Anti-rods/rings autoantibody generation in hepatitis C patients during interferon-α/ribavirin therapy

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Abstract

Chronic inflammation associated with hepatitis C virus (HCV) infection can lead to disabling liver diseases with progression to liver cirrhosis and hepatocellular carcinoma. Despite the recent availability of more effective and less toxic therapeutic options, in most parts of the world the standard treatment consists of a weekly injection of pegylated interferon α (IFN-α) together with a daily dose of ribavirin. HCV patients frequently present circulating non-organ-specific autoantibodies demonstrating a variety of staining patterns in the indirect immunofluorescence assay for antinuclear antibodies (ANA). Between 20% to 40% of HCV patients treated with IFN-α and ribavirin develop autoantibodies showing a peculiar ANA pattern characterized as rods and rings (RR) structures. The aim of this article is to review the recent reports regarding RR structures and anti-rods/rings (anti-RR) autoantibody production by HCV patients after IFN-α/ribavirin treatment. Anti-RR autoantibodies first appear around the sixth month of treatment and reach a plateau around the twelfth month. After treatment completion, anti-RR titers decrease/disappear in half the patients and remain steady in the other half. Some studies have observed a higher frequency of anti-RR antibodies in relapers, i.e., patients in which circulating virus reappears after initially successful therapy. The main target of anti-RR autoantibodies in HCV patients is inosine-5'-monophosphate dehydrogenase 2 (IMPDH2), the rate-limiting enzyme involved in the guanosine triphosphate biosynthesis pathway. Ribavirin
is a direct IMPDH2 inhibitor and is able to induce the formation of RR structures in vitro and in vivo. In conclusion, these observations led to the hypothesis that anti-RR autoantibody production is a human model of immunologic tolerance breakdown that allows us to explore the humoral autoimmune response from the beginning of the putative triggering event: exposure to ribavirin and interferon.

**Key words:** Rods and rings; Autoantibodies; Hepatitis C; Ribavirin; Interferon-α

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Core tip: Between 20% and 40% of hepatitis C virus patients treated with interferon-α and ribavirin develop autoantibodies showing a peculiar antinuclear antibodies pattern characterized as rods and rings (RR) structures. In those patients, the first appearance of anti-RR autoantibodies occurs around the sixth month of treatment and reaches a plateau around the twelfth month. The main target of anti-RR autoantibodies is the inosine-5’-monophosphate dehydrogenase 2 (IMPDH2) enzyme, critical in de novo GTP biosynthesis. In cell culture, IMPDH2 inhibition by ribavirin promotes its aggregation into RR structures. These observations led to the hypothesis that anti-RR autoantibody production represents a human model of immunologic tolerance breakdown that allows us to explore interesting aspects of the humoral autoimmune response from the beginning of the putative triggering event.


**INTRODUCTION**

Liver inflammation caused by infection with the hepatitis C virus (HCV) remains a major health challenge. HCV is transmitted by parenteral contact with contaminated blood, frequently through medical procedures. HCV is a small RNA virus 40 to 100 nm in diameter.[1] It has a single-stranded RNA genome that is used directly as messenger RNA in protein synthesis. This positive single-stranded RNA is copied to the negative strand form, which is used as a template for the production of new virus copies. It replicates in the cytosol and endoplasmic reticulum of the infected cells, usually hepatocytes, producing ten viral proteins. Some of these viral proteins inhibit apoptosis and others inhibit interferon effects. The pathological effects of HCV on the liver are mainly caused by the action of the host immune system on infected hepatocytes[2].

Until recently, in most countries, the standard treatment for hepatitis C consisted of weekly injections of 180 mcg of interferon alpha (IFN-α) 2a or 1.5 mcg/kg of IFN-α-2b, typically together with daily 15 mg/kg ribavirin for 48 to 72 wk.[3,4] IFN has potent antiviral activity but does not act directly on the virus or replication complex. Instead, it acts by inducing IFN-regulated genes (ISGs) that provide a non-specific antiviral response[5,6]. Ribavirin is a synthetic guanosine analogue that acts directly against RNA and DNA viruses, probably by inhibiting the virus-dependent RNA polymerase. As a guanosine analogue, ribavirin is intracellularly phosphorylated to generate the monophosphate (RMP), diphosphate (RDP), and triphosphate (RTP) forms. RTP is a competitive inhibitor of inosine-5’-monophosphate dehydrogenase 2 (IMPDH2), which leads to depletion of GTP required for the intracellular synthesis of viral RNA[7]. The incorporation of RTP instead of GTP by the virus-dependent RNA polymerase leads to inhibition of viral replication or to the production of defective virions. However, RTP has been shown to be a weak inhibitor of many viral polymerases[8]. RTP can also be incorporated into viral RNA, forming a template for pairing to CTP and UTP with equal efficiency. The frequency of transitions G→A and A→G in the viral genome will then increase, leading to lethal mutagenesis[9,10]. Therefore, ribavirin alone has no significant effect on HCV, but has a valuable adjuvant effect when used in combination with IFN-α therapy[11].

Autoantibodies are immunoglobulins directed against self-antigens. They can disturb cellular physiology and cause tissue damage by several mechanisms, such as (1) blocking membrane receptors; (2) causing cytolysis by means of antibody-dependent cytotoxic activity; (3) immune complex formation; and (4) complement activation, among others[2]. The presence of non-organ-specific autoantibodies in the sera of HCV patients is common. The proportion of ANA-positive HCV patients can vary from 7% to 50%, with an average of 20% to 30%, depending on the population studied and the methodology used. Some HCV patients also present autoantibodies normally associated with autoimmune liver diseases such as autoimmune hepatitis (AIH) and primary biliary cirrhosis[13,14]. Altogether, these observations suggest that chronic hepatitis C infection is a strong autoimmune condition[15].

Molecular mimicry, imbalance of effector T cells and regulatory T cells, and direct action over B lymphocytes are possible mechanisms leading to autoimmune manifestations of HCV[15]. CD81 on the surface of B lymphocytes is a natural ligand for HCV envelope 2 (E2) protein. B lymphocyte-specific protein CD21, a receptor for the complement C3d fragment, is closely related to CD81. The B cell threshold for polyclonal activation is lowered considerably when HCV E2 coated by C3d engages CD81 and CD21, favoring misleading B cell activation against autoantigens. In addition, the B lymphocyte activating factor (BAFF) is upregulated.
during HCV infection. BAFF binds CD19, a transducer of activation signal into the cell, adding to the production of autoantibodies and cryoglobulins\cite{15,17,18}.

Since autoantibodies against rods and rings (RR) structures have been observed by several laboratories, the aim of this article is to review the recent reports revealing the main characteristics of anti-RR autoantibody production by HCV patients, including its clinical relevance and close relationship with IFN-α plus ribavirin treatment. The major characteristics of RR structures and their molecular constituents are also discussed.

HCV TREATMENT INDUCES AUTOANTIBODIES AGAINST RR STRUCTURES

About 30% of HCV patients treated with IFN-α plus ribavirin (IFN-α/ribavirin) develop autoantibodies that recognize cytoplasmic and nuclear structures resembling rods and rings (RR) (Figure 1A) in the indirect immunofluorescence assay for antinuclear antibodies (ANA)\cite{19-21}. Despite occurring in high titers, anti-RR autoantibodies have not yet been clearly linked with demographic, clinical, or virological features\cite{20,22-24}. Instead, by analyzing sequential samples from several patients, we showed that anti-RR autoantibody production is closely related with IFN-α/ribavirin therapy\cite{20,25}. Anti-RR autoantibodies initially appeared around the sixth month of treatment in nearly half the patients (47%); the anti-RR titers also increased during treatment, reaching their highest levels towards the end of the standard therapy at twelve months. After treatment completion, there was a decrease in anti-RR titer in half the patients while titers remained steady in the other half\cite{20}. A recent publication by Novembrino et al\cite{22} also reported anti-RR titer decline after treatment cessation. They reported that the frequency of anti-RR increased in parallel with therapy duration, with rates of 9%, 38%, and 53% at weeks 12, 24, and 48, respectively\cite{22}.

Since the first reports on autoantibodies against RR structures in HCV patients came out, important questions have been raised regarding the clinical relevance of such autoantibodies. A summary of the available data from the literature is presented in Table 1. One of the earliest studies by Covini et al\cite{21} found that these autoantibodies were more prevalent in patients who did not respond to therapy or relapsed (HCV viral load increased six months after end of treatment) when compared with patients that eliminated the virus completely (33% vs 11%, $P = 0.037$)\cite{21}. The publication from Novembrino et al\cite{22} mentioned above
Table 1  Summary of findings relating the presence of anti-rods and rings autoantibodies to hepatitis C virus treatment outcome

<table>
<thead>
<tr>
<th>Publication</th>
<th>Patient cohort</th>
<th>Results</th>
<th>Conclusions</th>
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<tbody>
<tr>
<td>Covini et al[19] (2012)</td>
<td>Italian cohort: REL/NR n = 30; SVR n = 45; (total = 75)</td>
<td>The prevalence of anti-RR antibody was significantly higher in REL/NR (33%) than in SVR (11%, P = 0.037)</td>
<td>Higher prevalence of anti-RR in REL</td>
</tr>
<tr>
<td>Keppke et al[20] (2012)</td>
<td>Brazilian cohort: Anti-RR reactivity n = 39; No anti-RR reactivity n = 86; (total = 125)</td>
<td>The proportion of NR was equivalent in the 39 patients with anti-RR reactivity (77%) when compared with the 86 anti-RR negative (64%, P = 0.150)</td>
<td>No association between anti-RR reactivity and treatment outcome</td>
</tr>
<tr>
<td>Carcamo et al[19] (2013)</td>
<td>United States cohort: n = 47; Italian cohort: n = 46; (total = 93)</td>
<td>In the United States cohort, NR/REL had significantly higher anti-RR titers compared to SVR (about 1:3200 vs 1:100, P = 0.0016)</td>
<td>Higher titer of anti-RR in REL</td>
</tr>
<tr>
<td>Novembrino et al[21] (2014)</td>
<td>Italian cohort: SVR n = 53; REL n = 27; NR n = 8; (total = 88)</td>
<td>Anti-RR reactivity was significantly more frequent in REL (56%) than in SVR (30%) or NR (12%) (P = 0.0282)</td>
<td>Higher prevalence of anti-RR in REL</td>
</tr>
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</table>

NR: Non-responders, patients who did not respond to therapy; REL: Relapsers, hepatitis C virus viral load increased six months after end of treatment; SVR: Sustained virological response, patients that eliminated the virus completely.

reported a higher frequency of anti-RR autoantibodies in relapers when compared with patients that achieved sustained virological response (SVR) (56% vs 30%, P = 0.0282). Since these two studies found a higher prevalence of anti-RR reactivity in relapers, it should be mentioned that relapsing patients are usually submitted to a second or third round of IFN-α/ribavirin treatment. We discuss above that longer exposure to the treatment increases the chance that the patient will produce anti-RR autoantibodies. In a previous study, we found no association between the presence of anti-RR autoantibodies and the response to anti-HCV treatment with IFN-α/ribavirin in a cohort of 125 patients[20]. This difference between the studies may be related to the origin of the cohorts studied and SVR rates, since Covini et al[21] and Novembrino et al[22] studied Italian patients achieving SVR of approximately 60%, while we studied Brazilian patients with SVR at approximately 30% (Table 1).

The main target of anti-RR autoantibodies has been demonstrated in several studies, using different methods, to be the IMPDH2 enzyme[19,21,23-26]. In a 2013 report from Carcamo et al[19], 96% of samples from a cohort of 46 Italian patients with anti-RR reactivity recognized a 55 kDa band in immunoprecipitation (IP) corresponding with IMPDH2 mobility. In the same study, they also analyzed an American cohort of 47 patients; however, only 53% of American patients recognized a similar 55 kDa band in IP[19]. When we tested a group of Brazilian samples using the same methodology, 12 of 15 patients (80%) recognized the 55 kDa IMPDH2 band[25]. Probst et al[26] developed a cell-based indirect immunofluorescent assay with HEK293 cells expressing recombinant IMPDH2. Using this assay, they found that all 33 anti-RR-positive samples they examined recognized recombinant IMPDH2. Additionally, we performed a sandwich ELISA assay where the native antigen was captured by affinity-purified polyclonal anti-IMPDH2 antibody and found that 37 of the 53 (70%) anti-RR-positive samples presented reactivity above the cut-off[25]. Finally, double-labeling immunofluorescent studies showed that anti-RR autoantibodies label the same RR structures as a commercial anti-IMPDH2 antibody, but not filamentous structures labeled by an anti-cytidine triphosphate synthetase (CTPS) antibody, a critical enzyme in pyrimidine biosynthesis that aggregates into filamentary RR-like structures[23,27-29]. Altogether, these data indicate that IMPDH2 is a major target of anti-RR autoantibodies.

**RR STRUCTURES AND THEIR FUNCTIONS**

Over the last few years, a number of reports have described the ability of CTPS and IMPDH2, rate-limiting enzymes in the cytidine and guanine nucleotide biosynthesis pathways, respectively, to form large polymers[23,30-34]. Under certain conditions, these enzymes aggregate into structures in the shape of rods 3-10 μm in length and rings 2-5 μm in diameter (Figure 1). These structures have been designated rods and rings (or RR) when the structures are composed mainly of IMPDH2, or cytoophidia (Greek for “cellular snakes”) and CTPS filaments when the structures are composed mainly of CTPS, by different laboratories[23,28,29,35]. The first mention of RR-like structures dates back to 1987, when Willingham et al[26] published that they immunized Balb/c mice with Schmidt-Ruppin Rous sarcoma virus-transformed...
Balb 3T3 cells and obtained a monoclonal antibody that labeled cytoplasmic structures very similar to RR structures in indirect immunofluorescence. The putative antigen/structure was named “nematin” due to the worm-like appearance of the observed structures.

Enzyme aggregation into non-membrane-bound large bodies is a common feature in eukaryotic cells\(^{[27]}\). Although it is not known whether all aggregates represent functional entities or enzymatically inactive storage depots, examples of assembled polymers are discussed as a result of: (1) pathologic damage to enzymes (e.g., sickle-cell hemoglobin); (2) enhanced enzymatic activity (e.g., acetyl-CoA carboxylase); (3) formation of structural and functional elements (e.g., actin fibers and microtubules); and (4) as a means to store catalytic potential (e.g., CTPS filaments)\(^{[27]}\).

The function of RR structures is still unknown. To our knowledge, no study has specifically addressed the enzymatic activity state of the IMPDH2 enzyme while aggregated into RR. However, four very recent reports draw apparently contradicting conclusions regarding the enzymatic state of the CTPS enzyme when presented in the filamentary cytoophidia form. Three of the reports, from Barry et al\(^{[30]}\), Aughey et al\(^{[30]}\), and Noree et al\(^{[40]}\), agreed that the aggregation of CTPS into cytoophidia downregulates enzymatic activity\(^{[28-40]}\). Strohlic et al\(^{[41]}\), on the other hand, demonstrated that CTPS within the cytoophidia structures is catalytically active during Drosophila oogenesis\(^{[41]}\). Thus, the current hypothesis is that the assembly and disassembly of RR/cytoophidia structures allows for a highly sensitive control of enzymatic activity by keeping enzymes in active/inactive forms. This could be an important mechanism of regulation of the indispensable GTP/CTP biosynthesis pathways.

The observation that some RR structures disassemble after injection of anti-IMPDH2 antibody into live cells indicates that IMPDH2 molecules are the major building blocks of IMPDH2-based RR structures\(^{[27]}\). However, it also indicates that the binding among IMPDH2 molecules to form RR structures is not very strong, allowing its disassembly by putative chemical tension, allosteric interactions, or other unknown mechanisms generated by the binding of several antibodies. These observations reinforce the hypothesis that assembly and disassembly of RR structures represent highly sensitive maneuvers to control enzymatic activity as described in the previous paragraph\(^{[27]}\).

**Aggregation of IMPDH2 vs CTPS**

Several publications demonstrated the ability of IMPDH2 and CTPS to aggregate into large filamentary structures; however, those studies were focused on only one of these enzymes at a time\(^{[23,30-32]}\). While studying both enzymes simultaneously, we demonstrated the independent formation of IMPDH2-based (structures composed mainly of IMPDH2) and CTPS-based (structures composed mainly of CTPS) filamentous structures within the same cell. We also reported that after treatment with glutamine antagonist 6-diaz-o-5-oxo-L-norleucine (DON), both enzymes can interact in the formation of “mixed” RR structures that display a mosaic of IMPDH2 and CTPS aggregation (Figure 1B-D)\(^{[29]}\).

IMPDH is involved in purine biosynthesis, catalyzing the nicotinamide adenine dinucleotide (NAD+-dependent oxidation of inosine-5’-monophosphate (IMP) to xanthosine-5’-monophosphate (XMP), which is then converted into guanosine triphosphate (GTP), a precursor of the guanine nucleotide\(^{[42,43]}\). Humans express two distinct versions of IMPDH with 84% sequence resemblance and similar kinetic properties, encoded by different genes: IMPDH1 and IMPDH2\(^{[43]}\). Both IMPDH1 and IMPDH2 are expressed constitutively in most tissues, however IMPDH2 is highly expressed in cancer cells and proliferating tissues\(^{[44-46]}\). Therefore, IMPDH has been targeted by immunosuppressive drugs such as mycophenolate (mycophenolic acid or MPA). CTPS is involved in pyrimidine biosynthesis, catalyzing the final step in the biosynthesis of the nucleotide cytosine by converting uridine triphosphate (UTP) into cytidine triphosphate (CTP)\(^{[47,48]}\). In humans, two versions of CTPS are encoded by different genes: the CTPS1 gene for the enzyme CTPS1 and the CTPS2 gene for the enzyme CTPS2. Both are expressed constitutively in all tissues, as they are related to cellular growth and development, but have been shown to be overexpressed in cancer tissues, making them candidate targets for anti-cancer chemotherapy\(^{[48,49]}\).

IMPDH2 and CTPS seem to respond differently to conditions that induce their aggregation into RR/cytoophidia, such as the increase in intracellular concentrations of nucleotides\(^{[32,33]}\). In the presence of excess guanosine, IMPDH2-based RR formed by DON disassembled, but not CTPS-based cytoophidia\(^{[29]}\). This indicates that there are likely two distinct aggregation models for IMPDH and CTPS. RR and cytoophidia show very similar characteristics of formation and behavior, such as the morphological characteristics of rods and rings predominantly localizing to the cytoplasm and occasionally being observed within the nucleus as shorter, thinner structures. However, it has not yet been determined if the mechanisms that regulate the aggregation of each enzyme into RR/cytoophidia are related or not. While some progress has been made in the study of the enzymatic activity of CTPS filaments, the enzymatic state of IMPDH2 in its aggregated form is still totally unknown.

**TOLERANCE BREAKDOWN: THE ANTI-RR CASE**

Self-immune tolerance breakdown with autoantibody production is a multifactorial process that involves
intrinsic and extrinsic aspects. Intrinsic aspects depend on individual characteristics and certain abnormalities which may involve genes related to the major histocompatibility complex and several molecules involved in the control of the innate and adaptive response, as well as the hormonal environment. Extrinsic aspects could be various xenobiotics such as bacterial and viral infections or physical and chemical agents such as UV light exposure, pesticides, and drugs (including medications). Improper nutrition and lack of exercise are also possible contributors.

The generation of anti-RR/IMPDH2 autoantibody appears to depend on inhibition of the target enzyme by treatment with ribavirin. In a previous study from our laboratory, none of 166 treatment-naive HCV patients showed anti-RR reactivity. In fact, anti-RR/IMPDH2 antibodies were exclusively observed in patients who had undergone IFN-α/ribavirin therapy. The absence of anti-RR in HCV patients prior to IFN-α/ribavirin therapy was also described in other studies. However, it is possible that the immunological abnormalities associated with HCV infection and administration of IFN-α that stimulate the host immune system establish the conditions for ribavirin to act as an activator for the breakdown of tolerance with generation of anti-IMPDH2 autoantibodies (Figure 2). Indeed, we noticed that systemic lupus erythematosus patients treated with mycophenolate mofetil, an inhibitor of IMPDH2, do not develop anti-RR antibodies, except in extremely rare cases. In other words, the production of autoantibodies to IMPDH2 is unlikely to result from the inhibition of IMPDH2 and formation of RR alone (Figure 2).

In view of the facts that anti-RR autoantibodies primarily target IMPDH2, that inhibition of IMPDH2 by ribavirin leads to its aggregation into RR structures, and that HCV patients undergoing ribavirin treatment produce anti-RR/IMPDH2 antibodies, we hypothesize that this represents a human model of immunologic tolerance breakdown followed by autoantibody production. We explored such a model, aiming to determine the temporal kinetics of the humoral autoimmune response to IMPDH2 in patients from the onset of treatment with IFN-α/ribavirin. We demonstrated that regarding titer, avidity maturation, and isotype levels, the humoral autoimmunity response to IMPDH2 resembled that of a conventional humoral response to infectious agents, although at a considerably slower pace in titer increase and avidity maturation, as well as in isotype class switch, since these changes occurred over months in contrast to a time frame of weeks in the case of an infectious challenge. The temporal kinetics of the humoral autoimmune response is not readily accessible in human diseases, because we do not know when the triggering event occurs. The model of anti-RR/IMPDH2 autoantibody induced by ribavirin treatment provides a unique opportunity to study this aspect of the autoimmune response in humans. This difference may be related to the peculiarities in the adjuvant milieu in autoimmune and infectious diseases. The conventional infectious process is fueled by the strong adjuvant effect of the innate immune response associated with the inflammation caused by exposure to pathogen-associated molecular patterns (PAMPs) related to infectious agents. In the scenario of an autoimmune response, on the other hand, these elements are lacking or are present in minor proportions, thus possibly conveying different kinetics of the specific autoimmune response against self-antigens. Another element that might contribute to a slower pace in the maturation of the autoimmune humoral response is the existence of an array of counter-regulatory mechanisms that contribute to the maintenance of tolerance to self, including regulatory T and B cells.
CLINICAL RELEVANCE OF ANTI-RR AUTOANTIBODY

The possible clinical impact of anti-RR antibodies has been investigated by several laboratories, but no association has been found with disease severity, clinical evidence of autoimmunity, viral load or strain, or intensity of liver inflammation and injury.[20,22-24] On the other hand, as outlined above, some studies indicate that the presence of anti-RR autoantibodies, especially at high titer, are more frequently observed in HCV-treated patients classified as relapers. This association was observed in the cohorts of Italian and American patients,[19,21,22] but no such trend was observed in the Brazilian cohort[20]. These observations could suggest that the presence of anti-RR autoantibodies indicates a higher chance for poor response to IFN-α/ribavirin therapy, and might support interruption of the treatment and a switch to the new protease inhibitors available for HCV therapy.

However, we emphasize that there is no established evidence for this reasoning. The association observed in the Italian and American cohorts is marginally significant from a statistical point of view, and there is considerable overlap between responders and relapers with respect to the presence of anti-RR reactivity. In addition, no such association was found in the larger Brazilian cohort. In fact, we propose that the marginal association observed in some cohorts may operate from a different perspective. The production of autoantibodies against RR/IMPDH2 is stimulated by IFN-α/ribavirin treatment, save rare exceptions.[53] Ribavirin has been shown to induce IMPDH2 to aggregate into RR structures in vitro[23,29] and in vivo (Kepeke and Andrade, unpublished data). The strict association between anti-RR reactivity and IFN-α/ribavirin treatment in HCV patients strongly suggests that the ribavirin-induced IMPDH2 aggregate is the triggering immunogen in this drug-induced autoimmune reaction. It is therefore conceivable that longer exposure to the treatment would result in a higher chance of anti-RR autoantibody development. Unpublished observations from our laboratory show that up to approximately 70% of the patients treated for a second or third time present positive anti-RR reactivity as opposed to an approximately 40% frequency in patients treated for the first time. This finding adds strength to the hypothesis that longer treatment means a higher chance to produce anti-RR autoantibodies. Relapers are patients that often need to receive successive rounds of treatment with IFN-α/ribavirin. In view of this reasoning, we propose that the higher proportion of anti-RR reactivity in relapers observed in the Italian cohort might be attributed to the longer period of exposure to ribavirin in these patients. This hypothesis must be appropriately challenged in prospective follow-up studies with a large and heterogeneous cohort of patients. In the meantime, it might be appropriate to closely follow anti-RR-positive patients with more frequent viral load measurements.

In conclusion, the autoantibody response against IMPDH2 elicited by ribavirin treatment in hepatitis C patients has allowed us to explore interesting aspects of immunological tolerance breakdown in humans from the beginning of the triggering event. In addition, anti-RR autoantibodies turned out to be invaluable tools in the investigation of the intriguingly large cytoplasmic and nuclear structures known as rods and rings. The molecular constitution of these RR/typhoidia structures thus far appears to be largely based on the IMPDH2 and/or CTPS enzymes. Our laboratory and others have had the opportunity to verify that the RR structures may occur in many physiological and pathological instances. Currently, our efforts are dedicated to understanding the biological significance and the biochemical mechanisms involved in the process of aggregation of enzymes, especially the IMPDH2 enzyme, into RR structures. Future studies should also investigate why IMPDH2 is preferentially targeted by the immune system of HCV patients under IFN and ribavirin therapy, the role of IMPDH2 aggregation into RR filaments in this phenomenon, and to establish animal models for anti-RR tolerance breakdown as observed in HCV patients.

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