-recessive [37, 39, 40]. TNSALP mutations result in reduced enzyme activity and elevated concentrations of TNSALP substrates, including inorganic pyrophosphate, pyridoxal-50-phosphate and phosphoethanolamine [41–43]. It has been documented that pyrophosphate crystals stimulate the NLRP3 inflamasome resulting in Interleukin-1 production [44]. An inflammatory process secondary to the metabolic defect in hypophosphatasia involving the NLRP3 inflamasome may therefore be involved in the pathogenesis of CNO.

Since associations between CNO and Crohn's disease, a multifactorial autoimmune/inflammatory disease, have been reported [26], Morbach and colleagues [45] analyzed CNO patients for NOD2/CARD15 mutations. However, CNO without intestinal inflammation was not associated with common CARD15 gene variants [45].

In addition, susceptibility regions have been identified on chromosome 18 in two other diseases sharing similarities with CNO: familial expansile osteolysis and familial Paget's disease of bone [26, 46, 47]. The phenotypes of both diseases have been linked to mutations in the TNFRSF11A gene at 18q22.1, which encodes the receptor activator of nuclear factor kappa B (RANK) [46, 47].

Recently, we reported an association of CNO with IL10 promoter polymorphisms [3, 8]. IL-10 is an immune-regulatory cytokine that controls inflammation by limiting inflammatory cytokine expression and antigen presentation. Dysregulation in IL-10 expression, sometimes caused by single-nucleotide polymorphisms (SNPs) in the IL10 promoter have been associated to autoimmune and infectious diseases, such as SLE [48], asthma, chronic viral diseases,
IL10 promoter polymorphisms as an example for genomic variation, appear to play an important role in the interindividual variation of IL-10 expression [8, 52]. The IL10 promoter polymorphisms $-1082G>A$ (rs1800869), $-819C>T$ (rs1800871), and $-592C>A$ (rs1800872) are in tight linkage disequilibrium and form three well-defined or "classical" haplotypes: ATA, ACC, and GCC [3]. ATA is associated with low, ACC with intermediate, and GCC with high levels of IL-10 expression [48, 53, 54]. However, for the interindividual variability of IL-10 expression, additional host factors seem to play an important role [52].

As aforementioned, an association of IL10 promoter polymorphisms with CNO has been described [8], demonstrating an increased frequency of high IL-10 expressing $-1082G/G$ alleles, and resulting GCC haplotypes. Interestingly, monocytes from CNO patients failed to produce IL-10 in response to stimulation with LPS. This could be explained by (1) IL10 promoter polymorphisms as part of larger haplotypes, extending several hundred kilobases over the entire cytokine cluster, develop cumulative effects in a genomic setting [8]. This hypothesis is supported by a recent study [55] that failed to find a link between IL10 promoter SNPs and inflammatory bowel disease (IBD), but showed an association between a SNP 3′ to the IL10 gene and...
3.2. Epigenetic Mechanisms. The expression of pro- and anti-inflammatory cytokines, including IL-10, is considered to be under epigenetic control. Zhang et al. [57] reported inflammatory cytokines, including IL-10, is considered to the proliferation of various lymphocytic tissues, including B cells, and enhances antibody production [56]. Lymphocytes, but also plasma cells can be predominantly found in biopsies, taken from CNO lesions. Having the anti-inflammatory aspects of IL-10 expression in mind, an association with GCC haplotypes could partly explain the lymphocyte expansion in affected tissues [6]. (3) additional, namely, epigenetic mechanisms, could be involved in the dysregulation of cytokine expression in CNO (see below).

4. Conclusions

Only few CNO cases have been associated with mutations in single genes. However, they do not explain the pathophysiology of CNO in the vast majority of cases. Thus, neither the etiology nor the pathogenesis of CNO is completely understood. Mutations in the TNFα and IL1RA genes in humans and the Pstpip2 gene in mice appear to be promising in the search for pathomechanisms in CNO. The most recently described pathophysiological mechanism in CNO might involve impaired MAPK signaling, reduced H3S10 phosphorylation, and attenuated Sp1 recruitment to the IL10 promoter that results in an impaired gene expression.

Conflict of Interests

The authors declare that they have no financial conflict of interests.

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