Serotonin Metabolism in the Normal and Failing Hamster Heart

MICHAEL J. SOLE, ANDREW SHUM, AND GLEN R. VAN LOON

SUMMARY Serotonin has been found in the heart. Because cardiac serotonin is a potential endogenous source of inotropic support, an understanding of its metabolism in normal and failing hearts may be important. Cardiac serotonin was assayed in cardiomyopathic hamsters and their controls. Hearts were flushed free of platelets. Cardiac serotonin stores were 30-40% of those of norepinephrine. They were not affected by repeated injections of a mast cell granule depletor (H48/80) or the neurotoxins, 6-hydroxydopamine and 5,7-dihydroxytryptamine. Thus, cardiac serotonin appeared to be extraneural and not secondary to mast cell or platelet contamination. Inhibition of serotonin synthesis resulted in a prompt decrease, and inhibition of serotonin degradation led to a rapid increase in cardiac serotonin stores, demonstrating actual serotonin synthesis within the heart. Serotonin content (0.45 ± 0.012 µg/g in controls vs. 0.24 ± 0.009 µg/g in failing myopathic hearts) and synthesis (0.71 ± 0.016 µg/g per hour in controls vs. 0.028 ± 0.011 µg/g per hour in failing myopathic hearts) were significantly reduced in heart failure. Serotonin stores of uterus (a "control" organ) were identical for both strains. There was no difference in cardiac serotonin between the two strains in young hamsters. Human papillary muscles, taken at cardiac surgery, had serotonin levels (0.388 ± 0.027 µg/g) comparable to that found in hamster hearts. Thus, there are significant stores of serotonin synthesized within the heart. Both the stores and synthesis of serotonin are reduced in the failing myopathic hamster heart.

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SEROTONIN has been shown to exert a direct positive inotropic effect on mammalian myocardium (Buccino et al., 1967, Benfey et al., 1974). Recent studies have demonstrated the presence of this indolealkylamine in the heart and blood vessels of rats, cats, and dogs (Beauvallet et al., 1968; Berkowitz et al., 1974; Votavova et al., 1971; Madan et al., 1970). Though cardiac serotonin, like cardiac norepinephrine, appears to contribute little to basal myocardial contractility (Buccino et al., 1967), the presence of serotonin in the heart suggests it may be an endogenous source of inotropic support during physiological or pathological cardiac stress. Alterations in serotonin metabolism also have been associated with cardiac injury (Spatz, 1969; Crawford, 1963). Therefore, we decided to characterize the metabolism of cardiac serotonin and to determine whether cardiac stores of this compound were affected in a natural model of heart disease—the cardiomyopathic Syrian hamster (Gertz, 1972).

Methods

The dystrophic Syrian hamster is a useful, reproducible, spontaneous model for human myocardial disease (Gertz, 1972). Female cardiomyopathic (Bio 53.58) and matched control (Bio R.B.) Syrian hamsters, 90-110 and 240-270 days old, were used in these experiments. The former represented an early stage of the cardiomyopathy and the latter represented the stage of cardiac decompensation and failure. All hamsters were allowed at least 2 weeks to acclimatize to our laboratory animal facility after delivery from the breeder (TELACO). A 12-hour light, 12-hour dark cycle was maintained in the animal housing area. Hamsters were allowed water but deprived of food (Purina rat chow) for 24 hours preceding the experiment. The hamsters were killed by decapitation between 10 a.m. and 2 p.m. The hearts, in situ, were flushed free of blood with 20 ml of heparinized saline, administered by retrograde perfusion under
pressure through the aorta by hypodermic syringe; the perfusate drained through a right ventricular and a right atrial vent. The hearts then were removed, opened, and rinsed; the ventricles were dissected free of atria and great vessels and then immediately frozen on dry ice. The frozen tissues were weighed and homogenized with a Polytron homogenizer in 10 volumes of acidified butanol (0.85 mg of concentrated hydrochloric acid per liter of N-butanol). Serotonin and 5-hydroxyindoleacetic acid (5-HIAA) were measured spectrofluorometrically (Curzon and Green, 1970). Tryptophan was measured by the method of Denckla and Dewey (1967). The tissue catecholamines were assayed by the method of Sole and Hussain (1977).

A minimum of six hamsters in each of the control and cardiomyopathic groups was used for each experiment. Results are expressed as means ± SEM. The statistical significance of differences between groups was determined by Student's t-test.

Results

We established the presence of significant stores of serotonin in the normal hamster heart (Table 1). It was possible that these stores were localized largely in mast cells present within the myocardium. Thus, we administered 1 mg/kg of compound H48/80, an effective depletor of mast cell histamine and serotonin (Snyder et al., 1964), to hamsters by intraperitoneal injection every 8 hours for 3 days. The hamsters were killed 18 hours after the last dose. Cardiac serotonin was unaffected by H48/80 administration (Table 1).

We then wished to determine whether serotonin actually is synthesized within the heart or merely accumulated in mast cells present within the myocardium. Thus, we administered 1 mg/kg of compound H48/80, an effective depletor of mast cell histamine and serotonin (Snyder et al., 1964), to hamsters by intraperitoneal injection every 8 hours for 3 days. The hamsters were killed 18 hours after the last dose. Cardiac serotonin was unaffected by H48/80 administration (Table 1).

We found no significant difference in cardiac serotonin between young myopathic hamsters and their controls (Table 2). During the stage of cardiac decompensation, both the content and concentration of cardiac serotonin fell in the myopathic hamsters (Table 2). We also examined uterine serotonin stores to determine whether our observations were significant.

#### Table 1  Serotonin Concentration in Normal Hamster Hearts

<table>
<thead>
<tr>
<th></th>
<th>Serotonin concentration (µg/g)</th>
<th>5-HIAA concentration (µg/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>0.486 ± 0.013</td>
<td>0.064 ± 0.002</td>
</tr>
<tr>
<td>Saline vehicle</td>
<td>0.485 ± 0.009</td>
<td>0.059 ± 0.003</td>
</tr>
<tr>
<td>Compound 48/80</td>
<td>0.485 ± 0.010</td>
<td></td>
</tr>
<tr>
<td>α-Propyldopacetaimide</td>
<td>0.378 ± 0.013*</td>
<td>0.041 ± 0.005†</td>
</tr>
<tr>
<td>Pargyline</td>
<td>0.610 ± 0.018*</td>
<td></td>
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</tbody>
</table>

Results are expressed as mean ± SE.

* Differs from control and vehicle injected at \( P < 0.001 \).
† Differs from control and vehicle injected at \( P < 0.01 \).
FIGURE 1 Effect of neurotoxin administration on cardiac norepinephrine and serotonin contents in hamsters. On day 1, each received propranolol (5 mg/kg), phenoxybenzamine (10 mg/kg), and methysergide (1 mg/kg) by intraperitoneal injection. Fifteen minutes later, they received either 1 ml/g of vehicle (ascorbic acid (6 mg/ml) in degassed saline made to 10^-3 M HCl) or 6-hydroxydopamine hydrobromide (75 mg/kg), or 5,7-dihydroxytryptamine creatinine sulfate (110 mg/kg) in vehicle. Vehicle or neurotoxin administration (without the amine blockers) was repeated on day 3 and at double the dose on days 8 and 10. The hamsters were killed and their ventricles taken for assay on day 15. Each value is the mean ± SEM for eight hamster hearts. *Significantly different from control at P < 0.001.

merely a manifestation of a general alteration in peripheral serotonin metabolism. No change in uterine serotonin was found (Table 2). We had shown previously that the development of heart failure in the cardiomyopathic hamster is associated with an increase in cardiac sympathetic tone (Sole et al., 1975). We also described a reduction in the norepinephrine stores of the failing hamster heart that was secondary to this increase in sympathetic activity (Sole et al., 1975). We were able to restore cardiac norepinephrine content completely to normal by the administration of the peripheral ganglionic blocker, chlorisondamine. Administration of chlorisondamine (10 mg/kg, ip, every 6 hours for 24 hours) to myopathic hamsters did not affect the reduced serotonin content of the failing heart (0.360 ± 0.010 μg/g in untreated vs. 0.347 ± 0.013 μg/g in treated).

We studied the synthesis of cardiac serotonin in failing hamsters and their controls by examining the accumulation of serotonin in the heart, 1 hour after the administration of pargyline (75 mg/kg, ip) (Neff and Tozer, 1968). Serotonin synthesis appeared significantly reduced in the decompensating myopathic hearts (Table 3). As serotonin synthesis, at least in the brain, is dependent on the availability of tryptophan (Fernstrom and Wurtman, 1971), the decline in cardiac serotonin suggested a possible alteration in precursor tryptophan. Both groups of hamsters exhibited similar plasma tryptophan (12.97 ± 1.04 μg/ml in controls vs. 12.77 ± 0.54 μg/ml in failing) and cardiac tryptophan (10.92 ± 1.54 μg/g in controls vs. 9.30 ± 0.55 μg/g in failing) concentrations.

Discussion

Serotonin has been identified in the hearts of rats (Beauvallet et al., 1968, Berkowitz et al., 1974), cats (Votavova et al., 1971), and dogs (Madan et al., 1970). In this communication, we demonstrate significant endogenous stores of serotonin in both the hamster and human heart. In addition, we now describe some of the characteristics and metabolism of these stores.

The serotonin concentration of the hamster heart is 40–50% of that determined for cardiac norepinephrine (Fig. 1). Serotonin may be accumulated and stored by both platelets (Morrissey et al., 1977, Austen and Humphrey, 1963) and mast cells (Austen and Humphrey, 1963). We thoroughly flushed and rinsed the hearts prior to assay to minimize platelet contamination. Furthermore, the relatively high concentration of cardiac serotonin would seem to obviate an artifact due to platelet or mast cell contamination. It should be noted that serotonin is

Table 2
Serotonin Stores in Hearts and Uteri of Control and Myopathic Hamsters

<table>
<thead>
<tr>
<th></th>
<th>Serotonin concentration (μg/g)</th>
<th>Serotonin content (μg/heart)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hearts</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (90–110 days old)</td>
<td>0.490 ± 0.018</td>
<td>0.148 ± 0.009</td>
</tr>
<tr>
<td>Myopathic</td>
<td>0.486 ± 0.024</td>
<td>0.136 ± 0.003</td>
</tr>
<tr>
<td>Control (240–270 days old)</td>
<td>0.494 ± 0.007</td>
<td>0.206 ± 0.009</td>
</tr>
<tr>
<td>Myopathic</td>
<td>0.352 ± 0.013*</td>
<td>0.158 ± 0.007*</td>
</tr>
<tr>
<td><strong>Uteri</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (240–270 days old)</td>
<td>0.319 ± 0.015</td>
<td>0.089 ± 0.006</td>
</tr>
<tr>
<td>Myopathic</td>
<td>0.286 ± 0.010</td>
<td>0.108 ± 0.007</td>
</tr>
</tbody>
</table>

Results are expressed as mean ± SE. * Differ from age-matched control at P < 0.001.
not stored in the mast cells of man (Austen and Humphrey, 1963); thus, mast cell contamination could not account for the serotonin present in human papillary muscle. In an earlier study, Snyder and co-workers (1964) labeled rat hearts with exogenously administered $^{14}$C-serotonin. A rigorous injection schedule of H48/80, a depurator of mast cell serotonin, failed to deplete the label from the hearts. We did not alter endogenous cardiac stores of serotonin using a similar injection schedule. Although both platelets and mast cells are avid repositories for free circulating serotonin, they do not synthesize this compound (Morrissey et al., 1977). The former is relatively specific for catecholaminergic and serotonergic neurons also have been described recently (Helke and co-workers, 1978). These investigators have demonstrated an apparent role for peripheral serotonin in digitalis-induced cardiac arrhythmias. The infusion of serotonin into the cat resulted in a concomitant increase both in left ventricular serotonin content and in the susceptibility to arrhythmia induction during deslanoside infusion (Helke et al., 1978). Although treatment with drugs, such as serotonin antagonists or synthesis inhibitors, greatly increased the dose of deslanoside required to achieve toxicity, the depletion of brain serotonin alone had no ameliorating effect (Gillis et al., 1978).

Another possible clinical significance for cardiac serotonin recently has emerged from the studies of Helke and co-workers (1978). These investigators have demonstrated an apparent role for peripheral serotonin in digitalis-induced cardiac arrhythmias. The infusion of serotonin into the cat resulted in a concomitant increase both in left ventricular serotonin content and in the susceptibility to arrhythmia induction during deslanoside infusion (Helke et al., 1978). Although treatment with drugs, such as serotonin antagonists or synthesis inhibitors, greatly increased the dose of deslanoside required to achieve toxicity, the depletion of brain serotonin alone had no ameliorating effect (Gillis et al., 1978).

Abnormalities in the availability of serotonin or tryptophan have been implicated in the pathogenesis of cardiomyopathy and muscular dystrophy. The rate-limiting step for serotonin production appears to be at the stage of tryptophan hydroxylation (Jequier et al., 1967). Under most physiological circumstances, the enzyme is unsaturated relative to its substrate tryptophan; thus, the availability of this amino acid to the enzyme appears to be a major determinant for the control of serotonin synthesis (Fernstrom and Wurtman, 1971). Dietary trypto-

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### Table 3 Serotonin Synthesis in Control and Failing Hamster Hearts

<table>
<thead>
<tr>
<th></th>
<th>Serotonin concentration (µg/g) after</th>
<th>Serotonin accumulation (µg/g per hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Saline</td>
<td>Pargyline</td>
</tr>
<tr>
<td>Control</td>
<td>0.448 ± 0.012</td>
<td>0.519 ± 0.010</td>
</tr>
<tr>
<td>Failing</td>
<td>0.244 ± 0.009*</td>
<td>0.272 ± 0.021*</td>
</tr>
</tbody>
</table>

Results are expressed as mean ± SE.
* Differs from control at $P < 0.01$.
† Differs from control at $P < 0.05$. 
phosph deficiency produces endocardial and myocardial disease in guinea pigs and man (Reid and Berjak, 1967; Spatz, 1969). Tryptophan replacement is able to protect the heart effectively from injury (Spatz, 1969; Reid, 1970). Serotonin administration, in the guinea pig model, has similar beneficial results (Spatz, 1969). Administration of large amounts of serotonin has been used in the production of models of muscular dystrophy (Parker and Mendell, 1974; Meltzer, 1976). The pathology of the hearts in these paradigms has not been examined; however, an excess of serotonin, such as that found in the metastatic carcinoid syndrome, is well known to be cardiotoxic.

Thus, alterations in the metabolism of serotonin could conceivably play an etiological role in the pathogenesis of some of the primary cardiomyopathies. On the other hand, serotonin appears to increase myocardial contractility, suggesting that cardiac stores may act as an endogenous source of inotropic support for the failing heart. Therefore, it was of interest to examine the content and synthesis of cardiac serotonin during the development of heart failure in the Syrian hamster, a model of spontaneous cardiomyopathy. Young hamsters of both control and myopathic strains exhibited similar serotonin stores. Therefore, alterations in the content of this amine did not appear to have an etiological relationship to hamster heart disease. With the development of cardiac decompensation, both the stores and the rate of synthesis of cardiac serotonin decreased. A similar reduction in cardiac serotonin has been described following salt loading (Beauvallet et al., 1968) and heat stress (Godhwani and Sharma, 1970); turnover or synthesis was not measured in these studies. These reports suggested that our observations may be secondary to the increase in cardiac sympathetic tone previously found to be associated with cardiac decompensation in the hamster (Sole et al., 1975). Ganglionic blockade, however, had no effect on the depleted cardiac serotonin stores.

The reduction in cardiac serotonin does not appear to be a reflection of some general metabolic abnormality in hamster heart failure because the uterus [as well as certain brain regions (Sole et al., 1978)] exhibited similar serotonin stores in both failing and control hamsters. Plasma and cardiac tryptophan also did not differ in the two groups. Whether this alteration in serotonin metabolism can be corrected by dietary measures, such as tryptophan supplements (Fernstrom and Wurtman, 1971), and whether such supplementation has a beneficial effect on the failing heart remain to be defined.

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Modulating Effect of Regional Myocardial Performance on Local Myocardial Perfusion in the Dog

MARIO MARZILLI, SIDNEY GOLDSTEIN, HANI N. SABBAH, TENNYSON LEE, AND PAUL D. STEIN

SUMMARY We studied the effect of regional contractile performance on regional coronary blood flow and flow distribution in 10 dogs. The left anterior descending (LAD) coronary artery was cannulated and perfused. Maximal vasodilation was obtained with adenosine. Consequently, variations of LAD flow reflected changes of extravascular resistance. Lidocaine injected in the LAD caused a localized reduction of contractile performance as shown by the absence of systolic wall thickening. Global left ventricular performance and pressure were unchanged. Coronary extravascular resistance diminished and LAD flow increased from 4.8 ± 0.5 to 6.2 ± 0.6 ml/min per g (P < 0.02). The endocardial:epicardial ratio increased from 1.02 ± 0.07 to 1.28 ± 0.07 (P < 0.001). Isoproterenol in the LAD produced compression of coronary vessels, thereby increasing their resistance to blood flow (Sistonen and Gregg, 1957; Kirk and Horng, 1964; Armour and Randall, 1971). This resistance to flow, which results from compression of the coronary vessels, is termed extravascular resistance, in contradistinction to the vascular resistance. The latter reflects changes of vessel diameter that result from coronary vasomotor tone.
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