Electrocardiographic Abnormalities in a Murine Model Injected With IgG From Mothers of Children With Congenital Heart Block

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Background—It is a widely held view that congenital heart block (CHB) is caused by the transplacental transfer of maternal autoantibodies (anti-SSA/Ro and/or anti-SSB/La) into the fetal circulation. To test this hypothesis and to reproduce human CHB, an experimental mouse model (BALB/c) was developed by passive transfer of human autoantibodies into pregnant mice.

Methods and Results—Timed pregnant mice (n = 54) were injected with a single intravenous bolus of purified IgG containing human anti-SSA/Ro and anti-SSB/La antibodies from mothers of children with CHB. To parallel the “window period” of susceptibility to CHB in humans, 3 groups of mice were used: 8, 11, and 16 days of gestation. Within each group, we tested 10, 25, 50, and 100 μg of IgG. At delivery, ECGs were recorded and analyzed for conduction abnormalities. Bradycardia and PR interval were significantly increased in 8-, 11-, and 16-day gestational groups when compared with controls (P < 0.05). QRS duration was not significantly different between all groups. Antibody levels measured by ELISA in both mothers and their offspring confirmed the transplacental transfer of the human antibodies to the pups.

Conclusions—The passive transfer model demonstrated bradycardia, first-degree but not complete atrioventricular block in pups. The greater percentage and degree of bradycardia and PR prolongation in the 11-day mouse group correlates with the “window period” of susceptibility observed in humans. The high incidence of bradycardia suggests possible sinoatrial node involvement. All together, these data provide relevant insights into the pathogenesis of CHB.

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Key Words: antibodies | electrophysiology | atrioventricular node | heart block

Isolated congenital heart block (CHB) was first recognized in 1901 by Morquio and later by Plant and Steven with use of auscultation and electrocardiography. The association between isolated CHB and maternal connective tissue disease was described by Hull et al and others in the late 1960s and 1970s. This relation has since become well established and ascribed to the presence of SSA/Ro-SSB/La antibodies in maternal sera. SSA/Ro-SSB/La antibodies produce conduction abnormalities in the otherwise normally developing fetus yet have no effect on the adult conduction system.

The incidence of CHB in the general population is 1 in 20,000 births. In the lupus population with anti-SSA/Ro and anti-SSB/La antibodies, the incidence rises to 3 to 5 in 100. Patients at greatest risk are infants of mothers with a history of a CHB delivery, with a recurrence rate of 1 in 5 births. Screening mothers for anti-SSA/Ro and anti-SSB/La antibodies is limited because conduction abnormalities occur in the fetus independent of maternal disease. Moreover, maternal antibodies are usually sought only after the identification of CHB in utero. Approximately 30% of mothers with a CHB delivery are entirely asymptomatic at the time of delivery. Circulating SSA/Ro and/or SSB/La antibodies in the mother are a sensitive indicator of CHB but lack specificity. Although nearly every mother with an affected child has circulating anti-SSA/Ro and/or anti-SSB/La antibodies, only 1% to 2% will have a child with CHB. The IgG subclass of the maternal autoantibodies does not account for the susceptibility of one fetus versus another and is not helpful in identifying pregnancies at risk.

CHB is seen with first-, second-, or third-degree heart block. Third-degree heart block is most common and once manifest is always permanent. Mortality rate approaches 30%, usually within the first 3 months of life. Current therapies include dexamethasone, plasmapheresis, sympa-
thomimetics, and in utero cardiac pacing. None have significantly altered mortality rates.\textsuperscript{13}

The timing of fetal injury is not random. Instead, it occurs during a well-defined period between 15 and 24 weeks of gestation.\textsuperscript{14,15} The development of CHB after 24 weeks of gestation is less frequent. Advances in diagnostic or therapeutic modalities for CHB demand an understanding of how and why the SSA/Ro and SSB/La antibodies exert their pathogenic effects during this critical period. The precise “window period” of susceptibility during gestation suggests that a developmental event may be the deciding factor for CHB to occur. To characterize these arrhythmogenic effects in vivo and to study the “window period” of susceptibility, we devised an experimental murine model for passive transfer of purified human IgG containing anti-Ro (52 kDa and 60 kDa) and anti-La (48 kDa) antibodies into the circulation of pregnant BALB/c mice.

This animal model demonstrates that ECG abnormalities in pups significantly increase when antibodies are introduced during the time the conduction system develops. This may reflect a “window period” of increased susceptibility in the murine model. Marked bradycardia was also observed, suggesting significant sinoatrial (SA) nodal involvement.

**Methods**

**Mouse Model**

Mice were used because of their demonstrated success with passive antibody transfer in the amyotrophic lateral sclerosis, myasthenia gravis, and Eaton-Lambert syndrome models.\textsuperscript{16–18} Fifty-four timed pregnant BALB/c mice were obtained (Harlan Sprague Dawley, Indianapolis, Ind) as follows: Seven 8-day pregnant, seven 11-day pregnant, and six 16-day pregnant. Eleven 8-day pregnant, eleven 11-day pregnant, and eleven 16-day pregnant mice were obtained as controls.

The above-mentioned stages of pregnancy (term is at 19 days) were chosen for injection to target developmental milestones in the cardiac conduction system of the mouse. Embryology of the CFI-I mouse has been extensively studied and considered to be representative of most mice. In the CFI-I mouse, the heart begins its development on the eighth day of gestation and is completed by day 14.\textsuperscript{19} The conduction system matures by day 13.\textsuperscript{20} To target pre-, mid-, and post–cardiac conduction system developmental milestones, 8, 11, and 16 days of gestation, respectively, were chosen for passive antibody introduction.

**Purification of IgG Fractions**

Immunoglobulin fractions containing IgG from 2 mothers with a CHB delivery were purified from serum by protein A-Sepharose gel separation and confirmed to be pure by electrophoresis.

**SSA/Ro and SSB/La Antibodies and Immunizations**

Purified antibodies were diluted in 0.25 mL of normal saline and injected intravenously into the distal tail vein of the pregnant mice with a 30-gauge needle. Broad ranges of antibody dosages were administered to maximize the pathogenic effects of immunoglobulins while minimizing the maternal autoimmune response.

Wides ranges of antibody dosages were administered to maximize the pathogenic effects of immu-

**ECG Recordings**

The ECGs were performed at term on the day of a normal delivery from mothers and their pups. The pups were fixed in the supine position with gentle abdominal restraint with paper tape. No anesthesia was necessary. Leads I, II, and III were recorded with limb leads attached to the pups with miniature adhesive electrodes customized for this purpose. Two adjustable heating lamps were used to maintain body temperature within a range of 36\degree to 37\degree C.

ECGs from the mothers were similarly obtained with the use of a minimal inhalation anesthetic, metofane. Paper speed settings were adjusted to 25, 50, and 100 ms, with filter settings at 40 and 100 Hz. Voltage amplification was 20 mV. Tracings were analyzed for heart rate, QRS duration, and conduction abnormalities including first-, second-, and third-degree heart block. Bradycardia was defined as 40% less than controls.\textsuperscript{21} PR prolongation was defined as $>50$ ms, corresponding to the mean $\pm 2$ SD (mean control PR = 40.4 and SD = 4.9 ms).\textsuperscript{21} After ECG recordings, body weight of individual pups was assessed and compared between different groups.

**Blood Collection and ELISA**

Blood specimens were obtained from both mothers and pups. Blood specimens were centrifuged at 20 000 rpm for 15 minutes and analyzed by ELISA for antibody levels. ELISA was performed as previously described.\textsuperscript{22} Recombinant SSA/Ro and SSB/La proteins were used as ELISA substrates. Typically, 60-kDa and 52-kDa SSA/Ro recombinant protein fractions were diluted in PBS, 1000-fold and 16 000-fold, respectively, for coating 96-well microtiter plates ($=1$ $\mu$g for the 60-kDa protein and 0.1 $\mu$g for the 52-kDa protein). Plates were incubated overnight at 4\degree C. The plates were then washed with PBS containing 0.05% Tween 20 (PBS-Tween) and blocked with 1% BSA in PBS-Tween, followed by incubation with human antiserum at 1:100 dilution for 1 hour. Each serum was run in duplicate. After washing, F(ab)$^\prime_2$ goat anti-human or mouse IgG alkaline phosphate conjugate was added for 1 hour. The plates were then washed again and developed with p-nitrophenyl phosphate and disodium salt in diethanolamine buffer. Results were expressed as the optical absorbance at 405 nm less reagent blank.

**Statistical Analysis**

Data were presented as mean $\pm$ SEM and analyzed statistically with the paired Student’s $t$ test and ANOVA. A value of $P<0.05$ was considered significant.

**Results**

Significant bradycardia and PR prolongation were present in pups of the 8-, 11-, and 16-day gestation groups when compared with controls. In contrast, pups of mothers not injected, or injected with either control IgG or vehicle, had no conduction abnormalities. Figure 1 illustrates the averaged data for heart rates and PR interval in control and injected groups.

Bradycardia was present in 70% (7 out of 10) of pups from mothers injected at 11-day gestation. The average heart rate in the 11-day group was 233.9 $\pm$ 19 bpm ($n=10$), whereas control heart rates averaged 526.5 $\pm$ 8.1 bpm ($n=52$, $P<0.001$). In pups of mothers injected at 8-day and 16-day gestation, bradycardia was present in 44% (7 of 16 pups) and 33% (10 of 30 pups), respectively. Average heart rate was
Bradycardia or PR prolongation was not present in mothers injected in the 8-, 11-, or 16-day gestation groups. No significant difference was present in heart rate or PR interval of injected mothers before and after immunization. The average heart rate before the immunization was 397±45 bpm and the average PR interval was 47±2.9 ms (n=20). After immunization and giving birth, the heart rate was 401.3±36 bpm and 46.5±3.4 ms (n=20).

The group injected with 10 μg IgG had 100% bradycardia and first-degree heart block. Higher IgG doses caused fewer conduction abnormalities (Figure 3). These observations are typical of a passive model probably because of the exaggerated maternal immune response with anti-idiotype immunoglobulins to the higher injected dosages.

The body weight of individual pups from injected and control groups was not significantly different. Pups from immunized mothers in 8-, 11-, and 16-day gestation groups weighed 2.0±0.4 g (n=16), 2.2±0.5 g (n=10), and 2.1±0.7 g (n=30), respectively, versus 2.4±1.2 g (n=48) in the control group (P>0.05).

All immunized mothers and their corresponding pups showed increased levels of anti-SSA/Ro 52 (0.281 to 0.483) and 60-kDa (0.10 to 0.19) human antibodies, confirming transplacental passage of human antibodies to the pups. In contrast, no detectable antibody levels were present in controls (<0.02, Table 2). Levels of anti-SSB/La 48 kDa were not significant in both immunized and control mice.

**Discussion**

These results demonstrate that injection of pregnant mice with human IgG from mothers of children with CHB results in bradycardia and first-degree AV block but not complete heart block. In addition, ECG abnormalities are dependent on the period of gestation during which the injection was performed. This suggests that timing is critical in the development of conduction abnormalities during pregnancy.

**Window of Susceptibility**

In the clinical setting, conduction abnormalities occur between 15 and 24 weeks of gestation.14,15 In this model,
bradycardia and PR prolongation were observed in all 3 groups (8, 11, and 16 days of gestation) but most pronounced in the 11-day group. This suggests a critical time or “window period” during which the heart is most vulnerable to pathogenic antibodies.

Onset of the “window period” is most likely related to the earliest transplacental passage of IgG from the maternal circulation. SSA/Ro and SSB/La antibodies, like other maternal immunoglobulins, interact with the Fc receptors on the trophoblastic cell surface, are engulfed in endocytic vacuoles, are actively transported across the placenta, and are released by exocytosis into the fetal umbilical circulation. In humans, these IgGs are detectable as early as 6 to 11 weeks of gestation but increase significantly at approximately 16 to 17 weeks of gestation.22

Interestingly, by 16 weeks of gestation, the human conduction system is functionally mature, coinciding with the earliest reports of CHB manifestation in the fetus. It is tempting to speculate that the fetal heart may be exposed to autoantibodies at an earlier stage of development and that its effects are manifest after the conduction system is mature. Alternatively, the conduction abnormalities may only manifest once critical levels of antibodies are present. Although the highest percentage of bradycardia and first-degree AV block in the current model occurred with the lowest dose of antibodies, this probably resulted from an increased maternal immune response to higher doses and may not reflect the clinical setting. It is well known that when large amounts of antigen/antibody such as serum are introduced into the circulation, a serum sickness–type reaction may result.23

The immunologic pathogenesis depends on antigen antibody concentrations. Higher concentrations of antibodies can form large complexes, which are rapidly cleared, whereas small complexes persist because they fail to activate complement receptors.23

The mouse model was used to investigate the above hypotheses because the embryology of the mouse has been extensively studied.19 In the mouse, paired cardiac mesenchymal primordia begin fusing as early as 7 days. By 8 days, a tubular heart with the beginnings of myocardial contractions appears. The atrial and bulboventricular areas become clearly defined when the bulboventricular areas contract. By 9½ days of gestation, the interventricular septum is formed, and by 10 days of gestation, paired heart chambers may be seen. By day 12, the foramen ovale forms and the atrial and ventricular septum are almost complete. The AV node is established by day 13 of gestation.20 By 14½ days of gestation, the fetal circulatory system is complete and functioning. Our data revealed that first-degree AV block was most prominent in the 8- and 11-day groups, coinciding with the development of the conduction system in mice.

We previously reported the development of conduction abnormalities, including complete AV block, in pups from mothers actively immunized with a recombinant 52-kDa SSA/Ro protein.21 The most striking difference between the active and passive models is the absence of complete AV block in pups of the passive model. The exact mechanism is not yet clear. One explanation may be that murine autologous autoantibodies are more specific and therefore more pathogenic than passively introduced human antibodies.

**Bradycardia and SA Node Involvement**

Because abnormalities of the AV node characterize human autoantibody–associated CHB, the AV node rather than the SA node was the main focus of previous publications.21,24,25 Although Garcia et al,25 by using rabbit heart, and Boutjdir et al,21,24 by using rat and human fetal heart, have also observed sinus bradycardia in their models, this bradycardia was not emphasized. The high incidence of bradycardia in the current model suggests possible SA nodal involvement. Indeed, human fetal autopsies showed calcification of the SA node,26 further suggesting that the SA node may also be affected. Whether the observed sinus bradycardia is related to the prolonged PR interval remains to be elucidated. Sinus brady-

### Table 1. Summary of ECG Parameters in Control and Immunized Pups

| Pups, n | Heart Rate, bpm | PR, ms | QRS, ms | Bradycardia, % | I Degree, % | II and III Degree |
|---------|----------------|-------|---------|---------------|-------------|----------------|-------|
| Control | 52 | 526.5±8.1 | 40.4±1.1 | 22.2±1.21 | 0 | 0 | 0 |
| Passive | 8-day | 16 | 289.3±14.6* | 62.9±2.3* | 24±0.92 | 44 | 88 | 0 |
| 11-day | 10 | 233.9±19.0* | 74±4.5* | 24.5±1.25 | 70 | 90 | 0 |
| 16-day | 30 | 303.9±12.0* | 57.8±2.3* | 22.8±0.52 | 35 | 45 | 0 |

*P<0.05 compared with control.

### Table 2. Blood Levels From Pups of Mice Immunized With SSA/Ro and SSB/La Antibodies as Measured by ELISA

<table>
<thead>
<tr>
<th>Antibody</th>
<th>Anti-52 kDa</th>
<th>Anti-60 kDa</th>
<th>Anti-48 kDa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immunized</td>
<td>0.281–0.483</td>
<td>0.10–0.19</td>
<td>0.01–0.02</td>
</tr>
<tr>
<td>Control</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
<td>&lt;0.02</td>
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cardia that is due to intrinsic negative chronotropic effect or sinus node automaticity is not accompanied by slowing of AV nodal conduction. It could be argued that a slower input to the AV node might result in an improved cardiac velocity. On the other hand, an autonomic (vagotonic) bradycardic effect on the sinus node automaticity could also be associated with vagotonic slowing of AV nodal conduction. A vagotonic effect on the sinus node activity and AV nodal conduction secondary to the effect of autoantibodies cannot be ruled out. The exact mechanism by which autoantibodies affect the SA node would require further investigations of ion channels in the SA node.

Possible Target Epitopes

Investigators have long questioned how an intracellular Ro and La antigen can become accessible to extracellular circulating antibodies. Some hypotheses propose that the Ro or La proteins are trafficked to the cell surface during development by the induction of stress proteins, hormonal influences, viral infection, or by apoptosis.\(^{27-30}\)

The possibility that the antigenic activity of SSA/Ro antibodies may be independent of the Ro and La ribonuclear protein has been proposed. This hypothesis is supported by the observation that the precipitin activity remains after either treatment with RNase or separation from the RNA.\(^{31}\)

Our previous reports\(^{21,24}\) suggested that the arrhythmogenic effect of autoantibodies from mothers of children with CHB can be attributed partly to their interaction with calcium channels. The autoantibodies inhibited L-type calcium channels at the whole-cell and single-channel levels.\(^{21,24}\) If calcium channels are indeed the target epitope, this could account, at least in part, for the observed bradycardia and first-degree AV block because calcium channels are mainly responsible for electrogenesis both at the sinus node and the AV node.

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