Impact of the Length of Vitamin D Deficiency on Cardiac Remodeling

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Background—This study was aimed to evaluate the influence of vitamin D (VD) deficiency on cardiac metabolism, morphology, and function. Thus, we investigated the relationship of these changes with the length of the nutrient restriction.

Methods and Results—Male weanling Wistar rats were allocated into 4 groups: C2 (n=24), animals were fed an AIN-93G diet with 1000 IU VD/kg of chow and were kept under fluorescent light for 2 months; D2 (n=22), animals were fed a VD-deficient AIN-93G diet and were kept under incandescent light for 2 months; C4 (n=21) animals were kept in the same conditions of C2 for 4 months; and D4 (n=23) animals were kept in the same conditions of D2 for 4 months. Biochemical analyses showed lower β-hydroxyacyl coenzyme-A dehydrogenase activity and higher lactate dehydrogenase activity in VD-deficient animals. Furthermore, VD deficiency was related to increased cytokines release, oxidative stress, apoptosis, and fibrosis. Echocardiographic data showed left ventricular hypertrophy and lower fractional shortening and ejection fraction in VD-deficient animals. Difference became evident in the lactate dehydrogenase activity, left ventricular weight, right ventricle weight, and left ventricular mass after 4 months of VD deficiency.

Conclusions—Our data indicate that VD deficiency is associated with energetic metabolic changes, cardiac inflammation, oxidative stress, fibrosis and apoptosis, cardiac hypertrophy, left chambers alterations, and systolic dysfunction. Furthermore, length of the restriction influenced these cardiac changes. (Circ Heart Fail. 2013;6:809-816.)

Key Words: cardiac remodeling ■ oxidative stress ■ vitamin D deficiency

The classic effects of vitamin D (VD) are pivotal to bone development, growth, mineralization, maintenance of skeletal integrity and calcium, and phosphorus homeostasis. However, in recent years, a wide variety of extraskeletal conditions have also been associated with VD deficiency (VDD), including the regulation of cell proliferation/differentiation, modulation of the immune system, influence on pancreatic β-cell function and regulation of cardiac contractility, and hypertrophy.

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Epidemiological studies describe an association between VDD and several cardiovascular diseases, suggesting that VDD has a negative association with survival. Experimental studies also indicated that a VD-deficient diet is related to changes in contractile function in isolated myocytes, higher systolic blood pressure, myocardial relaxation, fibrosis, and hypertrophy. In addition, murine cardiomyocytes isolated from VD receptor knockout mice show accelerated contraction and relaxation rates and cellular hypertrophy of the heart myofibrils. Some of these cardiac changes associated with VDD are characteristic of cardiac remodeling.

Cardiac remodeling may be defined as changes in the size, geometry, shape, composition, and function of the heart in response to diverse stimuli. At first, ventricular remodeling is a compensatory process, and these morphological adaptations are essential to preserving cardiac function. However, chronic ventricular remodeling is recognized as a significant pathological process that results in progressive ventricular dysfunction and the eventual clinical presentation of heart failure or sudden death.

Despite several studies showing that a VD-deficient diet induces cardiac changes, the influence of the length of VD restriction on cardiac tissue is unknown. In addition, the mechanisms involved in this process remain to be elucidated. Given that ventricular remodeling is modulated by the degree of injury, we hypothesized that a longer exposure to a VD-deficient diet might be associated with greater degrees of cardiac morphological and functional alterations.
The aim of the present study was to assess the cardiac effects of VDD in an animal model in terms of metabolism, inflammation, oxidative stress, morphology, and function. In addition, because the extent of cardiac remodeling has been linked to the magnitude of injury, the second aim of the present study was to evaluate the consequences of VDD at 2 time points: 2 and 4 months after initiation of a VD-deficient diet.

Methods

Experimental Protocol
Male weanling Wistar rats were housed and taken care of in accordance with the National Institute of Health’s Guide for the Care and Use of Laboratory Animals. The experimental protocol was approved by the Animal Ethics Committee of the Botucatu School of Medicine-UNESP, Brazil (protocol No. 693/2008). The animals were randomly allocated into 4 groups (C2, D2, C4, and D4) and raised on different diets for 2 or 4 months (Figure 1). The animals in group C2 (n=24) were fed an AIN-93G diet with 1000 IU VD/kg of chow and were kept under fluorescent lights for 2 months. The animals in group D2 (n=22) were fed a VD-deficient AIN-93G diet that contained 0.7% calcium and 0.3% phosphorus and were kept under incandescent lights for 2 months to prevent VD cutaneous synthesis. The C4 (n=21) animals were kept in the same conditions of C2 for 4 months. The D4 (n=23) animals were kept in the same conditions of D2 for 4 months. The daily food consumption by individual rats was measured and body weight was measured weekly. After the period of treatment, each animal was submitted to an echocardiographic study and followed by euthanasia.

Tail Systolic Pressure
Systolic arterial pressure measurement was performed 2 weeks before euthanasia. A tail plethysmograph was used as described previously.12

Echocardiographic Study
All of the animals were evaluated with a transthoracic echocardiograph examination, according to a previously described method.13

Morphometric Analysis
After echocardiographic study, the animals were euthanized with large dose of pentobarbital, and their hearts and tibia were removed. The right and left ventricles (RV and LV), and the atrium were dissected, separated, and weighted. Transverse sections of LV were fixed in 10% buffered formalin and embedded in paraffin. Five-micrometer-thick sections were stained with hematoxylin and eosin or picrosirius red. The myocyte cross-sectional area and interstitial collagen volume fraction were measured as previously described.14

Figure 1. Study design. C2, 2 months on a diet with 1000 IU/kg of vitamin D; C4, 4 months on a diet with 1000 IU/kg of vitamin D; D2, 2 months on a diet with no vitamin D; and D4, 4 months on a diet with no vitamin D.

Connexin 43 and Caspase 3 Immunohistochemistry
Histological LV sections were processed as previously described for immunohistochemistry evaluation of connexin 43 (Connexin 43: polyclonal antirabbit connxin-43, GJA1, Abcam, Cambridge, MA) and caspase 3 (Caspase 3: cleaved caspase-3 [Asp175] [5A1] rabbit mAb).12

Vitamin D Determination
Serum concentrations of 25[OH]D, were measured by high performance liquid chromatography as described by Aksnes.15

Biochemical Analysis
Serum concentrations of calcium and phosphorus were measured using the aspensao III and colorimetric methods, respectively (test kit Labor Laboratory, São Paulo, Brazil). Serum concentrations of parathyroid hormone (PTH) were measured according to the PTH (Intact, Rat) Elisa Kit instructions (Alpco Immunoassays, Salem, NH).

Cytokine Production
The production of tumor necrosis factor-α (TNF-α), interferon-γ (IFN-γ) and interleukin-10 was evaluated by ELISA according to the manufacturer’s instructions (R&D Systems, Minneapolis, MN).16

Cardiac Lipid Hydroperoxide, Antioxidant Enzymes, and Energy Metabolism Analysis
Total protein, lipid hydroperoxide, glutathione peroxidase (E.C.1.11.1.9), superoxide dismutase (E.C.1.15.1.1), and catalase (E.C.1.11.1.6) activities were assessed as previously specified.17–19 Cardiac energy metabolism was assessed by β-hydroxyacyl coenzyme-A dehydrogenase (E.C.1.1.1.27) activities.20

Western Blotting Analysis
Nuclear and cytoplasmic protein extraction from the LV samples was performed with the NE-PER Nuclear and Cytoplasmic Extraction Reagents kit (Pierce Biotechnology, Rockford, IL). Nuclear extracts were used for Nrf-2 detection (Nrf2-2: C-20, rabbit Immunoglobulin G [Santa Cruz Biotechnology Inc, Europe]). The cytoplasmic extract was used for heme oxygenase-1 (HO-1-1 to heme oxygenase-1: ab13248; Abcam Inc, Cambridge) and glutathione peroxidase (GPx Rabbit polyclonal to GPx 1; ab22604, Abcam Inc, Cambridge) detection.

Statistical Analysis
The data are reported as the mean±SEM. The results were tested for normality (Kolmogorov–Smirnov test) and equal variance before the statistical analyses and all the data passed these tests. Also, the 4 groups of animals were independent. Therefore, data were analyzed by a 2-way ANOVA. One factor is the VD content in the diet, and the other factor is the length of the nutrient restriction. The first factor was called diet and the second factor is time. When an interaction was found to be significant, the mean values were compared using Tukey post hoc analysis. In the present study, there was no interest in analyzing the differences observed in the factor length of the nutrient restriction because this is an alteration related to normal rat development.

An ANCOVA test was also used to test the PTH and calcium influence on the cardiac variables.

The differences were considered statistically significant if P<0.05 and for some results the 95% confidence interval (CI) are presented. The statistical analyses were performed using Systat for Windows version 12.0 (Systat Software Inc, San Jose, CA).
Results

The animal model used in the present study was effective for inducing nutritional VDD because the treated animals showed lower 25(OH)D levels and higher PTH levels. An interaction was found when analyzing PTH. The PTH values were higher in VD-deficient animals both at 2 months (D2>C2; P=0.002; and 95% CI, −838 to −157) and at 4 months (D4>C4; P<0.001; and 95% CI, −1298 to −595; Figure 2). The PTH values increased with time (D4>D2; P=0.024; and 95% CI, −741 to −39). No interaction was observed for 25(OH)D or calcium levels. Lower values were found in deficient VD diet (DVD) animals for 25(OH)D (Figure 3; P<0.001; and 95% CI, 245–336) and calcium levels (Table 1; P<0.001; and 95% CI, 0.72–1.80) compared with sufficient VD animals (SVD). An ANCOVA test was performed to check the influence of serum PTH and calcium levels on all of the cardiac variables. No statistically significant influence was observed for either covariate (data not shown).

No interaction between the factors and no significant differences related to VD content in the diet factor were observed for final body weight, tibia length, food consumption, phosphorus levels, or systolic pressure, as shown in Table 1.

Biochemical analyses of cardiac energy metabolism are shown in Figure 4. An interaction was observed for β-hydroxyacyl coenzyme-A dehydrogenase activity, which was lower in DVD animals at 2 months (D2>C2; P=0.001; and 95% CI, 9.35–41.80) and at 4 months (D4>C4; P<0.001; and 95% CI, 61.7–94.1). Furthermore, D4 animals showed lower enzyme activity than D2 animals (P<0.001 and 95% CI, 13.2–45.6). An interaction was also observed for lactate dehydrogenase activity, which was higher in DVD animals at 4 months (D4>C4; P<0.001; and 95% CI, −198 to −90).

No interaction between factors was observed for cardiac inflammation. However, differences were observed for the factor of VD content in the diet. TNF-α (P=0.013 and 95% CI, −4.20 to −0.67) and INF-γ (P=0.031 and 95% CI, −10.14 to −0.71) were higher in DVD animals than in SVD animals, showing that VDD was related to increased cytokine release (Table 2).

Table 3 shows data related to cardiac oxidative stress. No interaction was observed for all variables. However, a statistical significance was found for the factor of VD content in the diet. The lipid hydroperoxide levels (P<0.001 and 95% CI, −154 to −89), Nrf-2 (P=0.002 and 95% CI, −0.32 to −0.08), heme oxygenase-1 (P=0.012 and 95% CI, −0.60 to −0.09), and GP (P=0.029 and 95% CI, −0.75 to −0.05) amounts were higher in DVD animals than in SVD animals. Catalase (P=0.011 and 95% CI, 0.11–7.72) and glutathione peroxidase (P<0.001 and 95% CI, 7.74–22.20) activity were lower in DVD animals.

The data describing the cardiac caspase 3, connexin 43, and cardiac morphometric analyses are listed in Table 4. An interaction between factors was observed for LV weight and RV weight. LV weight and RV weight were higher in DVD animals at 4 months (D4>C4; LV weight: P=0.022 and 95% CI, −0.037 to −0.002; and RV weight: P=0.020 and 95% CI, −1.40 to −0.09). Furthermore, LV weight was higher in C4 and D4 animals than in C2 (P=0.049 and 95% CI, −0.035 to 0.000) and D2 (P<0.001 and 95% CI, −0.060 to 0.025) animals. A difference for the factor of VD content in the diet was observed for caspase 3 (P=0.040 and 95% CI, −24.7 to −0.67) and interstitial collagen (P=0.046 and 95% CI, −2.17 to −0.06). DVD animals had higher numbers of labeled caspase 3 cells and increased interstitial collagen compared with SVD animals, increased apoptosis and fibrosis because of VDD.

The echocardiographic data are presented in Table 5. Interactions were found when analyzing the right atrium area and the LV mass. Right atrium area and LV mass were higher in DVD animals at 4 months (D4>C4; right atrium area: P=0.045 and 95% CI, −0.052 to 0.000; and LV mass: P=0.003 and 95% CI, −239 to −37). Differences were also observed for the VD content in the diet factor. The left ventricle end-diastolic diameter (P=0.006 and 95% CI, −0.108 to −0.025) was lower in DVD than in SVD animals showing that VDD was related to increased cytokine release (Table 2).

Figure 2. The data are expressed as the mean of the mean. C2, 2 months on a diet with 1000 IU/kg of vitamin D; C4, 4 months on a diet with 1000 IU/kg of vitamin D; D2, 2 months on a diet with no vitamin D; D4, 4 months on a diet with no vitamin D; and PTH, serum parathyroid hormone levels. Diet, P value factor <0.001; time, P value factor 0.079; and diet×time, P value interaction 0.018. Interactions were observed and the significant differences are shown.

Figure 3. The data are expressed as the mean of the mean. C2, 2 months on a diet with 1000 IU/kg of vitamin D; C4, 4 months on a diet with 1000 IU/kg of vitamin D; D2, 2 months on a diet with no vitamin D; D4, 4 months on a diet with no vitamin D; and 25(OH)D3, serum vitamin D3 levels. Diet, P value factor <0.001; time, P value factor 0.856; and diet×time, P value interaction 0.880.
Table 1. Body Weight, Tibial Length, Food Ingestion, Systolic Pressure, and Biochemical Analysis

<table>
<thead>
<tr>
<th>Variable</th>
<th>Groups</th>
<th>Diet</th>
<th>Time</th>
<th>Diet×Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>BW, g</td>
<td>C2</td>
<td>D2</td>
<td>C4</td>
<td>D4</td>
</tr>
<tr>
<td></td>
<td>375.2±9.0</td>
<td>371.3±8.6</td>
<td>461.6±9.3</td>
<td>484.7±8.6</td>
</tr>
<tr>
<td>Tiabial length, mm</td>
<td>39.4±0.3</td>
<td>39.6±0.3</td>
<td>41.9±0.3</td>
<td>41.9±0.3</td>
</tr>
<tr>
<td>Food consumption, g/d</td>
<td>16.2±0.3</td>
<td>16.0±0.3</td>
<td>18.3±0.3</td>
<td>18.4±0.3</td>
</tr>
<tr>
<td>Systolic pressure, mm Hg</td>
<td>110.8±4.2</td>
<td>113.6±4.1</td>
<td>137.5±4.4</td>
<td>131.8±4.3</td>
</tr>
<tr>
<td>Ca, mg/dL</td>
<td>10.7±0.3</td>
<td>9.9±0.3</td>
<td>11.5±0.3</td>
<td>9.7±0.3</td>
</tr>
<tr>
<td>P, mg/dL</td>
<td>10.2±0.4</td>
<td>9.9±0.4</td>
<td>9.4±0.4</td>
<td>8.8±0.4</td>
</tr>
</tbody>
</table>

The data are expressed as the mean±SE of the mean. BW indicates body weight; C2, 2 mo on a diet with 1000 IU/kg of vitamin D; C4, 4 mo on a diet with 1000 IU/kg of vitamin D; Ca, serum calcium; D2, 2 mo on a diet with no vitamin D; D4, 4 mo on a diet with no vitamin D; diet (factor vitamin D content in the diet), P value of the vitamin D content in the diet effect; diet×time, P value of the interaction; P, serum phosphorus; and time (factor length of the nutrient restriction), P value of the time effect.

Discussion

25(OH)D is the primary storage form of vitamin D and the metabolite that best represents the state of vitamin D sufficiency. The characterization of the deficient state was obtained by measuring plasma levels of 25(OH)D, and the experimental model used in the present study proved effective at inducing a nutritional deficiency in the present study proved effective at inducing a nutritional deficiency.

Several studies show that vitamin D deficiency is associated with hypocalcemia and secondary hyperparathyroidism. Calcium and PTH can directly influence cardiac function. Certain studies that have used the vitamin D-deficient diet model increase the amount of calcium and phosphorus in the chow to maintain calcium, phosphorus, and PTH within the normal range. In the present study, hypocalcemia and hyperparathyroidism were observed, despite the increase in the maximal amount of calcium and phosphorus supplementation in the rat chow. Therefore, to adjust for the influence of the serum calcium and PTH levels, an ANCOVA test was performed. We observed no influence of calcium and PTH on the cardiac variables. These results corroborate other studies, showing that the cardiac alterations because of vitamin D deficiency occur independently of calcium and PTH.

It is well known that vitamin D plays a direct or indirect role on multiple genes in different organs and tissues. Therefore, some studies have shown that vitamin D can influence energetic metabolism, inflammation, and oxidative stress. These changes are part of the cardiac remodeling process.

Heart tissue is capable of meeting its energy needs through the oxidation of fatty acids, glucose, lactate, and other oxidizable substrates. Under normal physiological conditions in the heart, fatty acids are the preferred source of energy generated via β-oxidation. The increase in the β-hydroxyacyl coenzyme-A dehydrogenase in C4 group suggests a better fatty acid oxidation metabolism with a reduced use of glucose oxidation as fuel for the heart. Disturbances in myocardial substrate used have adverse effects in the failing myocardium, and shifting the substrate preference of the heart away from fatty acids toward carbohydrate oxidation can improve pump function and slow the progression of heart failure. In the present study, we hypothesize that vitamin D deficiency has a change in the oxidation of fatty acids toward carbohydrate oxidation can improve pump function and slow the progression of heart failure.
substrate utilization. Activation of glycolytic pathway and reduced β-oxidation is a marker of cardiac remodeling and heart failure.

In different heart failure models, cytokine production can modulate cardiac remodeling. Indeed, increased INF-γ and especially TNF-α levels are associated with left ventricle dysfunction, activation of fetal gene programming, apoptosis, hypertrophy, and fibrosis.37 In the present study, the remodeling process in VD-deficient animals was associated with altered cardiac levels of INF-γ and TNF-α. In fact, this result was expected because VD has a role in the modulation of immune and inflammatory responses.39 In the inactive form, Nrf-2 is bound to the protein Keap1 in the cytoplasm. Lipid hydroperoxides can promote conformational changes of the Keap1 and Nrf-2 active sites,41 leading to release of Keap1 and migration of Nrf-2 to the nucleus. Many antioxidant genes, such as GPx and heme oxygenase-1, contain an antioxidant response element in the promoter.42 Thus, in the present study, we hypothesize that VDD could be related to higher expression of nuclear Nrf-2 and cytoplasmic GPx and heme oxygenase-1 in cardiomyocytes, which was an attempt of the cardiac cells to improve the enzymatic antioxidant defense system.

Oxidative stress and proinflammatory cytokines are related to increased fibrosis and apoptosis. Myocardial fibroblast cells activated by proinflammatory cytokines and oxidative stress become highly proliferative and invasive and actively remodel the cardiac interstitium. In addition, cardiac cell apoptosis is mediated through several signaling systems that involve reactive oxygen species and inflammatory cytokines. The end point is the activation of the caspase pathway.43 In

Table 2. Cardiac Inflammation

<table>
<thead>
<tr>
<th>Variable</th>
<th>C2 (IL-10, pg/mg)</th>
<th>D2 (IL-10, pg/mg)</th>
<th>C4 (IL-10, pg/mg)</th>
<th>D4 (IL-10, pg/mg)</th>
<th>Diet</th>
<th>Time</th>
<th>Diet×Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>IL-10, pg/mg</td>
<td>13.4±3.5</td>
<td>10.9±2.7</td>
<td>8.6±3.0</td>
<td>15.5±3.0</td>
<td>0.490</td>
<td>0.974</td>
<td>0.151</td>
</tr>
<tr>
<td>TNF-α, pg/mg</td>
<td>2.1±1.0</td>
<td>4.9±0.8</td>
<td>3.1±0.7</td>
<td>5.2±0.8</td>
<td>0.013</td>
<td>0.471</td>
<td>0.664</td>
</tr>
<tr>
<td>INF-γ, pg/mg</td>
<td>3.6±2.8</td>
<td>9.7±2.2</td>
<td>6.2±2.0</td>
<td>10.9±2.2</td>
<td>0.031</td>
<td>0.423</td>
<td>0.780</td>
</tr>
<tr>
<td>ICAM-1, pg/mg</td>
<td>52.0±8.1</td>
<td>61.3±6.3</td>
<td>54.4±7.0</td>
<td>58.6±6.3</td>
<td>0.351</td>
<td>0.979</td>
<td>0.719</td>
</tr>
</tbody>
</table>

The data are expressed as the mean±SE of the mean. C2 indicates 2 mo on a diet with 1000 IU/kg of vitamin D; C4, 4 mo on a diet with 1000 IU/kg of vitamin D; D2, 2 mo on a diet with no vitamin D; D4, 4 mo on a diet with no vitamin D; diet (factor vitamin D content in the diet), P value of the vitamin D content in the diet effect; diet×time, P value of the interaction; ICAM-1, intercellular adhesion molecule-1; IL-10, interleukin-10; INF-γ, interferon-γ; time (factor length of the nutrient restriction), P value of the time effect; and TNF-α, tumor necrosis factor-α.

Table 3. Cardiac Oxidative Stress: Protein Activity and Quantification

<table>
<thead>
<tr>
<th>Variable</th>
<th>C2 (NH₄, nmol/g tissue)</th>
<th>D2 (NH₄, nmol/g tissue)</th>
<th>C4 (NH₄, nmol/g tissue)</th>
<th>D4 (NH₄, nmol/g tissue)</th>
<th>Diet</th>
<th>Time</th>
<th>Diet×Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH, nmol/g tissue</td>
<td>160.7±15.6</td>
<td>289.4±15.6</td>
<td>143.5±15.6</td>
<td>257.4±15.6</td>
<td>&lt;0.001</td>
<td>0.131</td>
<td>0.642</td>
</tr>
<tr>
<td>CAT, μmol/mg protein,</td>
<td>1.6±0.2</td>
<td>1.0±0.2</td>
<td>1.4±0.2</td>
<td>1.1±0.2</td>
<td>0.011</td>
<td>0.553</td>
<td>0.253</td>
</tr>
<tr>
<td>GSHPx, nmol/g tissue</td>
<td>59.1±3.5</td>
<td>37.6±3.5</td>
<td>45.5±3.5</td>
<td>37.1±3.5</td>
<td>&lt;0.001</td>
<td>0.054</td>
<td>0.075</td>
</tr>
<tr>
<td>SOD, μmol/g protein</td>
<td>13.1±1.4</td>
<td>13.3±1.4</td>
<td>11.9±1.4</td>
<td>8.7±1.4</td>
<td>0.303</td>
<td>0.055</td>
<td>0.253</td>
</tr>
<tr>
<td>Nrf-2</td>
<td>0.69±0.06</td>
<td>0.37±0.06</td>
<td>0.37±0.06</td>
<td>0.10±0.06</td>
<td>0.002</td>
<td>0.063</td>
<td>0.735</td>
</tr>
<tr>
<td>HO-1</td>
<td>1.49±0.15</td>
<td>1.74±0.11</td>
<td>1.79±0.12</td>
<td>2.18±0.11</td>
<td>0.020</td>
<td>0.008</td>
<td>0.586</td>
</tr>
<tr>
<td>GPx</td>
<td>1.34±0.19</td>
<td>1.72±0.16</td>
<td>1.24±0.21</td>
<td>1.77±0.16</td>
<td>0.019</td>
<td>0.877</td>
<td>0.669</td>
</tr>
</tbody>
</table>

The data are expressed as the mean±SE of the mean. C2 indicates 2 mo on a diet with 1000 IU/kg of vitamin D; C4, 4 mo on a diet with 1000 IU/kg of vitamin D; CAT, catalase activity; D2, 2 mo on a diet with no vitamin D; D4, 4 mo on a diet with no vitamin D; diet (factor vitamin D content in the diet), P value of the vitamin D content in the diet effect; diet×time, P value of the interaction; GPx, glutathione peroxidase; GSHPx, glutathione peroxidase activity; HO-1, heme oxygenase-1; LH, lipid hydroperoxide; Nrf-2, nuclear erythroid factor-2; SOD, superoxide dismutase activity; and time (factor length of the nutrient restriction), P value of the time effect.
the present study, VDD was associated with abnormal interstitial collagen accumulation and with higher apoptosis as assessed by caspase 3. The fibrosis and cell loss that occurs through apoptosis contributes to morphological alterations and also plays an important role in the impairment of cardiac performance.

Considering the morphological and functional consequences of VDD, in the present study, we observed cardiac hypertrophy and enlargement of the left chambers with preserved relative wall thickness featuring eccentric remodeling.43 It is well accepted that the ventricular remodeling process plays a fundamental role in the pathophysiology of ventricular dysfunction.44 In accordance with this concept, VDD was associated with an impaired systolic function, which was characterized by reduced fractional shortening and ejection fraction.

As mentioned, the present study also aimed to analyze the influence of length of nutrient restriction on the cardiac variables. Importantly, the length of VDD influenced certain changes. Although PTH levels and β-hydroxyacyl coenzyme-A dehydrogenase activity were significantly different after 2 months of deficient VD diet use, this difference became more evident after 4 months. These findings show that the VDD was an ongoing process. In relation to lactate dehydrogenase activity, LV, RV, right atrium area, and LV mass, no significant differences were detected after 2 months of deficient VD diet use. However, after 4 months of VDD, the difference became evident. Thus, it was possible to analyze the worsening evolution of the variables over time and conclude that, especially for variables indicative of cardiac

| Table 4. Morphometric and Immunohistochemistry Data |
|-------------------------------|---------|---------|---------|---------|---------|---------|---------|---------|
| Variable                      | C2      | D2      | C4      | D4      | Diet    | Time    | Diet×Time|
| LV weight/tibia               | 0.20±0.01†| 0.19±0.00‡| 0.22±0.00*†| 0.24±0.01*‡| 0.151   | <0.001  | 0.008   |
| RV weight/tibia               | 5.56±0.17†| 5.43±0.18| 5.05±0.18*†| 5.79±0.17*| 0.087   | 0.694   | 0.015   |
| Atrium/tibia                 | 0.88±0.08| 0.82±0.08| 0.79±0.08| 0.98±0.08| 0.446   | 0.699   | 0.116   |
| Caspase 3                    | 13.4±5.5| 29.1±5.5| 15.1±6.1| 24.8±5.5| 0.040   | 0.822   | 0.602   |
| Localization connexin 43     | 2.2±0.2| 2.1±0.2| 2.0±0.2| 2.5±0.2| 0.392   | 0.725   | 0.266   |
| Intensity connexin 43        | 2.5±0.2| 2.7±0.1| 2.4±0.1| 2.5±0.2| 0.291   | 0.461   | 0.859   |
| MCA, μm²                     | 215.9±15.7| 236.6±14.6| 275.8±14.6| 283.4±15.7| 0.359   | 0.002   | 0.669   |
| Interstitial collagen, %     | 4.1±0.5| 4.2±0.5| 3.8±0.4| 5.3±0.7| 0.046   | 0.938   | 0.524   |

The data are expressed as the mean±SE of the mean. C2 indicates 2 mo on a diet with 1000 IU/kg of vitamin D; C4, 4 mo on a diet with 1000 IU/kg of vitamin D; D2, 2 mo on a diet with no vitamin D; D4, 4 mo on a diet with no vitamin D; diet (factor vitamin D content in the diet), P value of the vitamin D content in the diet effect; diet×time, P value of the interaction; LV, left ventricle; MCA, myocyte cross-sectional area; RV, right ventricle; and time (factor length of the nutrient restriction), P value of the time effect.

When interactions were observed, the same superscript letters show the significant differences (*C4≠D4; †C2≠C4; and ‡D2≠D4).

| Table 5. Echocardiography Data |
|-------------------------------|---------|---------|---------|---------|---------|---------|---------|
| Variable                      | C2      | D2      | C4      | D4      | Diet    | Time    | Diet×Time|
| LVDD/tibia                    | 1.60±0.02| 1.63±0.02| 1.63±0.02| 1.72±0.02| 0.006   | 0.009   | 0.114   |
| LWT, mm                       | 1.32±0.04| 1.33±0.04| 1.35±0.04| 1.47±0.04| 0.083   | 0.034   | 0.140   |
| RWT                           | 0.42±0.01| 0.42±0.01| 0.40±0.01| 0.41±0.01| 0.745   | 0.244   | 0.514   |
| LA/tibia                      | 0.09±0.002| 0.09±0.002| 0.08±0.002| 0.10±0.002| <0.001  | 0.464   | 0.079   |
| RAA, mg/dL                    | 0.17±0.01| 0.16±0.0‡| 0.18±0.01*| 0.20±0.01*‡| 0.381   | 0.001   | 0.008   |
| LVM, mg                       | 499.2±25.6†| 520±27.1‡| 585±27.9*†| 722±26.5*‡| 0.004   | <0.001  | 0.034   |
| E, cm/s                       | 76.8±4.1| 79.1±4.3| 84.3±4.4| 76.4±4.1| 0.498   | 0.571   | 0.231   |
| A, cm/s                       | 62.4±4.1| 65.4±4.2| 61.9±4.3| 67.2±4.1| 0.322   | 0.875   | 0.778   |
| E/A                           | 1.32±0.10| 1.27±0.10| 1.46±0.11| 1.26±0.10| 0.209   | 0.516   | 0.494   |
| TRV, ms                       | 21.8±1.2| 22.6±1.2| 21.1±1.6| 20.5±1.2| 0.935   | 0.280   | 0.601   |
| LVSDD/tibia                   | 0.56±0.03| 0.62±0.03| 0.61±0.03| 0.73±0.03| 0.002   | 0.003   | 0.267   |
| FS                            | 0.65±0.02| 0.62±0.02| 0.62±0.02| 0.58±0.02| 0.018   | 0.026   | 0.544   |
| EF                            | 0.95±0.01| 0.94±0.01| 0.94±0.01| 0.92±0.01| 0.023   | 0.010   | 0.344   |

The data are expressed as the mean±SE of the mean. A indicates A wave; C2, 2 mo on a diet with 1000 IU/kg of vitamin D; C4, 4 mo on a diet with 1000 IU/kg of vitamin D; D2, 2 mo on a diet with no vitamin D; D4, 4 mo on a diet with no vitamin D; diet (factor vitamin D content in the diet), P value of the vitamin D content in the diet effect; diet×time, P value of the interaction; E, A wave; EF, ejection fraction; FS, fractional shortening; LA, left atrium; LV, left ventricle; LVDV, LV end-diastolic diameter; LVM, LV mass; LVSDD, LV end-systolic diameter; LWT, LV wall thickness; RAA, right atrium area; RWT, relative wall thickness (2×LWT/LVDV); time (factor length of the nutrient restriction), P value of the time effect; and TRV, isovolumetric relaxation time.

When interactions were observed, the same superscript letters show the significant differences (*C4≠D4; †C2≠C4; and ‡D2≠D4).
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Disclosures

None.

References


hypertrophy, longer VDD highlights changes that are not observed with shorter times.

Finally, we should consider the potential limitations of this study. It is well accepted that the investigation of diastolic function is challenging. Indeed, although expected in the present analysis, diastolic dysfunction was not observed. It seems to be related to the methodology in evaluation of diastolic function by conventional echocardiogram. In addition, another limitation to measure diastolic function in this model is the high cardiac frequency in rats. Unfortunately, our study did not use tissue echocardiogram, which is the most sensitive noninvasive method for the assessment of diastolic function. Thus, the effects of VDD on diastolic function remain to be elucidated.

In conclusion, VDD in a restriction diet model is an ongoing process that is associated with cardiac remodeling, and the duration of this deficiency determines the intensity of the alterations.


Several observational studies report that poor vitamin D (VD) status is highly prevalent among heart failure patients and indicates an increased risk of mortality. Nevertheless, despite accumulating data on the association of VD deficiency (VDD) with heart diseases and related increased mortality, the mechanism by which VDD is involved in the pathogenesis of heart disease is not completely elucidated. In a rat model, we evaluated the influence of VDD and its duration on cardiac metabolism, morphology, and function. Our data indicate that VDD is associated with energetic metabolic changes, cardiac inflammation, oxidative stress, fibrosis and apoptosis, cardiac hypertrophy, and systolic dysfunction, and that the duration of deficiency influences that magnitude of these abnormalities. These data can contribute to the understanding of possible mechanisms by which VDD is related to heart disease.

**CLINICAL PERSPECTIVE**

Several observational studies report that poor vitamin D (VD) status is highly prevalent among heart failure patients and indicates an increased risk of mortality. Nevertheless, despite accumulating data on the association of VD deficiency (VDD) with heart diseases and related increased mortality, the mechanism by which VDD is involved in the pathogenesis of heart disease is not completely elucidated. In a rat model, we evaluated the influence of VDD and its duration on cardiac metabolism, morphology, and function. Our data indicate that VDD is associated with energetic metabolic changes, cardiac inflammation, oxidative stress, fibrosis and apoptosis, cardiac hypertrophy, and systolic dysfunction, and that the duration of deficiency influences that magnitude of these abnormalities. These data can contribute to the understanding of possible mechanisms by which VDD is related to heart disease.
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