Verapamil Preserves Myocardial Contractility in the Hereditary Cardiomyopathy of the Syrian Hamster


From the Cardiovascular Research Institute, the Cardiovascular Division of the Department of Medicine, and the Department of Anatomy, University of California, San Francisco, California

SUMMARY. We attempted to alter the inherited myocardial damage and loss of contractility of the cardiomyopathic Syrian hamster (strain U-MX7-1) by giving cardiac drugs that altered intracellular calcium and myocardial workload. Thirty-seven 21-day-old cardiomyopathic and thirty-seven 21-day-old normal hamsters were divided into five groups each: verapamil-, propranolol-, digoxin-, hydralazine-, and saline-injected. On their 90th day of life, the hamsters were killed. Of the five cardiomyopathic groups, only verapamil reduced myocardial damage. When both "control" and cardiomyopathic hamsters were treated with saline, digoxin, or propranolol, the cardiomyopathic hamsters had significantly less contractile force, maximal rate of force development, and maximum velocity of unloaded shortening. When both groups were treated with verapamil or hydralazine, there were no significant group differences in the indices of contractility. However, when saline-treated cardiomyopathic hamsters were compared with drug-treated cardiomyopathic hamsters, only verapamil preserved myocardial contractility. There was also a weak correlation between the $V_{\text{max}}$ and the actin-activated ATPase activity of the cardiomyopathic hamsters ($r = 0.63$, $P < 0.001$). We conclude that verapamil helped protect the myocardium of genetically cardiomyopathic hamsters against structural damage, and helped preserve myocardial contractility (Circ Res 50:405-412, 1982)

As cardiac muscle fails, its contractility decreases (Spann et al., 1967). The reason for this loss of contractility is not clear, although several associated biochemical abnormalities have been identified. Of these, three may be important. First, sarcoplasmic reticular function is abnormal, leading to a slower calcium uptake and release (Harigaya and Schwartz, 1969), and to an abnormal intracellular calcium distribution (Ito and Chidsey, 1971). As a result, less calcium is available for myofibrillar activation, relaxation is impaired (Dhalla, 1975), and mitochondrial function is impaired (Peng et al., 1977). Second, because mitochondrial function is impaired and because of an increased energy demand on the remaining cells, the concentration of high energy phosphates falls (Pool et al., 1967). Although the availability of ATP is thought to be adequate for mechanical function, a regional lack of energy for cellular reconstruction cannot be ruled out (Katz, 1975). Finally, associated with the decrease in contractility there is a decrease in myofibrillar ATPase activity (Chandler et al., 1967) and actin-activated myosin ATPase activity (Wikman-Coffelt et al., 1979).

It has been hypothesized that one factor that contributes to the pathogenesis of some forms of heart failure is calcium overload. The cardiomyopathic hamster has a defect in calcium handling that leads to intracellular calcium overload (Lossnitzer, 1975; Ma and Bailey, 1979). The necrotic lesions peak at about the same time as the calcium overload and disappear by the 100th day of the hamster's life (Lossnitzer, 1975). As many as 25% of the cardiac cells die, leaving the remaining 75% to do the work (Jasmin and Bajusz, 1974). The remaining myocardium hypertrophies and eventually fails (Forman et al., 1972). The reflex increase in sympathetic tone and myocardial norepinephrine production may only serve to worsen both the calcium overload and necrosis (Lossnitzer, 1975). The failing myocardium of the cardiomyopathic hamster resembles that of the failing human myocardium in its biochemical and mechanical properties (Gertz et al., 1970; Forman et al., 1972; Lossnitzer, 1975; Pang and Weglicki, 1980).

In this study, by giving four different cardiac drugs, we attempted to alter the degree of structural damage and the decrease in contractility which typifies the failing heart of the cardiomyopathic Syrian hamster. In line with the calcium overload hypothesis, verapamil and propranolol were given to decrease intracellular calcium and to decrease oxygen consumption (Shand, 1975; Singh et al., 1978). Hydralazine was given in an attempt to decrease afterload (Ablad, 1963; Chatterjee, et al., 1976), and digoxin was given, presumably to increase intracellular calcium (Smith and Haber, 1973).

Methods

Drug Protocol

Twenty-one-day-old cardiomyopathic Syrian hamsters ($n = 37$) of strain U-MX7-1 were chosen for the study (Jasmin and Bajusz, 1974). The hamsters were divided into four groups of seven and one group of nine, with one littermate and the same number of females in each group...
Muscle Mechanics

The hamsters were killed by a guillotine, the heart removed, and the left ventricle cut open. The tendinous end of the best papillary muscle was tied with a piece of 7-0 Deknatel suture, excised, and mounted in an isolated muscle bath. The base of the muscle was held in a Lucite clamp and the tendinous end was tied to a lever with an electromagnetic feedback system to allow control of force, length, and velocity (Brutsaert et al., 1973). The muscle was stimulated (5-msec stimuli with voltage 2HjO, 2.54; and dextrose, 5.0), which was kept at 29°C and a pH of 7.4, and was gassed with 95% oxygen and 5% CO₂, 2 HjO, 2.54; and dextrose, 5.0), which was kept at 29°C and a pH of 7.4, and was gassed with 95% oxygen and 5% CO₂.

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The muscles were stimulated (5-msec stimuli with voltage 10% above threshold) at three times per minute but a Grass S-88 stimulator through platinum field electrodes. The muscles were permitted to stabilize for 2 hours, the peak of the force-length relationship (Lₐₘₐₓ) determined, and the muscles permitted to stabilize again. The experiment was conducted at Lₐₘₐₓ length. The average cross-sectional area of muscle was calculated by dividing the muscle weight by its length, assuming a general cylindrical shape and a specific gravity of 1.0.

To assess contractility, the maximal force and dF/dt were measured at the peak of the force-frequency curve at three stimuli per minute (Forman et al., 1972). After adjusting the elastic damping of the force-length velocity lever feedback system to compensate for the electromechanical transients, the maximum velocity of unloaded muscle shortening was obtained at six stimuli per minute, by abruptly decreasing the load of the muscle at the time of activation. The lever system is identical to that described in detail by Brutsaert et al. (1973). This measurement was used as a close approximation of Vₐₘₐₓ, and is more reproducible than an "extrapolated Vₐₘₐₓ" from a series of isotonic afterloaded contractions. The equivalent mass of the lever and coil was 190 mg, the static compliance was 3.5 μg, and the dynamic compliance was 0.5 μg/sec.

Histological Protocol

In an attempt to better quantify the degree of protection afforded to the left ventricular myocardium against spontaneously occurring structural damage, we developed a morphometric counting system, building on the semiquantitative approach used earlier (Bajusz, 1969). The strength of the morphometric approach, i.e., its surprising reproducibility from relatively small numbers of animals, comes from the randomization of sampling and counting (Weibel, 1969).

As each hamster was killed, a sample approximately 0.5 cm x 0.5 cm in size was excised from the entire thickness of the left ventricular myocardium, midway along the ventricular free wall, and fixed in 6% glutaraldehyde buffered to pH 7.2 with 0.1 M sodium cacodylate. It was subsequently dehydrated in ethanol and embedded with random orientation in glycol methacrylate (GMA) plastic. The sample was cut into 4 μm-thick sections on three levels, each separated from the next by at least 100 μm. The sections were stained with lead hematoxylin (Scolia et al., 1969). Each level was analyzed separately and the results pooled for each hamster. A sampling grid 1 mm x 1 mm square, subdivided into one hundred smaller squares, was inserted into the microscopic ocular and used for assessing myocardial damage. Four fields were chosen randomly at each level, and the number of squares overlapping damaged areas of the myocardium was recorded for each. Damaged myocardium included necrosed or hypercontracted fibers, areas of scarring, and areas of calcification. From the scores for the four randomly selected fields assessed from the three separate levels of each sample, the percentage of myocardial area which was normal, i.e., not abnormal microscopically, was derived for each hamster.

Biochemical Protocol

Actin-activated myosin ATPase activity was measured because of its known association with Vₐₘₐₓ, an index of muscle contractility (Barany, 1967). The remaining portion of the hamster hearts were immediately frozen (−80°C) after excision from the hamsters. Myosin was purified from the frozen hamster hearts using a high acceleration-deceleration centrifuge (Wikman-Coffelt and Coffelt, 1981). Briefly, the frozen heart was minced in 10 volumes (wt/vol) of buffer #1, which contained in mM 1.0 MgCl₂, 0.1 EGTA,
1.0 DTT, 5.0 ATP, 0.05 K2HPO4, 10.0 Na pyrophosphate, 1.0 NaF, and 1.0 Na azide) at pH 6.8. This buffer relaxes the myofibrils and thus allows for subsequent separation of undesirable proteins from myosin. The substrate and the reducing agent protect the ATPase activity of myosin, and NaF and Na azide inhibit phosphatase activity. The low salt concentration keeps myosin insoluble even though many other contaminating proteins are solubilized in this buffer. The minced tissue was blended in a Sorvall Omnimixer for 15 seconds and by centrifugation at 1500 X g (± 1 g) for 100 seconds (± 1 second). The buffer was decanted and the extracting procedure was repeated two more times. After the third extraction, the myosin sediments were homogenized in 6 vol (wt/vol) of a high-salt buffer, buffer #2, for solubilizing myosin. This buffer contained (in mM) 100 K2HPO4, 10 Na pyrophosphate, 300 mM KC1, 1 DTT, 5 ATP, and 1 NaF. The mixture was stirred for 10 minutes (4°C) and then centrifuged at 5,000 g for 200 seconds. After centrifugation, the supernatant was saturated with (NH4)2 SO4 to 45%, stirred for 3 minutes, and again centrifuged at 5,000 g for 200 seconds. The pellet containing myosin was dissolved in 10 mM Tes, pH 7.0, containing 150 mM KC1 and dialyzed overnight with a large volume of water containing 1 mM EDTA to further purify mosin and release actin. Myosin was sedimented by centrifugation (5,000 g for 200 seconds) and again solubilized in 10 mM Tes, pH 7.0 containing 500 mM KC1.

The actin used in the activation of the myosin was purified from rabbit skeletal muscle according to the procedures of Spudick and Watt (1971). To adjust for myosin concentration in the suspension, the protein concentration was determined by the Biuret method (Gornall et al., 1949). Actin + Mg2+-activated myosin ATPase activity was measured in a medium containing (mM) 50 Tes (pH 7.0), 50 KC1, 4 MgCl, 1 ATP with 0.1 mg of myosin/ml and 0.1 mg of actin/ml at 30°C. The time was chosen so that less than 15% of ATP was hydrolyzed during the course of the reaction. Pi was estimated by the method of Muklen and Eisenberg (1976). The actin-activated myosin ATPase activity of the normal propranolol-injected hamsters was not measured due to technical reasons.

Statistics

The hamster and myocardial characteristics for all 10 groups were compared by a one-way analysis of variance using a Student-Newmann-Keuls test. The mechanical, histological, and biochemical characteristics were compared separately in cardiomyopathic hamsters and in the normal hamsters by one-way analysis of variance using the Student-Newmann-Keuls test. The variables of the cardiomyopathic hamsters were compared to those of the corresponding normal hamsters by an unpaired t-test.

Results

Hamster and Myocardial Characteristics

The mean weight of the propranolol-injected cardiomyopathic hamsters was lower than that of all other groups (Table 1). There was no difference for any group in the heart weight, the heart weight:body weight ratio, or in the myocardial wet-to-dry weight ratio. The muscle length and cross-section and the mean preloads were the same for all 10 groups. Four of the digoxin-injected cardiomyopathic hamsters had left ventricular thrombi, and one also had left atrial thrombi and a pericardial effusion. Only one saline-injected, and none of the other cardiomyopathic hamsters had left ventricular thrombi.

Muscle Mechanics

The papillary muscle force and dF/dt were greater in cardiomyopathic hamsters given verapamil than in cardiomyopathic hamsters given any other drug (Fig. 1; Table 2). Force, but not dF/dt, was greater after hydralazine than after digoxin. In the normal hamsters, the force and dF/dt of the different groups was the same. After verapamil and hydralazine, but not after the other drugs, force and dF/dt were similar to those in normal hamsters given the same drugs (Fig. 1).

The mean Vmax was greater in cardiomyopathic hamsters given verapamil than in cardiomyopathic hamsters given any other drugs except hydralazine (Fig. 2, Table 2). The Vmax after hydralazine was greater than after digoxin. In the normal hamsters, the Vmax of the different groups was the same. After verapamil and hydralazine, but not after the other drugs, Vmax was similar to those in hamsters given the same drugs (Fig. 2).

Histology

Qualitative Features

The histological characteristics of the spontaneously occurring myocardial lesions could be categorized into muscle damage, healing, and calcification (Fig. 3). Features of damage to myocytes included: clear areas ("halos") around nuclei, loss of cellular stainability usually accompanied by localized myofibril breakdown, hypercontraction and disintegration of individual myocytes. Features of healing included infiltration of damaged areas and coating of the fascia of blood vessels by nonmuscle cells. Calcification usually occurred superimposed on the zones of healing calcified lesions, but occasionally smaller calcified areas were present at foci of myocyte breakdown.

The effect of each drug tested was to accent or suppress some of these features in a fairly characteristic fashion. Myocardium from the cardiomyopathic hamsters given digoxin was the least unique, but was characterized by a high frequency of nuclear "halos" and stages of myocyte damage short of breakdown. Propranolol-treated cardiomyopathic myocardium characteristically displayed myocyte breakdown in some areas, but somewhat fewer areas of calcification. Hydralazine-treated cardiomyopathic myocardium displayed generalized infiltration by fibroblastic cells. Verapamil-treated cardiomyopathic myocardium was unique in displaying large areas of lighter staining myocytes which appeared otherwise undamaged, and by an obvious lack of calcification (Fig. 4).

Quantitative Features

Morphometric derivation of the percentage of undamaged (microscopically normal) myocardium of hamsters administered the various drugs is presented in Table 3. Only verapamil-treated hamsters dis-
played an amount of undamaged myocardium (84.2 ± 16.7%) significantly better than the saline-treated or the other groups, means for which ranged from 66.9 to 71.5%. Thus, within the limits of the preparation and statistical techniques used, only verapamil clearly provided structural protection.

Biochemistry

The actin-activated myosin ATPase activity of the various groups were not statistically different (Table 2). There was, however, a significant correlation between the actin-activated myosin ATPase activity and the Vmax of the cardiomyopathic hamsters (r = 0.63, P < 0.001) (Fig. 5). There was no difference between the actin-activated myosin ATPase activities of any of the drug-treated normal hamsters (Table 3), but the actin-activated myosin ATPase activity of each of the normal drug-treated groups was higher than that of their cardiomyopathic counterparts (Fig. 2).

Discussion

This study demonstrates that verapamil helps protect the myocardium of the cardiomyopathic hamsters from damage and preserves the contractility of the remaining overloaded myocardium.

Since only single dose levels of each drug were used, however, any comparison between drugs is difficult, without a knowledge of their comparative dose-response relationships. As detailed in the Methods, however, the dose was selected to be a relatively large one.

In our study, verapamil, a calcium-blocking agent (Singh et al., 1978) decreased myocardial damage and preserved the contractility of the remaining myocardium. Verapamil is thought to prevent damage in the cardiomyopathic hamster by decreasing intracellular calcium and thus preventing the toxic effects of calcium overload (Jasmin and Jajusz, 1974; Lossnitzer, 1975). Verapamil may also prevent focal damage by

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### Table 1

<table>
<thead>
<tr>
<th>Hamster and Myocardial Muscle Characteristics</th>
<th>Normal hamsters</th>
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<tbody>
<tr>
<td>Cardiomyopathic hamsters</td>
<td>Propranolol</td>
</tr>
<tr>
<td>Saline</td>
<td>Digoxin</td>
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<tr>
<td>Verapamil</td>
<td>Hydralazine</td>
</tr>
<tr>
<td>Heart</td>
<td>Saline</td>
</tr>
<tr>
<td>Weight (g)</td>
<td>Digoxin</td>
</tr>
<tr>
<td>Heart</td>
<td>Verapamil</td>
</tr>
<tr>
<td>Weight (mg)</td>
<td>Hydralazine</td>
</tr>
<tr>
<td>Weight/body weight (X 10^-6)</td>
<td>Propranolol</td>
</tr>
<tr>
<td>Left ventricular water (%)</td>
<td></td>
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<tr>
<td>Muscle cross-section (mm^2)</td>
<td></td>
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<tr>
<td>Muscle length (mm)</td>
<td></td>
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<tr>
<td>Preload (g/mm^3)</td>
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</table>

Data are mean ± sd. The muscle length and preload were measured at Lmax. The muscle cross-sectional area was calculated by dividing the weight by the length (assuming a muscle specific gravity of 1.0).

* P < 0.05 Propranolol injected cardiomyopathic hamsters compared to other groups.
preventing coronary microvascular spasm (Factor et al., 1980). How verapamil preserves contractility is purely speculative and probably multifactorial. Mechanisms which need further investigation include decreasing inotropy and systemic vascular resistance (Singh et al., 1978), thus preserving ATP; and by decreasing calcium, which, besides decreasing the use of ATP, may prevent the calcium-mediated inhibition of mitochondrial ATP production (Peng et al., 1977). Hydralazine, a potent vasodilator (Ablad, 1963), did not prevent myocardial damage, but may have helped preserve the contractility of the remaining muscle. In hydralazine-treated cardiomyopathic animals, there was no significant reduction in force, df/dt, or \( V_{\text{max}} \), as compared to normal animals treated with hydralazine. These three indices of contractility, however, were not statistically better than the saline-treated cardiomyopathic animals. Thus, the effects of hydralazine on preserving contractility were equivocal. The potential mechanism for preserving contractility is uncertain, but might include reduction of microvascular spasm (Factor et al., 1980), or "vasodilator therapy" of the accompanying heart failure (Chatterjee et al., 1976; Cohn, 1978). However, since the in vivo hemodynamic effects of hydralazine could not be measured, its effects on contractility may have been mediated by mechanisms other than afterload reduction.

Propranolol, a \( \beta \)-blocker (Shand, 1975), did not decrease myocardial damage or preserve contractility. A previous study (Jasmin and Bajusz, 1978) found that propranolol partially protected against damage. Why propranolol did not prevent damage or preserve contractility in our study is not clear, but a number of possibilities exist. We treated our hamsters more than twice as long as Jasmin did but used only half the daily dose. Thus, our lower dose may not have provided sufficient protection. Alternatively, the longer time interval between sacrifice may have been an adverse factor.

Digoxin, a positive inotropic agent (Smith and Haber, 1973), did not protect the myocardium from damage or loss of contractility. On gross examination, the cardiomyopathic hamsters treated with digoxin had the most severe failure, with most of them having left ventricular thrombi and one having left atrial thrombi and a pericardial effusion. Although these hamsters had the lowest force, df/dt, \( V_{\text{max}} \), and myosin ATPase, these changes were not significantly different from those of the saline-injected cardiomyopathic hamsters, because of the large variability in the severity of disease from litter to litter. Digoxin did not prevent myocardial damage and may have caused a further decrease in contractility by increasing the intracellular calcium and the work of already overloaded cells (Smith and Haber, 1973).

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**TABLE 2**

<table>
<thead>
<tr>
<th></th>
<th>Saline</th>
<th>Digoxin</th>
<th>Verapamil</th>
<th>Hydralazine</th>
<th>Propranolol</th>
</tr>
</thead>
<tbody>
<tr>
<td>-force (g/mm²)</td>
<td>1.59±0.43</td>
<td>1.19±0.56</td>
<td>3.08±0.97*</td>
<td>2.21±0.92</td>
<td>1.60±0.32</td>
</tr>
<tr>
<td>df/dt (g/mm² per sec)</td>
<td>24.1±4.6</td>
<td>18.2±7.4</td>
<td>39.4±10.2*</td>
<td>29.3±10.9</td>
<td>24.9±5.7</td>
</tr>
<tr>
<td>( V_{\text{max}} ) (L/msec)</td>
<td>1.95±0.51</td>
<td>1.53±0.47</td>
<td>2.75±0.47</td>
<td>2.32±0.41</td>
<td>1.94±0.48</td>
</tr>
<tr>
<td>myocardial ATPase (µmol of Pi/mg per min)</td>
<td>0.136±0.030</td>
<td>0.129±0.030</td>
<td>0.164±0.030</td>
<td>0.163±0.04</td>
<td>0.136±0.04</td>
</tr>
</tbody>
</table>

* P < 0.005 as compared to saline group.

Data are mean ± SDM.

force = Developed isometric force/cross-sectional area at \( L_{\text{max}} \).

df/dt = Maximum rate of force development at \( L_{\text{max}} \).

\( V_{\text{max}} \) = Maximum measured velocity of unloaded muscle shortening.

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**Figure 2.** The effects of various drugs on the maximum velocity of shortening (\( V_{\text{max}} \)) (upper panel) and actin-activated myosin ATPase (lower panel) of the myocardium of normal and cardiomyopathic hamsters. The \( V_{\text{max}} \) of the saline-, digoxin-, and propranolol-injected cardiomyopathic hamsters was lower than that of the corresponding normal hamsters. The actin-activated myosin ATPase activity of the five cardiomyopathic drug-injected groups was lower than that of the corresponding normal hamsters. Actin-activated myosin ATPase activity was not assessed for the propranolol-injected hamsters. Data are mean ± SDM. * P < 0.05 as compared to their corresponding controls.
FIGURE 3. Saline-treated myopathic myocardium magnified × 3,150. This badly deteriorated area displays partial myofibril breakdown, total myofibril breakdown and myocytes collapse (hatched area), supercontracted myocytes (arrows), and zones of beginning calcification (arrowhead). At the bottom right, an infiltrate of nonmuscle cells is evident.

FIGURE 4. Verapamil-treated myopathic myocardium magnified ×3,150. This representative area is indistinguishable from nonmyopathic hamster myocardium, except for subtle myofibril damage seen in the hatched zone.
FIGURE 5. Correlation between the maximum velocity of shortening \( V_{\text{max}} \) of the papillary muscles and the actin-activated myosin ATPase activity of the myocardium in the same cardiomyopathic animals. Each point represents data from a single animal \((n = 36)\). 

\[
r = 0.63, P < 0.001, L_{\text{max}} = \text{muscle length at the peak of the length-tension curve.}
\]

An interrelationship has been established between maximum rate of skeletal muscle shortening and myosin ATPase activity (Barany, 1967), cardiac muscle shortening, and myosin ATPase activity from the same species (Hamrell and Low, 1978; Carey et al., 1978), and the cardiac muscle shortening and actomyosin ATPase activity from the same animal (Alpert et al., 1974). However, this is the first study correlating maximum rate of cardiac muscle shortening with actin-activated myosin ATPase activity from the same animals. However, despite maintaining a normal \( V_{\text{max}} \), the hydralazine and verapamil cardiomyopathic groups had lower actin-activated myosin ATPase activities than did their normal counterparts. This could be the result of a genetically predetermined myosin isoynme (Affara et al., 1980), or the result of in vivo factors not adequately considered in situ. Some of these factors are: magnesium (Best et al., 1977), calcium (Potter and Gergely, 1975), ATP (Cooke and Bialek, 1979), pH (Wikman-Coffelt et al., 1975), temperature (Alpert, 1979), and other factors which regulate myosin in vivo. Also, calmodulin, which influences many cellular reactions via phosphorylation, may not have influenced the biochemical studies, but could have influenced the isolated muscle studies. Finally, the degree of in vivo hydrolysis shown to be present in muscle of dystrophic animals (Stracher et al., 1976), but not present in our purified proteins used for in vitro measurements, may have played an important role in the in vivo activity of myosin, and thus be reflected only in the physiological measurements.

In conclusion, verapamil reduced the degree of myocardial damage and preserved the contractility of the cardiomyopathic Syrian hamster. There was a weak correlation between the maximum velocity of shortening and the actin-activated myosin ATPase activity. Although the verapamil results are compatible with the calcium overload hypothesis of myocardial damage, further studies will be required to firmly establish this hypothesis.

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