Cardiac Remodeling in Obesity

Gerard P. Aurigemma, MD; Giovanni de Simone, MD; Timothy P. Fitzgibbons, MD, PhD

Obesity has generated much interest within the cardiovascular community within the past 2 decades. It is now recognized that obesity is an important contributor to cardiac and all-cause mortality, independent of its association with other cardiovascular risk factors and increases the risk for cardiovascular morbidity, including heart failure (Figure 1). The malefic consequences of obesity are due both to the associated structural and functional cardiac alterations as well as the high prevalence of coexisting conditions, such as coronary artery disease, hypertension, sleep-disordered breathing (SDB), and diabetes mellitus. To better understand the relationship between obesity and heart failure, we will review what is known about cardiac structural remodeling in obesity as well as the evidence for preclinical abnormalities in left-ventricular (LV) systolic and diastolic functions. We will place particular emphasis on newer concepts and findings suggested by contemporary imaging methods.

Cardiac Remodeling in Obesity

By National Institutes of Health criteria, obesity is defined as a body mass index (BMI) ≥30 kg/m² and severe obesity as a BMI≥240 kg/m². Obesity involves the growth of both lean body mass and adipose tissue and is characterized by a disproportionate growth of adipose tissue in relationship to lean body mass. It is now recognized that adipose tissue is not a homogeneous organ, but is differentiated in relation to its metabolic activity. Whereas fat accumulating in the subcutaneous region does not require substantial blood supply, fat surrounding organs (abdominal, epicardial) is metabolically active, requires energy, and produces a number of compounds that affect the cardiovascular system both directly and indirectly. The high metabolic requirements of both lean and visceral adipose body mass drive a higher cardiac output and workload, and an increase in LV mass. This augmented cardiac output is related to the accumulation of both fat-free mass and central fat mass, and is sustained by increase in both stroke volume and heart rate. As a consequence, obese individuals exhibit increased stroke work, attributable to both volume overload and the lack of an offsetting decrease in peripheral resistance. Even in the absence of hypertension, obesity is frequently associated with nonoptimal blood pressure values, which contribute to an elevated stroke work, the latter being a powerful stimulus to increasing LV mass. Obesity and hypertension frequently coexist, as has been established in a number of epidemiological studies, and obesity is an independent risk factor for arterial hypertension. When obesity and hypertension coexist, there is a substantial increase in the prevalence of LV hypertrophy, at any level of BMI (Figure 2).

LV Hypertrophy and the Importance of Body Size Normalization

Based on contemporary physiology studies in mammals and on equations developed in a large population samples of normotensive and normal-weight individuals, encompassing the entire age-span, we proposed normalization of LV mass for height (in meters) to the power of 2.7. This allometric signal is geometrically consistent, because it is close to the exponent of 3 that would regulate the relationship between the 3-dimensional (3D) LV mass and the mono-dimensional height, based on isometric scaling. Using LV mass/height³, the prevalence of LV hypertrophy (LVH) ranges from 13% in obese, normotensive individuals to over 75% in individuals with severe obesity who are also hypertensive. At the same time, normalization by height is associated with a comparable, or at most modestly decreased, hazard ratio for incident cardiovascular morbidity, compared with normalization with BSA. As a consequence, in populations with a high prevalence of obesity, the population risk attributable to LV hypertrophy that is identified with normalization of LV mass for height is substantially greater than with normalization for BSA or height as a linear measure or using other allometric signals.

LV Geometry in Obesity

There has been a shift in the thinking concerning LV remodeling and geometry in obesity. The traditional paradigm, established in the 1980s, holds that obesity is associated with eccentric LV hypertrophy, attributable to the predominance of the obesity-related volume overload. Newer data challenge this paradigm. For example, Lavie et al. evaluated LV geometry in a large population of obese subjects with preserved ejection fraction (EF), a group with similar demographics as the original studies from the 1980s. Normalizing LV mass for BSA, the authors found a very low prevalence of clear-cut LV hypertrophy (7% and 8% for eccentric and concentric LV hypertrophy, respectively), with an overwhelming prevalence of concentric LV remodeling (34%), a geometric pattern which is usually associated with low cardiac output and high peripheral resistance. Other work has highlighted a similar high prevalence of concentric LV geometry in obese subjects.
For example, in their study of 309 obese subjects of African descent, Woodiwiss et al showed that concentric LV geometry (hypertrophy and remodeling, using LV mass to height$^{2.7}$) was more prevalent than eccentric hypertrophy; they also demonstrated that waist circumference was related to both LV wall thickness and relative wall thickness, and the remodeling observations were independent of clinic, central arterial, or ambulatory blood pressure measurements.

To date most studies of LV remodeling in obesity have been performed with 2D echocardiography, a method which has limitations in obese patients. Data using MRI are emerging, and are concordant with the more recent echocardiographic literature (Figures 3 and 4). In a cross-sectional analysis of the Multi-Ethnic Study of Atherosclerosis (MESA) population, Turkbey et al reported a significant correlation between BMI and the LV mass/volume ratio, a 3D measure of concentric geometry of the LV. In their study, the LV mass/volume ratio was linearly correlated with fat mass and waist-to-hip ratio.

**Mechanisms for Geometric Remodeling in Obesity**

As noted above, the traditional axiom holds that a predominant volume load results in eccentric LV hypertrophy, characterized by a normal relative wall thickness and normal mass/volume ratio. However, more recent echocardiographic and MRI data show that concentric rather than eccentric LV hypertrophy might be the predominant LV pattern in obesity (Figure 4). What are the potential explanations for this discrepancy?

Obese subjects exhibit a higher cardiac output than normal. Although the high cardiac output in subjects with concentric LVH is typically less than that observed in obese subjects with eccentric LVH, the higher cardiac output is often associated with some LV chamber enlargement. The paradigm suggested by Khouri et al may, therefore, be appropriate for obese subjects (Figures 3 and 4). In this study, participants in the Dallas Heart Study underwent comprehensive MRI of LV structure. The distribution of geometric subtypes among obese (BMI $\geq$ 30) and very obese (BMI $\geq$ 35) is shown in Figure 4, and supports the position that concentric hypertrophy is more prevalent than eccentric hypertrophy among obese individuals.

In addition, it is important to emphasize that obese subjects classified as normotensive still have higher blood pressures than their normal-weight peers. Hemorheological components of total peripheral resistance influence blood pressure, and are associated with concentric LV geometry, and are altered in obesity. Thus, pressure load in obese individuals is consistently higher than in normal-weight persons, even in the presence of blood pressure values that fall within the normal range. Avelar et al have speculated that even mild increases in blood pressure that still fall within the reference range may have exaggerated effects on LV mass in obese subjects. They have also postulated that a training effect on the heart exists in obesity, attributable to the greatly exaggerated body weight that has to be lifted during normal activities.
Two additional factors deserve consideration: a normal office blood pressure does not completely exclude the presence of arterial hypertension, and it has been shown that masked hypertension is more frequent in obese than in normal-weight individuals. In addition, some of the LV remodeling observed may be attributable to SDB. In fact, LV hypertrophy (LVH) in SDB is as closely related to the severity of the sleep disturbances as it is to the levels of blood pressure and BMI.

Left Atrial Remodeling
Concentric LV geometry is invariably associated with left atrial (LA) remodeling and geometry. LA enlargement is reported in obesity no matter what the method of body size normalization is used. Both LA antero-posterior linear dimension and LA volume become progressively greater as the severity of obesity increases. Obesity is reported to be the closest correlate of LA size in arterial hypertension and also is correlated to the progression of LA dilatation over time. Data from the Cardiovascular Health Study, a longitudinal examination of cardiac structure in subjects older than 65, demonstrated that LA volumes correlated more strongly with indices of body size than with any other variable.

LV Mass and Weight Loss
Weight loss is almost invariably associated with reduction of LV hypertrophy in obese individuals, an association that appears to be even stronger than the decrease in LV mass associated with blood pressure reduction. In large populations of high-risk hypertensive patients, for a comparable decrease in blood pressure, there was substantially less LV hypertrophy as well.

Figure 3. Patterns of remodeling. The paradigm is based on work published by Khouri et al, based on MRI data compiled in the Dallas Heart study. The 2 upper panels designate subjects with high relative wall thickness (or mass/volume ratio) and is a modification of a simpler, 4-element (normal, concentric hypertrophy, concentric remodeling, and eccentric hypertrophy) paradigm developed and popularized by Ganau et al. Khouri et al modified this concept by subdividing the 2 hypertrophy patterns further, depending on whether the absolute value for the LV wall thickness is elevated. Accordingly, hypertrophy with a normal mass/volume ratio is deemed eccentric if the mass/volume ratio is normal. We have used the term magnification for individuals whose LV mass and volume are both high, but in whom the mass/volume ratio is normal and whose absolute wall thickness is normal.

Figure 4. Composite figure showing the prevalence of the various forms of cardiac remodeling in obese subjects in the Dallas Heart Study, using the classification scheme outlined in Figure 3. In this Figure, only subjects enrolled in the Dallas Heart Study classified as obese were included, using data published by Khouri et al (MRI images from reference 41, used with permission). As can be seen, eccentric LV hypertrophy (LVH) is much less prevalent than concentric hypertrophy. BMI indicates body mass index.
mass regression when obesity was present. Obesity is also a strong obstacle for achieving optimal blood pressure control by antihypertensive medications.

A clear effect of weight loss on reduction of LV mass has been more recently confirmed in a series of obese patients undergoing bariatric surgery, as described by Owan et al. In their study of 423 subjects who reduced their BMI by an average of 15 kg/m², LV mass decreased by 30 g, on average. The mechanisms of improvement of LV geometry with weight loss appear to be primarily hemodynamic. In the study by Owan et al., there was a correlation between change in BMI and changes in both diastolic blood pressure and LV mass index, 2 years after surgery. Interestingly, the changes associated with weight loss might also be macroscopically observed with the substantial reduction of epicardial fat, detected by 2D echocardiography.

**Right Ventricular Remodeling**

There is a paucity of data regarding even normal imaging parameters of the right ventricle (RV). In contrast to the ellipsoid shape of the LV, the RV is irregular and crescentic in shape, and presents a challenge to accurate imaging with 2D echocardiography; MRI and 3D echocardiography overcome some of these limitations. These caveats aside, data and interest regarding the RV are accumulating, and with strict attention to detail and standardization of echocardiographic views and measurements, important information about RV size and function can be obtained in most patients. Of note, in contrast to the LV, normal values for RV size, dimensions, and systolic/diastolic functions have not yet been systematically indexed to height.

**RV Structural Abnormalities in Obesity**

To the extent that obesity is a systemic disorder independently associated with LV hypertrophy, one would expect that the RV is also subject to hypertrophy. Wong et al. showed that obese individuals had greater RV free wall thickness and end-diastolic volumes, even when SDB was accounted for. Data from the MESA study confirmed these findings. Using cardiac MRI in 4127 patients without cardiovascular disease, they found that overweight and obese had greater RV mass and RV end-diastolic volume than lean subjects; these differences remained despite adjustment for height, LV dimensions, hypertension, or obesity. It is important to note that although the differences in RV morphology were significant when LV parameters were accounted for, they were slightly attenuated. The authors concluded that there were both weight dependent and independent effects on RV size. Perhaps most interestingly, there was a non-linear increase in RV mass which exceeded the increase in RV end-diastolic volume (RVEDV) with increasing BMI. In the former study, the effects of SDB were controlled for, and obesity was shown to have independent effects on RV size; SDB was not controlled for in the MESA study, and is one of the potential independent contributors to the increase in RV mass seen in obese patients. Earlier studies indicated that as many as 70% of patients with SDB may have isolated RVH. As with hypertrophy of the LV, other factors may act synergistically with obesity to have an additive effect on RV hypertrophy. For example, data from the Framingham Heart Study showed that when matched for obesity, patients with severe SDB (respiratory disturbance index >90th percentile) had greater mean RV wall thickness than those with less severe SDB (respiratory disturbance index <10th percentile; 0.78±0.02 versus 0.68±0.02 cm; P<0.005).

**Obesity and Subclinical Cardiac Dysfunction**

Many, if not most, of the newer noninvasive imaging techniques have been applied to study obesity-related cardiac dysfunction. Newer and more sophisticated methods used to evaluate regional and global LV functions include MRI tagging, tissue Doppler Imaging, and strain imaging, which permits the ability to assess myocardial rotation and twist. We will review data accumulated to date concerning subclinical ventricular systolic and diastolic dysfunction and speculate on the possible underlying mechanisms.

**LV Systolic Function**

Global LV chamber function is assessed, most commonly, by means of the EF, usually without regard to loading conditions. In one of the few contemporary studies, which presented invasive data derived from cardiac catheterization, Powell et al. have shown a lack of relationship between BMI and EF, and that EF can be normal even in...
patients with BMI $\geq 40$. These data are supported by the non-invasive data compiled (Table 1), which show that EF is usually normal in obese subjects. However, few clinical studies of global LV function have taken into account either myocardial afterload or preload74,76 (Table 1).

The strain studies thus far published have used Doppler,73,81,86 myocardial systolic and diastolic velocities,67 or both82 (Figure 6), and velocity vector imaging to investigate LV twist and rotation. These studies consistently demonstrate lower levels of strain, velocities, strain rates, and torsion in obese patients with normal EF, compared with the control subjects.

As has been reviewed elsewhere79,88–90 midwall shortening is a measure of regional systolic function and is particularly useful when the geometry of the LV is concentric74; this attribute makes it an appropriate index of function in obese subjects. However, the data reported to date on the utility of midwall shortening in this instance have been mixed. In studies of middle age subjects with hypertension, mild obesity, or both, we and others could detect no significant abnormality in midwall mechanics.8,80,83,91 Of note is the fact the patients in these studies were without much evidence of concentric remodeling of the LV.8,80

By contrast, Avelar24 found midwall shortening values that were slightly reduced only in obese subjects with extremely high values of BMI, paralleling a relative wall thickness that was higher than in controls. Interestingly, the same group reported that midwall shortening improved after bariatric surgery, in parallel with improvement in LV geometry and a slight reduction in LV EF.64 We interpret these data to mean that systolic function abnormalities detected by midwall shortening are closely related to the abnormalities in LV geometry.92 Interestingly, strain values have also been demonstrated to decrease in parallel with increasing levels of relative wall thickness, as well as with increasing values for BMI and waist-to-hip ratio.79,84

### Table 1. LV Systolic Function in Obesity

<table>
<thead>
<tr>
<th>Author</th>
<th>n</th>
<th>Mean BMI</th>
<th>HTN/DM</th>
<th>Technique</th>
<th>Load Accounted For</th>
<th>Relative Wall Thickness</th>
<th>Principal Findings in Obese Subjects Compared With Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>de Simone79</td>
<td>737</td>
<td>$&gt;18$</td>
<td>Included/excluded</td>
<td>Midwall shortening</td>
<td>Yes</td>
<td>0.34/0.39 in obese</td>
<td>Midwall shortening normal when normalized for afterload, lower when normalized for preload</td>
</tr>
<tr>
<td>Mureddu80</td>
<td>40</td>
<td>36</td>
<td>Excluded/excluded</td>
<td>Midwall shortening</td>
<td>Yes</td>
<td>0.33</td>
<td>Midwall shortening normal</td>
</tr>
<tr>
<td>Wong73</td>
<td>109 (3 groups)</td>
<td>28, 33, 46</td>
<td>Excluded/excluded</td>
<td>TDI velocities and systolic strains</td>
<td>Yes</td>
<td>0.44 in highest BMI category</td>
<td>Strains and velocities inversely related to BMI</td>
</tr>
<tr>
<td>Peterson72</td>
<td>51 (women only)</td>
<td>37</td>
<td>Excluded/excluded</td>
<td>TDI velocities and systolic strains</td>
<td>No; BP higher in obese group</td>
<td>0.40</td>
<td>Global strain lower</td>
</tr>
<tr>
<td>Powell85</td>
<td>4281</td>
<td>NA; patients grouped by BMI</td>
<td>Included/excluded</td>
<td>LV EF</td>
<td>No</td>
<td>NA</td>
<td>No relationship between LV EF and BMI; stroke volume varies directly with BMI category</td>
</tr>
<tr>
<td>DiBello81</td>
<td>48</td>
<td>46</td>
<td>Excluded/excluded</td>
<td>TDI velocities and strain</td>
<td>No; BP higher in obese group</td>
<td>0.48</td>
<td>Lower strains; good correlation between BMI and strain</td>
</tr>
<tr>
<td>Avelar24</td>
<td>455</td>
<td>43</td>
<td>Not excluded</td>
<td>Midwall shortening</td>
<td>No; BP higher in obese group</td>
<td>0.46</td>
<td>Lower midwall shortening; $O_2$ saturation variable most strongly related to LVMi</td>
</tr>
<tr>
<td>Tumuklu82</td>
<td>33</td>
<td>37</td>
<td>Excluded/excluded</td>
<td>TDI velocities and strain</td>
<td>No</td>
<td>0.46</td>
<td>Velocities and strains inversely related to BMI</td>
</tr>
<tr>
<td>Iacobellis83</td>
<td>55</td>
<td>51</td>
<td>Excluded/excluded</td>
<td>Midwall shortening</td>
<td>Yes</td>
<td>0.36</td>
<td>Midwall shortening normal; end systolic stress similar</td>
</tr>
<tr>
<td>Kuznetsova84</td>
<td>480</td>
<td>NA</td>
<td>Included</td>
<td>TDI velocities and strain</td>
<td>No</td>
<td>NA</td>
<td>Longitudinal strains negatively correlated with waist/hip ratio; radial strains inversely correlated with body weight</td>
</tr>
<tr>
<td>Deng85</td>
<td>30</td>
<td>53</td>
<td>Excluded/excluded</td>
<td>Velocity vector imaging; rotation and torsion</td>
<td>No; BP higher in obese group</td>
<td>0.42</td>
<td>Lower values for apical rotation and torsion</td>
</tr>
<tr>
<td>Barbosa86</td>
<td>92</td>
<td>53</td>
<td>Included</td>
<td>TDI strain</td>
<td>Multivariable regression</td>
<td>0.46</td>
<td>LV and RV strains both reduced</td>
</tr>
<tr>
<td>Willens87</td>
<td>51</td>
<td>$\geq 35$</td>
<td>Included/excluded</td>
<td>Transmitral flow and TDI</td>
<td>No</td>
<td>0.44</td>
<td>Normal ejection fraction; reduced annular tissue Doppler velocity</td>
</tr>
</tbody>
</table>

BMI indicates body mass index; DM, diabetes mellitus; HTN, hypertension LV EF, left-ventricular ejection fraction; and TDI, tissue Doppler Imaging.
LV Diastolic Function

Studies examining diastolic function in obesity, using transmural and tissue Doppler Imaging velocities, are summarized in Table 2. The majority of studies of diastolic filling in obesity show mild diastolic filling abnormalities (Table 2). Specifically, most studies have clearly demonstrated prolonged active relaxation in the presence of even mild-moderate obesity. Russo et al employed multivariable regression analysis to control for hypertension and diabetes mellitus in their study of diastolic filling in obesity. They found (Table 2) that the relation between BMI and abnormalities of parameters of diastolic function was continuous and that even the overweight status was associated with diastolic dysfunction. As noted by the authors, there was little difference in most parameters of diastolic dysfunction between obese and overweight subjects. However, in this population, the prevalence of hypertension among overweight subjects was >70% and that of diabetes mellitus, a little <30%. The continuous relationship between BMI and the E/e' ratio (used a surrogate...
for LA pressure) suggests that obese individuals with a large prevalence of other major risk factors have higher than normal LA pressures at rest. To date, it is clear that isolated obesity (ie, no diabetes mellitus, no hypertension, normal LV mass index) is often associated with prolonged LV relaxation and, therefore, mild diastolic dysfunction (Table 2).2

Mechanism of LV Systolic and Diastolic Function Abnormalities in Obesity

As we have seen, available data concerning LV systolic function show normal EF, even in markedly obese subjects. These data make a strong case against the notion of a dose–response relationship between BMI and LV systolic dysfunction. However, in our opinion, the literature also supports the notion that subtle and likely preclinical abnormalities in systolic function exist, at least when the LV geometry is concentric and when the degree of obesity is severe. Limited data exist, however, which prove that this preclinical systolic dysfunction is independent of loading conditions or LV geometry. Assuming that the data are demonstrating a true subtle myocardial depression, what could be the explanation(s)?

First, systolic loads are increased in obesity, as has been discussed, even when frank hypertension is not present. Second, LV geometric changes are associated with impaired mechanics.
To the extent that concentric geometry of the LV is commonly encountered in severely obese individuals, we do not find the observed abnormalities in strain or midwall shortening to be surprising. Whether there is a cause–effect relationship between relative wall thickness and subclinical dysfunction, or whether the dysfunction occurs pari passu with remodeling, is not clear at this point. However, there is evidence suggesting that concentric LV remodeling preserves LV chamber function when wall mechanics are impaired,109,110 suggesting that myocardial dysfunction may be the inciting abnormality.

The diastolic function abnormalities observed in human obesity are similar in magnitude to what is observed in systolic function, indicating the presence of mild, subclinical dysfunction in LV relaxation and, for more severe degrees of obesity, in filling rates and filling pressure. In fact, the abnormalities in tissue Doppler systolic and diastolic velocities display a similar negative correlation with BMI.73,111 It is also reasonable to conclude that diastolic filling rate abnormality is proportional to the increase in BMI (Table 2). As it is the case with systolic dysfunction in obesity, we can only speculate as to the operative mechanisms. The same factors which may contribute to subclinical systolic dysfunction have been demonstrated to be associated with impaired relaxation: increased arterial pressure and concentric geometry.74

Abnormalities in RV Function

That obesity results in early and significant changes in RV systolic function is evident by recent studies showing that obese children have biventricular abnormalities in deformation in comparison to their lean counterparts.103 Di Salvo et al103 showed that peak systolic strain of the basal and mid RV free wall was reduced in obese children compared with lean controls. Obese adults have also been shown to have reduced longitudinal strain of the RV, which correlates both with BMI and duration of obesity.104 In addition to their findings on RV structural remodeling in obesity, Wong et al108 found that there was a dose-dependent negative effect of BMI and age on peak systolic (S) and early diastolic (E) RV velocities. Others have also found evidence of decreased RV diastolic function in obese patients compared with lean controls.105 Whether or not these abnormalities in diastolic and systolic functions detected by strain and tissue Doppler imaging progress to overt abnormalities in RV function detectable by RVEF or % FAC is yet to be determined. However, studies from patients before and after bariatric surgery and obese controls who have not had surgery suggest that there is progression of some parameters of adverse RV remodeling.105 Likewise, a recent study from Owam et al64 showed that, after bariatric surgery, patients had decreased RV cavity area and increased RV % FAC compared with controls.64

Summary

We have reviewed data concerning cardiac structure and function. We believe that the following conclusions are justified by the data available. Cardiac remodeling in obesity is characterized by concentric geometry at least as often as eccentric geometry (Figure 7). Most, but not all studies also demonstrate subtle, likely subclinical, abnormalities in myocardial function and diastolic filling, some of which are reversible with weight loss. Given the prevalence of obesity, the frequency of these subtle findings is not only of academic interest. If LV remodeling precedes preclinical systolic dysfunction, identification of structural and functional abnormalities might allow us to certain patients for special counseling regarding weight loss, by pointing out that they already have evidence of heart disease.

Disclosures

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