Cardiac Myosin and the TH1/TH2 Paradigm in Autoimmune Myocarditis

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Myocarditis and dilated cardiomyopathy may represent acute and chronic stages of a progressive organ-specific autoimmune disease of the myocardium. Myocarditis is an inflammatory disease of the heart that is characterized by a cellular infiltrate in the myocardium, and dilated cardiomyopathy is a chronic heart muscle disease characterized by ventricular hypertrophy. Dilated cardiomyopathy is a primary cause of severe heart failure with subsequent transplantation or death within several years after diagnosis. The direct result of cellular infiltration of the myocardium is necrosis and loss of myocytes leading to the development of contractile dysfunction and ventricular dilatation. The loss of myocytes and formation of scar tissue in the myocardium would lead to loss of contractile function and ventricular enlargement. In a small percentage of individuals, loss of myocyte function and development of dilated cardiomyopathy can result from mutations in or viral proteolytic digestion of dystrophin or dystrophin-associated glycoproteins that lead to cytoskeletal disruption and loss of overall contractile function in the heart.

However, the most common cause of myocarditis is viral infection. An exhaustive list of myocarditis-inducing agents including microbial pathogens and toxins is provided by Brown and O’Connell in a review of myocarditis and dilated cardiomyopathy. Among the most common viral causes of human myocarditis are coxsackieviruses. Mouse models of coxsackievirus-induced myocarditis were studied by Woodruff and colleagues, who demonstrated that lymphocytes from mouse models of myocarditis could destroy cardiomyocytes in culture. Gauntt and colleagues also investigated the role of virulent myocarditis versus nonvirulent myocarditis in mouse models of myocarditis. In their studies, there appeared to be several stages of disease in their mouse model. The first early stage of viral replication and cell lysis in the heart showed no evidence of heart failure or cellular inflammation, however, with the onset of specific immune responses, cellular infiltration of the myocardium was observed in susceptible mice. The cellular infiltrates in the myocardium were minimal to severe and led to the loss of myocytes by necrosis. The development of dilated cardiomyopathy is thought to represent the third and more chronic stage of heart disease that develops after the cellular inflammation. It would follow that once the damage has been done to the cardiomyocyte function either by elimination of large numbers of myocytes because of inflammation, necrosis, and scarring or by disruption of the cytoskeleton so that the myocyte is dysfunctional, then anti-inflammatory therapy would not be effective. Anti-inflammatory therapies would only be efficacious during the time of inflammatory onset. In fact, immunosuppressive therapy was not effective in the Myocarditis Trial. By the time myocarditis symptoms present, many cases may have already advanced to a stage in which necrosis and scarring have already led to ventricular dilatation and contractile dysfunction. For comparison, in rheumatic carditis, the valve is insidiously and permanently damaged by autoimmune attack after streptococcal pharyngitis. In rheumatic carditis, valve injury may not be evident until a heart murmur is perceived that reflects the scarred valve. In myocarditis, the end-stage of disease may represent a physical, structural defect as a result of autoimmune-mediated damage during the inflammatory stage of the disease.

Mechanisms in the Pathogenesis of Myocarditis

Cardiac Myosin and Infection: the Mimicking Autoantigen

Although infectious pathogens, including viruses, group A streptococci, or chlamydia, are important...
etiological agents of inflammatory heart disease, immune and specifically autoimmune mechanisms are the major effectors of pathogenic injury. The autoantigen most often associated with both myocarditis and rheumatic carditis is cardiac myosin. In 1985, myosin was identified as an autoantigen involved in coxsackieviral infection. In this time, evidence has supported the molecular mimicry hypothesis that streptococcal M protein and the group A streptococcus M protein that mimics cardiac myosin tolerance of M-TCR. In fact, immunological mimicry was demonstrated between streptococcal M protein and myocarditic coxsackieviruses and was linked to cytotoxic antibody against heart cells as well as T lymphocyte responses. Interestingly, a myocarditic peptide of streptococcal M protein that mimics cardiac myosin tolerance was demonstrated between streptococcal M protein and myocarditic coxsackieviruses and was linked to cytotoxic antibody against heart cells as well as T lymphocyte responses. Nevertheless, it is debated as to whether or not mimicry between coxsackieviruses and cardiac myosin plays a role in the pathogenesis of myocarditis.

There is strong evidence that cardiac myosin is a dominant autoantigen in autoimmune myocarditis and viral-induced myocarditis. Cardiac myosin-induced myocarditis histologically resembles the viral-induced disease. Investigators have demonstrated that myocardium of myocarditis can be adoptively transferred by CD4+ T lymphocytes. Although CD4+ lymphocytes can transfer disease, it has been shown that autoimmune myocarditis can occur in mice lacking CD4 or CD8 molecules, and that myocardial infiltrates consisted of T cells that were double-negative T cells with αβTCR. In addition to T cells, passive administration of anti-myosin monoclonal antibody was found to induce myocarditis in DBA/2 mice but not BALB/c mice because of the presence of myosin or a myosin-like protein in the extracellular matrix of DBA/2 mice. Gaunt and colleagues investigated the relationship between coxsackievirus and myosin and suggested that molecular mimicry between myosin and coxsackieviruses may play a role in myocarditis. Anti-coxsackieviral-neutralizing antibody produced myocardial inflammation in mice. Therefore, both antibody and T cells may contribute to the pathogenesis of inflammatory myocardial lesions. Susceptibility to anti-myosin antibody-induced myocarditis was dependent on the strain of mice. For example, different pathogenic mechanisms have been reported in DBA/2 (antibody-mediated disease) and BALB/c (T-cell-mediated) mouse strains. Susceptibility may be related to genetic factors including target organ sensitivity or influences such as infection and polarizing TH1/TH2 cytokines. Antibodies against myosin were elevated after coxsackieviral infection of susceptible mouse strains. In rheumatic carditis, infection plays a major role as well as anti-myosin antibody that has been shown to be cytotoxic for heart cells in culture and to recognize cell surface cross-reactive antigen laminin on the valve and myocyte cell surface. In rheumatic carditis, antibodies deposit in myocardium as well as valvular endothelium and T cells infiltrate the valve. There have been a number of studies that have demonstrated anti-cardiac myosin or anti-heart antibodies in acute and chronic myocarditis and soluble interleukin-2 levels were correlated with disease severity and cardiac autoantibodies. Thus, in inflammatory heart diseases, myocarditis and rheumatic carditis, both antibody and T cells are implicated in the disease.

**Susceptibility to Myocarditis in Rodent Models**

Using rodent models, the role of cardiac myosin as an autoantigen in the pathogenesis of autoimmune myocarditis has been well established. Myocarditis can be induced by cardiac myosin in A/J mice, BALB/c mice, and in Lewis rats. However, C57BL/6 mice are resistant to myosin-induced myocarditis. Induction of coxsackievirus-induced myocarditis is seen in a similar group of mouse strains including A/J and A.SW. C3H, and BALB/c and DBA/2. BALB/c mice that have disruption of the gene for the negative immunoregulatory receptor PD-1 develop dilated cardiomyopathy with diffuse deposition of IgG throughout the heart and on the surface of cardiomyocytes. Autoantibodies in the disease model reacted with an unidentified 33-kd heart-specific protein.

Exposure of cardiac myosin in the heart may be an important event leading to the onset of disease in the susceptible host. Evidence has shown that in normal myocardium myosin-class II major histocompatibility antigen complexes are present before the induction of autoimmune myocarditis. Induction of myocarditis is seen only with cardiac myosin and not skeletal myosin or other α-helical coiled-coil proteins such as tropomyosin (Galvin and Cunningham, unpublished data). Streptococcal M protein mimics cardiac myosin sequences or epitopes and immunization with the M protein or peptides leads to myocardial and valvular inflammatory heart lesions in BALB/c mice and Lewis rats. Therefore, it would seem that the α-helical structure is not the critical factor in breaking self tolerance, but that unique and/or cryptic epitopes present in cardiac myosin are the decisive factor. In fact, unique epitopes within cardiac myosin have been described to produce myocarditis. Myocarditis was induced by amino acid residues 334 to 352, located in the S1 region of A/J mouse cardiac myosin, residues 736 to 1032 in BALB/c cardiac myosin, acetylated residues 614 to 643 of rat cardiac myosin produced disease in BALB/c mice, residues 1070 to 1165 of porcine cardiac myosin induced disease in Lewis rats, residues 1107 to 1186 in the Lewis rat, and acetylated Lewis rat LMM region residues 1539 to 1555. Our studies in Lewis rats (Galvin et al, manuscript in preparation) suggest that epitopes within the LMM region produce valvulitis whereas the most severe myocarditis is produced by an epitope within the S2 region of cardiac myosin (Cunningham and Li, unpublished data). A diagram of the myosin molecule and its fragments is shown in Figure 1. It has been proposed that only self epitopes would induce autoimmune myocarditis, however, it was reported that both murine and porcine cardiac myosins produced the same disease immunologically (IgG sub-
Influence of Cytokines on Myocarditis and TH1/TH2 Immune Responses

Infection is a strong inducer of either TH1 or TH2 cytokines (Table 1), depending on the type of infectious pathogen, such as intracellular microorganisms, viruses, extracellular bacteria, and superantigens, or parasitic microbes. Infection as well as genetic predisposition may play an important role in the cytokine phenotype expressed and the subsequent onset of autoimmune myocarditis.

Pathogenic mechanisms in myocarditis may be related to specific cytokine production in a particular animal strain or individual and participate in onset and further development of myocarditis. Cytokines are important in controlling T cells responsive to self antigens and are critical in shifting the immune response toward a TH1 or TH2 pattern. Recent evidence suggests that both B and T cells are involved in polarized cytokine production and CD4+ and CD8+ T cells as well as natural killer and dendritic cells may also be involved in production of polarizing cytokines. The TH1 response shifts the cytokine profile toward delayed hypersensitivity, macrophage activation, and a proinflammatory T cell response associated with IFN-γ and interleukin (IL)-12, whereas the TH2 response is associated with B cell activation and humoral immunity, and IL-4, -5, -10, and IgE production. IL-12 has been shown to induce the differentiation of TH1 autoreactive T cells and to enhance autoimmune disease in certain animal models. TH1 T cells secrete IL-2 and IFN-γ that suppresses TH2 responses, whereas TH2 T cells secrete IL-4 and IL-10 that inhibit TH1 responses. Previous studies in the Lewis rat model of cardiac myosin-induced myocarditis have shown that cardiac myosin-sensitized T lymphocytes could transfer myocarditis to naive recipient rats more effectively when cultured in vitro with IL-12, whereas IL-2 was less effective, and IL-12 induced IFN-γ production in lymph node cells. The CD4+ T cells were found to be required for the transfer and infiltration of the myocardium, whereas CD8+ T cells were not required to cause myocarditis in the Lewis rat model of myosin-induced myocarditis. In addition, the study found that IL-12 (p40) mRNA was expressed by macrophages infiltrating the heart. In addition, administration of IL-12 enhanced myocarditis in the rat. Thus, autoimmune myocarditis in the Lewis rat model was promoted by a TH1 response.

Table 1. Table Illustrating the TH1/TH2 Paradigm Indicating the Characteristics of TH1 and TH2 T Cell Subsets

<table>
<thead>
<tr>
<th>TH1</th>
<th>TH2</th>
</tr>
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<tbody>
<tr>
<td>Activate macrophages</td>
<td>Activate B cells (humoral immunity)</td>
</tr>
<tr>
<td>(delayed-type hypersensitivity)</td>
<td>IL-4 induces TH2 subset</td>
</tr>
<tr>
<td>IL-12 and IFN-γ Induces TH1 Subset</td>
<td>Secrete IL-4 and IL-10 which inhibit TH1</td>
</tr>
<tr>
<td>Secrete IFN-γ and IL-2 that inhibit TH2</td>
<td>IgE, IgG1 (mice), IgG4 (humans)</td>
</tr>
<tr>
<td>IgG 2a (mice), IgG1, IgG3 (humans)</td>
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</tbody>
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Recent evidence suggests that both B and T cells are involved in polarized cytokine production and CD4+ and CD8+ T cells as well as natural killer and dendritic cells may also be involved in production of polarizing cytokines.
However, it is important to understand that pathogenic mechanisms among the susceptible animal models of myocarditis may not all be identical. In the A/J and BALB/c strains studied by Afanasyeva and colleagues,87 in this issue of The American Journal of Pathology, the TH2 response is favored. In BALB/c mice, IL-4 renders T cells unresponsive to IL-12.88 The study by Afanasyeva and colleagues in this issue of the American Journal of Pathology describes the role of TH2 cytokines, IL-4 in particular, in the development of myocarditis. The importance of TH1/TH2 immune responses is the power of specific cytokines to drive the immune response in an individual or particular animal model toward or away from disease. In the myocarditis model described in A/J mice, anti-IL-4 treatment markedly reduced myocarditis presumably by switching the cytokine production from a TH2 to TH1 profile that would be a switch in cytokine production from IL-4 to up-regulation of IFN-γ. The TH1 phenotype is associated with production of IFN-γ and TH1 T cell development, activation of macrophages, induction of delayed-type hypersensitivity, and production of IgG2a subclass in mice (IgG1 and IgG3 in humans).

However, in the TH2 phenotype, IL-4 is produced with activation of B cells, allergic reactions, and the production of IgG1 in mice and IgG4 in humans and IgE in both. The work describes A/J mice (and BALB/c mice as well), which are susceptible to cardiac myosin-induced myocarditis, to have eosinophils in the cellular infiltrate in the myocardium as well as giant cells within the heart lesions. The presence of eosinophils and giant cells were presented as suggestive histopathological evidence for a TH2 response in the myocarditis in A/J mice. Eosinophils are well known to be associated with production of cytokines IL-4, IL-5, IL-10, and IgE.89–91 In 1988, a report demonstrated that IL-4 induced formation of giant multinucleated cells in culture.92 However, it is well known that giant multinucleated cells are associated with granulomatous lesions formed in response to intracellular bacteria such as Mycobacterium tuberculosis.93 and it may be possible that giant cell formation occurs under either TH1 or TH2 conditions. Granulomatous lesions contain macrophages/monocytes from which the multinucleated giant cells form.92 In the pattern of granulomatous lesions, lymphocytes are recruited and surround the macrophages/monocytes. Granulomas containing activated macrophages are the immune response against intracellular bacteria and part of the response to TH1 cytokines such as IFN-γ. Organ-specific autoimmune diseases have been attributed to TH1 mechanisms and tissue damage that could be down-regulated by switching the autoimmune disease model to TH2 cytokine production.92,93 The role of IFN-γ in progressive autoimmune disease may be related to its effect on increasing uptake and presentation of self epitopes in target organs.93 As described by Falcone and Sarvetnick,93 the classical inflammatory pathway is characterized by production of the cytokines IL-1, tumor necrosis factor (TNF), and free radicals that are induced in activated macrophages by IFN-γ and inhibited by IL-4. An alternative nonclassical inflammatory cytokine pathway is exhibited by IL-4 that can induce macrophage activation and enhance phago-cytosis as well as expression of MHC class II molecules.83,94 In addition, the timing of cytokine production may enhance or abrogate autoimmune disease. Large amounts of IL-12 or TNF produced early in disease may lead to progression of autoimmunity whereas their production later in disease could institute terminal differentiation and death of T cells and abrogation of disease.83 Therefore, IFN-γ can be protective against autoimmune disease in certain instances.85 Regulatory T cell subsets may require IFN-γ to maintain their down-regulatory mechanisms.95,96

In the A/J mouse, a TH2 pathogenic mechanism accounted for severe myocarditis that correlated with eosinophilic infiltrates, giant cell formation, and IgG1 and IgE antibody responses against myosin. Abrogation of myocarditis was observed when anti-IL4 was administered suggesting that TH2 immune responses were very important in development of myocarditis in the A/J mouse model of myosin-induced myocarditis. Administration of anti-IFN-γ exacerbated disease demonstrating a protective effect by IFN-γ. A/J mice that are known to produce strong TH2 responses are partially deficient in IL-12 and develop asthma. Myocarditis in humans is less well understood compared to animal models, but could result from either a TH1 or a TH2 response. The A/J mouse model of TH2-mediated disease is an excellent example of how IL-4 can mediate myocarditis and IFN-γ can protect against disease. Therefore, modulation of the TH1/TH2 cytokines as a therapy for myocarditis will require careful evaluation for it to be safe and efficacious in humans. It is possible that the different stages of myocarditis may be associated with different cytokine profiles.

In previous studies of coxsackievirus-induced myocarditis, IL-1 and TNF-α have been shown to promote myocarditis in myocarditis-resistant C57BL6 congenic mice, indicating that the immune system in resistant mouse strains can be provoked to generate an autoimmune response against the heart.97 In A/J mice, monoclonal antibody neutralization of TNF-α reduced the severity of myocarditis whereas anti-IFN-γ increased the severity of disease.98 TNF-α is believed to be produced by heart-infiltrating macrophages in the rat model of myocarditis and to be important in cardiovascular diseases.99 It has been reported that the lack of TNF-α receptor (TNF-R) p55 gene expression could interfere with either lymphocyte activation or target organ susceptibility.100 In fact, A/J mice lacking TNF-R p55 are susceptible to Listeria infections,101 but were protected from cardiac myosin-induced myocarditis.100 TNF-α when administered to animals induces MHC class II molecule expression.102 In animals lacking the TNF-R p55, no MHC class II expression was observed after cardiac myosin injection as compared with wild-type animals expressing the TNF-R and MHC class II molecules.100 These data link the TNF-R with myocarditis and MHC class II expression in the myocardium.

Recently, a study of a transgenic mouse model of IFN-γ expression in the pancreas indicated that the IFN-γ protected the mice against lethal coxsackie virus infection and subsequent myocarditis.39 In this model, IFN-γ...
expression was limited to the pancreas and was not expressed in the heart.\textsuperscript{39} The protective mechanism proposed was that viral infection in the heart was subdued, and therefore, myosin was not released from the lysis of infected myocytes and induction of autoimmune heart disease would not occur. Protection was attributed to the antiviral effect of IFN-\(\gamma\). In the study of the transgenic animals, viremia was reduced in the heart.\textsuperscript{39} Other factors besides reduction of viremia may play a role in protection against viral-induced autoimmune myocarditis. In the study reported herein, in the absence of viral infection but in the presence of immunization with cardiac myosin, IFN-\(\gamma\) protected against myocarditis presumably by controlling the expression of IL-4 by T cells. The myocardial cytokine environment and the release of myosin in the heart may be two very important factors in generation or prevention of myocardial inflammatory disease. Cardiac myosin epitopes presented in the heart may lead to a loss of tolerance against cardiac-specific cryptic epitopes in the presence of threshold concentrations of cytokines. In the myocarditis models, it will be important to evaluate the local cytokine environment in the heart during the different stages of myocarditis and compare it with circulating and inducible cytokines in the spleen.

**Genes in Myocarditis**

To understand the multiple factors involved in the onset and progression of myocarditis, studies are beginning to determine some of the genes that are involved in causing the inflammatory and autoimmune disease state in myo- cardium. It is clear that structural genes are involved in hereditary forms of cardiomyopathy and have been documented in a review by Towbin and colleagues.\textsuperscript{4} Mutations in genes encoding sarcomeric proteins including cardiac myosin heavy and light chains, cardiac troponymosin, cardiac troponins, and myosin-binding protein C have been associated with familial hypertrophic cardiomyopathy.\textsuperscript{103} Overexpression of calcinurin, a calcium-regulated phosphatase, can in transgenic mice lead to cardiac hypertrophy and dilated cardiomyopathy.\textsuperscript{105} Mutations in dystrophin, dystrophin-associated glycoproteins, and actin lead to dilated cardiomyopathy.\textsuperscript{4} The role of the coxsackieviral 2A protease in cleavage of dystrophin leads to dilated cardiomyopathy.\textsuperscript{6,7} Abnormalities of the cytoskeletal proteins lead to dilated cardiomyopathy.

Obviously, expression of cytokine genes in transgenic mice lead to either enhancement or protection against myocarditis. Other genes that have been reported to be involved in inflammatory myocarditis include Fas ligand when expressed in the heart led to a mild inflammatory infiltrate\textsuperscript{104} and apolipoprotein J/clusterin that was found to limit the severity of murine autoimmune myocarditis presumably by binding immunoglobulin and complement and protecting cardiomyocytes from injury.\textsuperscript{105} Disruption of the gene encoding the negative immunoregulatory receptor PD-1 led to dilated cardiomyopathy with sudden death and congestive heart failure in mice.\textsuperscript{61} Hearts from PD-1-deficient mice exhibited diffuse deposition of IgG on the surface of myocytes and antibody in the disease recognized a 33-kd protein specific to heart tissues. PD-1 may contribute to protection against autoimmune myocarditis. Studies of DBA/2 \(\times\) CbyD2F1 mice susceptible to myocarditis revealed a locus on chromosome 12 that was strongly linked with myocardial inflammation. DBA/2 mice are susceptible to anti-myosin antibody mediated myocarditis whereas BALB/c are resistant. The investigation of genes involved in myocarditis indicates that they are diverse and are related to several different mechanisms of pathogenesis.

**Perspectives**

The study on TH2 cytokines in myocarditis in A/J mice may be an important guide for understanding human myocarditis as well as other myocarditis animal models in mice and rats. Further studies of human myocarditis will be informative as well as investigation of the cytokine profiles in the heart, spleen, and circulation of animal models of carditis. Not enough is known about cytokines or the TH1/TH2 paradigm in our animal models or in the human disease. In humans with rheumatic carditis following streptococcal infection, IgG1 and IgG3 antibody subclasses were elevated against streptococcal M protein as well as cytotoxic antibody suggesting a TH1 response after development of acute rheumatic heart disease.\textsuperscript{106} The investigation of the A/J mouse model of myocarditis will no doubt lead to studies in other models and humans to determine the TH1/TH2 phenotype.

Because development of the different stages or types of myocarditis is dependent on several factors, it is difficult to ascribe the disease to a single entity. However, cytokines are a prominent influence on the disease as can be seen in the investigation of the A/J model. As the human genome is investigated further and genes controlling autoimmune disease as well as inflammation in the heart are revealed, we will learn more about how myocarditis develops with its different stages or phenotypes and the relationship of the protective or enhancement genes found in different animal models to human disease.

**References**

25. Neu N, Beisel KW, Trastymen MD, Rose NR, Craig SW: Autoantibodies specific for the cardiac myosin isoform are found in mice susceptible to coxsackievirus B3 induced myocarditis. J Immunol 1987, 138:2488–2492
35. Huber SA, Moraska A, Cunningham M: Alterations in major histocompatibility complex association of myocarditis induced by coxsackievirus B3 mutants selected with monoclonal antibodies to group A streptococci. Proc Natl Acad Sci USA 1994, 91:5543–5547
38. Rose NR: Viral damage or “molecular mimicry”—placing the blame in myocarditis. Nat Med 2000, 6:631–632
1. Sakaguchi S. Regulatory T cells: key controllers of immunologic 

2. Smith SC, Allen PM: Expression of myosin-class II major histocom-
patibility molecules in mice with coxsackievirus B3- and cardiac myosin-induced autoimmune myocarditis. J Immunol 1993, 
152:343–350

3. Limas CJ, Goldenberg IF, Limas C: Soluble interleukin-2 levels in 
patients with dilated cardiomyopathy. Correlation with disease se-

Zamborelli TJ, Penninger JM, Neu N: Identification of cardiac myosin 

5. Inomata T, Hanawa T, Mihasi E, Yajima S, Nakayama T, Maia M, 
Kodama T, Izumi A, Shibata A, Abo T: Localization of porcine car-
diac myosin epitopes that induce experimental autoimmune myo-

6. Wegmann KW, Zhao W, Griffin AC, Hickey WF: Identification of 
myocarditogenic peptides derived from cardiac myosin capable of 
inducing experimental allergic myocarditis in the Lewis rat. J Immu-
nol 1994, 153:892–900

7. Liao L, Sindhwani R, Leinwand L, Diamond B, Factor S: Cardiac 
α-myosin heavy chains differ in their induction of myocarditis: iden-

8. Liblau RS, Sercarz E: Induction or protection from experimental au-
toimmune encephalomyelitis depends on the cytokine secretion pro-
files of TCR-peptide specific regulatory CD4 T cells. J Immunol 1998, 
161:6585–6591


