Imaging studies in patients with heart failure: Current and evolving technologies

Helene Glassberg, MD; James Kirkpatrick, MD; Victor A. Ferrari, MD

Technological advances continue to expand the clinical role of echocardiography in the intensive care unit, particularly in patients with heart failure. It has many advantages over tomographic techniques such as echo cardiac magnetic resonance imaging and cardiac computed tomography, can provide rapid bedside cardiac assessment, and facilitate emergent decision-making for critically ill patients. Image quality problems in the intensive care setting have largely been overcome by the use of harmonic imaging, contrast opacification, and when indicated, transesophageal echocardiography. Newer techniques promise to advance the scope and prognostic power of echocardiography, and to expand the portability and availability of this tool. (Crit Care Med 2008; 36[Suppl.]:S28–S39)

New technological advances continue to expand the clinical role of echocardiography (echo) in the intensive care unit (ICU), particularly in patients with heart failure. Despite rapid growth in other advanced imaging methods, echo retains many advantages over tomographic techniques such as cardiac magnetic resonance imaging and cardiac computed tomography. As the most common cardiac noninvasive imaging technology, echo is readily available in most hospitals. Echo can provide rapid bedside cardiac assessment and facilitate emergent decision-making for critically ill patients. Major indications for echo in the ICU patient with heart failure include hypotension of uncertain etiology, suspicion of left or right ventricular dysfunction, myocardial infarction, significant valvular disease, prosthetic valve dysfunction, pericardial disease, and unexplained hemodynamic alterations. Perhaps the most basic and useful information obtained from echo in patients with heart failure are measures of ventricular function and anatomy. In addition, other important parameters include diastolic and valvular function, hemodynamic measurements, and a variety of prognostic and therapeutic markers (Table 1). A recent editorial described echo as “the single most useful diagnostic test in the evaluation of patients with unexplained heart failure” (1). This section will review the vital role of echocardiography in the management of heart failure in the critical care setting.

**DEFINITION OF ETIOLOGY (SYSTOLIC VS. DIASTOLIC DYSFUNCTION)**

**Echocardiographic Findings of Dilated Cardiomyopathy.** In dilated cardiomyopathy, the left ventricle (LV) becomes more spherical in shape, overall LV systolic function is reduced, wall thickness is normal or reduced, and systolic wall thickening is impaired. On M-mode echocardiography, additional features of systolic dysfunction are increased separation of the mitral leaflet E point from the septum, poor mitral and aortic valve opening, and early closure of the aortic valve due to reduced stroke volume (2). In addition, images often reveal left atrial enlargement and/or four-chamber dilation. Right ventricular (RV) dysfunction, either secondary to increased pulmonary pressures or to direct involvement of the RV in the pathologic process, may be seen. Doppler echocardiography is used in dilated cardiomyopathy to assess stroke volume and contractile function; acceleration or deceleration of the mitral regurgitant jet can be used as an analog of dP/dt (the change in LV pressure over time) (3). In a study of patients with LV dysfunction, a dP/dt <600 mm Hg/sec and –dP/dT <450 mm Hg/sec predicted worsened survival in patients with heart failure (4).

**Viral Myocarditis.** Evidence suggests that both immune- and viral-mediated cardiac damage occurs in this form of dilated cardiomyopathy (5). There is an extensive list of viral infections implicated in the cause of myocarditis; the most common is Coxsackie B. The clinical manifestations are variable; however, the majority have antecedent flu-like symptoms. Some patients may present with chest pain, LV dysfunction, and ECG changes that may mimic myocardial infarction. Arrhythmias and conduction disturbances can occur. Echocardiography is often helpful, but usually not diagnostic. Severe, diffuse myocarditis can result in dilation of all cardiac chambers. LV dysfunction is usually seen, and may be segmental, reflecting the focal nature of myocarditis. A trabeculated pattern of wall thickening may be seen if inflammation is substantial (6, 7).

Echocardiography also can detect intracardiac thrombi, functional mitral or tricuspid regurgitation, and pericardial involvement. Patients with fulminating myocarditis usually have near normal LV diastolic dimensions and increased septal thickness, while those with acute myocarditis tend to have increased LV diastolic dimensions and normal septal thickness (8).

**Familial Dilated Cardiomyopathy.** This diagnosis generally is made when...
is greater than twice the width of the compacted myocardium (13). Echocardiography identified patients with idiopathic dilated cardiomyopathy as those with LV enlargement and systolic dysfunction as defined by a fractional shortening <25%. Twenty-three percent of relatives had abnormal findings: 4.6% had dilated cardiomyopathy, 15.5% had LV enlargement without systolic dysfunction, and 2.7% had decreased fractional shortening <25% without LV enlargement (13).

**Left Ventricular Noncompaction.** LV noncompaction, also called LV hypertrabeculation or spongy myocardium, is an uncommon cause of dilated cardiomyopathy that results from arrest of compaction of the loose interwoven meshwork during fetal development. This diagnosis should be suspected when heavy LV trabeculation is noted, particularly at the apex (14, 15). Characteristically, there is a normally compacted epicardial layer and a very thickened (noncompacted) endocardial layer with trabeculations and deep recesses (16, 17). Echocardiographic criteria for diagnosis include the absence of coexisting cardiac abnormalities and a ratio of noncompacted to compacted myocardium ≥2:1 at end-systole (Fig. 1).

Other findings on echocardiography include reduced LV systolic function, diastolic dysfunction, LV thrombi, and abnormal papillary muscle structure (17). Contrast echocardiography may aid in establishing the diagnosis (18).

**Ischemic Cardiomyopathy.** The majority of patients with ischemic cardiomyopathy have known coronary heart disease; however, it may present as an occult dilated cardiomyopathy. Ischemic cardiomyopathy can be difficult to differentiate from idiopathic dilated cardiomyopathy by echocardiography. In both forms, LV wall motion abnormalities can be segmental. In most patients, ischemic cardiomyopathy is associated with regional remodeling, and ischemic cardiomyopathy also tends to exhibit areas of endocardial scarring in the areas of infarction (19).

**Takotsubo Cardiomyopathy.** Takotsubo cardiomyopathy, also called stress-induced or transient LV apical ballooning, is an increasingly recognized cardiac disorder. It is typically triggered by intense physical or emotional stress, and presents similarly to an acute myocardial infarction. Coronary angiography reveals no significant obstructive disease. Echocardiography reveals the characteristic finding of transient apical dysfunction, with compensatory hyperdynamic function of the base, producing apical ballooning (20–25) (Fig. 2).

**Echocardiographic Features of Hypertrophic Cardiomyopathy.** Hypertrophic cardiomyopathy is characterized by increased LV mass. When present without apparent etiology, it is considered to be a primary hypertrophic cardiomyopathy, most frequently genetic in origin. The hypertrophy is typically asymmetric in primary hypertrophic cardiomyopathy and symmetric in secondary disease, such as hypertensive-mediated hypertrophy (26, 27).

**Primary Hypertrophic Cardiomyopathy.** The most characteristic finding on echocardiography is asymmetric septal hypertrophy, with increased wall thickening in the left ventricular outflow tract and left ventricular cavity. The hypertrophy is typically asymmetric in primary hypertrophic cardiomyopathy and symmetric in secondary disease, such as hypertensive-mediated hypertrophy (26, 27).

Table 1. Commonly used echocardiographic parameters for the assessment of heart failure in the intensive care setting

<table>
<thead>
<tr>
<th>Exam</th>
<th>Assessments to Be Made During Exam</th>
</tr>
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<tbody>
<tr>
<td>LV systolic function</td>
<td>LV ejection fraction (load dependent)</td>
</tr>
<tr>
<td></td>
<td>Strain rate (load independent)—in validation process</td>
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<tr>
<td>LV diastolic function</td>
<td>Pulsed wave Doppler of the mitral inflow</td>
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<td></td>
<td>Pulmonary venous flow</td>
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<td></td>
<td>Tissue Doppler of the mitral annulus</td>
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<td></td>
<td>Color M-mode of mitral inflow</td>
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<tr>
<td>Hemodynamics</td>
<td>Pulmonary artery pressure (determined using the tricuspid regurgitant jet)</td>
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<td></td>
<td>Pulmonary artery mean and diastolic pressures from pulmonic regurgitation jet</td>
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<tr>
<td></td>
<td>LV filling pressure (estimated)</td>
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<tr>
<td></td>
<td>Inferior vena caval collapsibility index</td>
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<tr>
<td>Prognosis</td>
<td>Reduced LV systolic function (LV ejection fraction)</td>
</tr>
<tr>
<td></td>
<td>Right ventricular enlargement and dysfunction</td>
</tr>
<tr>
<td></td>
<td>Restrictive filling pattern</td>
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</table>

LV, left ventricular.

Figure 1. Noncompaction of the left ventricular myocardium. Parasternal short axis view, just apical to the papillary muscles, shows intense trabeculation. The depth of the intratrabecular recesses (Crypt) is greater than twice the width of the compacted myocardium (Compacted).

 idiopathic dilated cardiomyopathy is found in two or more closely related family members. Epidemiologic studies report variable rates of inheritance, ranging from 20% to >50% (9–11). The weight of evidence in the literature supports the efficacy (class IIa indication in 2005 American College of Cardiology/American Heart Association guidelines) of screening asymptomatic first-degree relatives with an electrocardiogram and echocardiography (12). A prospective cohort study evaluated >700 asymptomatic first- and second-degree relatives of 189 patients with idiopathic dilated cardiomyopathy (13). Echocardiography identified patients with dilated cardiomyopathy as those with LV enlargement and systolic dysfunction as defined by a fractional shortening <25%. Twenty-three percent of relatives had abnormal findings: 4.6% had dilated cardiomyopathy, 15.5% had LV enlargement without systolic dysfunction, and 2.7% had decreased fractional shortening <25% without LV enlargement (13).

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**Primary Hypertrophic Cardiomyopathy.** The most characteristic finding on echocardiography is asymmetric septal hypertrophy, with increased wall thick-
trophied LV with a wall thickness is based upon the findings of a hyper-
diagnosis of hypertrophic cardiomyopa-
thesis localized to the basal septum (26–
In an uncommon variant of asymmetric septal hypertrophy, the apex is the
site of the most intensive hypertrophy, so-called apical hypertrophy (29). This is
sometimes difficult to identify by echocardiography, because the apex tends to
be more difficult to image, and in some circumstances it may be helpful to use a
contrast agent. The echocardiographic diagnosis of hypertrophic cardiomyopa-
athy is based upon the findings of a hypertrophied LV with a wall thickness ≥15
mm that is not associated with systemic hypertension (30). Classic hypertrophic
obstructive cardiomyopathy has the following features: asymmetric septal hy-
pertrophy, systolic anterior motion of the mitral valve, crowding of the LV outflow
tract by the mitral apparatus, and partial mid-systolic closure of the aortic valve. When obstructive hypertrophic cardio-
mypathy is suspected, it is useful to perform some sort of provocation during the
echocardiogram; the most frequently used maneuver is the Valsalva maneuver and,
less commonly, a pharmacologic intervention is used, such as amyl nitrate
inhalation. Provocation can demon-
strate the dynamic nature of the out-
flow tract obstruction and even determine its severity.
Use of Doppler techniques, particularly continuous wave, is necessary. The
systolic flow velocity is measured in the LV outflow tract and midcavity at rest and
during maneuvers (31). Doppler also will recognize dynamic mitral regurgitation
that often appears in conjunction with outflow tract obstruction. Systolic ante-
rior movement of the mitral valve on two-dimensional and M-mode imaging
provides independent evidence of dy-
namic obstruction (31, 32) (Fig. 3). If obstruction worsens with provocative
testing, the systolic anterior motion of the mitral valve also will worsen. Assess-
ment of the aortic valve during the prov-
ocation will provide secondary evidence of obstruction by demonstrating midsys-
tolic closure. The Valsalva maneuver usu-
ally is performed first, and if this fails to provoke changes, provocation by amyl nit-
rate inhalation may be performed.
Hypertensive Cardiomyopathy. Sec-
ondary LV hypertrophy is most often a
c omplication of hypertension. Echocardi-
ography is the procedure of choice for identification, because the sensitivity of
the various ECG criteria may be as low
as 7% to 35% with mild LV hypertrophy and only 10% to 50% with moderate to
severe disease (33). Current criteria for the diagnosis of LV hypertrophy on M-
mode echocardiography are an LV mass
index ≥134 and ≥110 g/m² body sur-
face area in men and women, respecti-
vively (34, 35).
Echocardiographic Features of Re-
strictive Cardiomyopathies. Restrictive
cardiomyopathies are more difficult to di-
agnose with echocardiography and can be
difficult to distinguish from constrictive pericarditis. Restrictive LV filling is char-
acterized by a low diastolic volume, nor-
mal or only mildly reduced LV ejection
fraction, and abnormal diastolic function.
Frequently, the atrial dilation is out of
proportion to the degree of valvular dis-
ease (regurgitation or stenosis).
Amyloid Cardiomyopathy. Cardiac in-
volve ment can occur in primary or sec-
ondary amyloidosis or as an isolated car-
diac condition in patients with senile
amyloidosis. The rigid amyloid fibrils lead
to relaxation abnormalities; therefore, di-
astolic dysfunction is the most common
and earliest echocardiographic abnormal-
ity in cardiac amyloidosis (36). Ulti-
mately, systolic dysfunction can develop.
Echocardiography in patients with
ovet cardiac amyloidosis demonstrates
ymmetric thickening of the LV wall (of-
ten with low voltage noted on electrocar-
diography, which is in contrast to thick-
ening seen with LV hypertrophy due to
primary hypertrophic or hypertensive
cardiomyopathy with high voltage on
electrocardiography), a granular “spar-
kled” appearance of the myocardium (this
sign is less useful when harmonic imag-
ing is performed), small ventricular
chambers, thickening of the atrial sep-
tum, and dilated atria (37, 38). Increased
RV wall thickness also may be present
and can be associated with RV diastolic
function (38). Disproportionate RV
enlargement also may occur (39, 40). Not
uncommonly, there is thickening and re-
gurgitation of all valves, and a pericardial
effusion may be present. Although the
sparkled appearance is relatively nonspe-
cific (39–41), the combination of this
finding and atrial septal thickening are
highly suggestive of cardiac amyloid (40,
41). Valvular abnormalities, such as
“functional” mitral regurgitation, may
arise from ventricular dilation.

Figure 2. ‘Takotsubo’ stress-induced cardiomyopathy, apical four-chamber views: (a) end-diastole; and
(b) end-systole in the initial echocardiogram showed normal contraction at the base of the heart with
akinesis from the midventricle to apex (arrows). Two weeks later, the (c) end-diastolic; and (d)
end-systolic frames demonstrated normal contraction of the apex.
Echocardiographic Findings of Complications of Myocardial Infarction.

There are three major mechanical complications of acute myocardial infarction (MI): rupture of the LV free wall; rupture of the interventricular septum; and the development of mitral regurgitation, frequently due to partial or complete papillary muscle rupture. Echocardiography is the initial test of choice in detecting each disorder. Delayed hospitalization (>24 hrs) and postinfarction angina increase the risk of ventricular rupture in predisposed patients (42). Rupture occurs within the first five days after MI in about one half of cases and within 2 wks in >90% of cases (42–45). Echocardiography reveals hemopericardium and findings of cardiac tamponade. Subacute rupture of the LV free wall can occur when thrombus forms and the pericardium seals the perforation. This can develop into frank rupture with cardiac tamponade, or may develop into an aneurysm (44–46). In one study, echocardiographic and hemodynamic indices of cardiac tamponade were present in 85% of patients (44). The diagnosis of subacute rupture is confirmed by transthoracic echocardiography (47).

Ventricular Septal Rupture. Ventricular septal rupture typically occurs 3–5 days after an acute MI. It may, however, develop within the first 24 hrs or as late as 2 wks. Septal rupture occurs equally in anterior and nonanterior infarctions (48). With anterior MI, the defect is most commonly found in the apical septum, and with inferior MI, most often occurs at the base of the heart. Patients with a ruptured septum usually present with hypotension, biventricular failure, and a new murmur. The defect can be diagnosed by 2-dimensional transthoracic echocardiography with color flow Doppler imaging (42, 49, 50). One small study evaluated 43 patients with a post-MI ventricular septal defect and found that 2-D echocardiography alone visualized the defect in only 40% of the patients (49). The addition of Doppler color flow demonstrated an area of turbulent transseptal flow and systolic flow abnormality within the RV in all patients. Transesophageal echocardiography may occasionally be necessary (51).

Acute Mitral Regurgitation. The causes of mitral regurgitation after acute MI include ischemic papillary muscle dysfunction, LV dilation or aneurysm, and papillary muscle or chordal rupture (50, 52, 53). Papillary muscle rupture is a life-threatening complication of acute MI that usually occurs within 1 wk after the infarct (52, 53). The rupture may be partial or complete. The diagnosis of papillary muscle rupture should be considered when there is hemodynamic compromise and a new systolic murmur in the setting of an acute myocardial infarction. In a small echocardiographic study, 43 of 50 patients studied had a ventricular septal defect and seven had papillary muscle rupture or severe dysfunction (50). Transthoracic echocardiography often demonstrates a flail mitral valve segment, and within the LV cavity a highly mobile papillary muscle or chordae can be seen. Not infrequently, because of tachycardia and limited image quality in acutely ill patients, transesophageal echocardiography is required to establish the diagnosis.

RV Infarction. Another important role for echocardiography in the setting of an acute myocardial infarction is identifying RV infarction. Evidence of RV infarction should be sought in patients with inferior ST-elevation infarction, particularly those with the triad of hypotension, clear lungs, and elevated jugular venous pressure. Echocardiography may show RV dilation, abnormal interventricular septal motion, and RV dysfunction (54).

Echocardiography and Unexplained Hypotension. There are various findings on the echocardiogram that may be helpful in identifying the etiology of hypotension in the ICU patient. A small ventricular cavity with hypercontractile function is usually consistent with hypovolemia or vasodilation (e.g., sepsis, anaphylactic shock). In hypotension due to cardiogenic shock, the LV ejection fraction is usually severely reduced, and the LV size may be normal or dilated, depending on the etiology of the dysfunction. In chronic ischemic heart disease, the LV is often dilated,

Figure 3. Asymmetric septal hypertrophy with obstructive cardiomyopathy: (a) apical five- and (b) apical long-axis views of the left ventricle demonstrating severe systolic anterior motion of the mitral valve apparatus resulting in obstruction of the left ventricular outflow tract (LVOT; white arrows). c, continuous wave Doppler technique quantifies a peak systolic gradient of 104 mm Hg across the obstruction during a Valsalva (VALS) maneuver.
HEMODYNAMIC ASSESSMENT

Many studies have demonstrated the limitations of the physical examination for assessment of volume status (55, 56). Others have shown that invasive monitoring with central venous and pulmonary artery catheters, while accurate, sometimes carries significant risk with little or no demonstrable benefit (57). A recent report demonstrated increased inhospital adverse events and no benefit regarding mortality or duration of hospitalization using pulmonary artery catheters to guide therapy in heart failure patients (58). Doppler echocardiography can measure hemodynamic status with greater accuracy than the physical examination and less risk than invasive techniques. In selected patients, Doppler echo techniques effectively can function as an “echo Swan,” estimating cardiac output (59–61); right atrial pressure (62, 63); pulmonary artery systolic, mean, and diastolic pressures (64–66); and LV filling pressure (67–69) (Table 2), (Fig. 4).

ASSESSING PROGNOSIS/ GUIDING THERAPY

Important prognostic information can be obtained from echocardiography in many cardiac disorders. In dilated cardiomyopathy, it had been shown that there is a considerably worsened prognosis when there is RV dilation and/or a reduced RV ejection fraction (70, 71). A potentially useful measurement of RV function is the tricuspid annular plane systolic excursion (descent of the base). In one report, an excursion ≤14 mm added significant prognostic information to the other clinical and echocardiographic findings (72). Mitral inflow patterns can identify restrictive physiology because of advanced grade diastolic dysfunction. Grade 3 diastolic dysfunction describes a restrictive filling pattern that improves with maneuvers to reduce left atrial pressure (Valsalva) and/or heart failure therapy, while grade 4 diastolic dysfunction is characterized by persis-

Table 2. Echocardiographically determined hemodynamic parameters

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Doppler Echo Technique</th>
<th>Doppler Echo Measurement or Formula</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>1. PW Doppler in LVOT for VTI 2. LVOT diameter (d)</td>
<td>CO (=) VTI (\times) ((d/2)^2) (\times) (\pi) (\times) HR</td>
<td>1. Overestimated in AI 2. Measurement errors of LVOT diameter</td>
</tr>
<tr>
<td>PA systolic pressure</td>
<td>Maximum tricuspid regurgitant velocity by CW Doppler</td>
<td>(4 \times \text{velocity}^2 + \text{RAP})</td>
<td>1. Not valid in pulmonic stenosis 2. Requires tricuspid regurgitation 3. Nonparallel alignment of CW jet leads to underestimation</td>
</tr>
<tr>
<td>PA mean pressure</td>
<td>Maximum pulmonary regurgitant velocity by CW Doppler</td>
<td>(4 \times \text{velocity}^2)</td>
<td>1. Requires pulmonic valve regurgitation 2. Nonparallel alignment of CW jet leads to underestimation</td>
</tr>
<tr>
<td>PA diastolic pressure</td>
<td>End diastolic pulmonary regurgitant velocity by CW Doppler</td>
<td>(4 \times \text{velocity}^2 + \text{RAP})</td>
<td>1. Requires pulmonic valve regurgitation 2. Nonparallel alignment of CW jet leads to underestimation</td>
</tr>
<tr>
<td>PCWP</td>
<td>Multiple techniques 1. Ratio of maximum early mitral inflow velocity (E) by PW Doppler to maximum early diastolic mitral annular velocity by tissue Doppler (e’). 2. 1.7–2.0 cm and % collapsibility</td>
<td>(E/e’ &lt; 8 = \text{PCWP} &lt; 15 \text{ mm Hg}) (2. \ E/e’ &gt; 15 = \text{PCWP} &gt; 15 \text{ mm Hg})</td>
<td>(E/e’ 8–15 = \text{PCWP indeterminate})</td>
</tr>
</tbody>
</table>

CO, cardiac output; PW, pulse wave; LVOT, left ventricular outflow tract; VTI, velocity time integral; HR, heart rate; AI, aortic insufficiency; RAP, right atrial pressure; PA, pulmonary artery; Max, maximum; CW, continuous wave; PCWP, pulmonary capillary wedge pressure.
tence of the restrictive filling pattern despite these interventions. The advanced diastolic dysfunction patterns predict a poor prognosis and can be useful in guiding therapy (73, 74).

An analysis of one study was conducted to identify echocardiographic predictors of survival among patients with nonischemic cardiomyopathy and heart failure, and to assess the potential additional prognostic significance of these echocardiographic findings as compared with clinical predictors. Seven of ten routine echocardiographic findings were significantly associated with death. These included mitral regurgitation, LV ejection fraction <20%, LV size, and restrictive filling pattern. The study concluded that these echocardiographic parameters, when added to the clinical examination, significantly improve the ability to determine prognosis among patients with nonischemic cardiomyopathy and heart failure (75).

Therapeutic Guidance

Echo also is useful in guiding therapy, by selecting patients who may benefit from an assist device or surgical intervention for the various complications outlined above. Serial echocardiography assists in the evaluation of efficacy of the therapy. Echo also may provide helpful clues as to whether a patient with heart failure should be anticoagulated, as is indicated when a thrombus is detected.

Harmonic Imaging and Microbubble Contrast

Echo in ICU patients is limited by a number of technical problems, including lung disease, body habitus, subcutaneous emphysema, mechanical ventilation, bandages, chest tubes and other treatment devices, inability to cooperate, and suboptimal positioning. The percentage of ICU studies that lack adequate ultrasound images when performed by trained sonographers using full feature echocardiographic platforms is 26% to 30% (76, 77). Harmonic imaging and echocardiographic contrast agents for chamber opacification are now standard measures that make LV and RV imaging possible in almost all patients.

Harmonic imaging is the default imaging mode on most echocardiographic machines. Echocardiographic transducers emit ultrasound at a specific, "fundamental" frequency. When the beam strikes a cardiac structure, reflected signals are produced at the fundamental frequencies and also multiples of the fundamental frequencies, termed harmonics. By listening for these harmonic frequencies, the ultrasound transducer receives much more information from which to construct echocardiographic images, resulting in improved definition of cardiac structures, especially the blood–endocardial interface (78).

Echocardiographic contrast agents initially were developed for use with harmonic imaging (79). These agents are composed of an inert gas enclosed in lipid spheres, which are smaller than red blood cells. The spheres reflect ultrasound waves much more intensely than blood and tissue. The microbubbles cross the pulmonary circulation, and can therefore be used to opacify the LV, improving endocardial definition. Several studies have demonstrated an important role for contrast echocardiography in the ICU for evaluation of cardiac function (80) and detection of wall motion abnormalities (76) (Fig. 5).

TRANSSESOPHAGEAL ECHOCARDIOGRAPHY

Although transthoracic echocardiography, aided by harmonic imaging and contrast administration, may answer many of the clinical questions that arise in the ICU patient, there are still patients and indications for which transthoracic imaging is inadequate. One study demonstrated that a new diagnosis was established or another excluded by transesophageal echocardiography (TEE) in 45% of patients after cardiac surgery, and that TEE had an impact on management in 73% of cases (81). Dr. Costachescu and colleagues (82) reported the diagnostic superiority of TEE compared with conventional monitoring with pulmonary artery catheters in determining the etiology of hemodynamic instability in the early postoperative period in cardiac surgery patients.

Indications. TEE may be useful in many circumstances, including LV and/or RV failure, tamponade, hypovolemic, and valvular dysfunction (83). In one series, the clinical indications for TEE were: cardiac sources of embolism (36%); endocarditis (14%); prosthetic heart valve function (12%); native valvular disease, aortic dissection or aneurysm, or intracardiac tumor, mass, or thrombus (6% to 8% each); and congenital heart disease (4%) (84). In another study examining the utility of TEE in the ICU, unexplained hypotension accounted for 40% of cases, suspected endocarditis 27%, assessment of ventricular function 15%, pulmonary edema 5%, cardiac source of embolism 4%, and assessment of the aorta and others 5% (85). In this study, TEE revealed the cause of instability in 67% of hypotensive patients, leading to a change in management, including recommending surgery in 22%. Overall, TEE led to a significant change in management in 32% of cases. TEE is a unique diagnostic modality, in that it also can be performed during elective or emergent surgery to assess LV and RV function or adequacy of valve repair/replacement, guide placement of an atrial or ventricular septal patch, and assess the adequacy of defect closure. It is frequently used to assess the etiology of intraoperative hemodynamic instability in noncardiac surgery, and for guiding management during difficulty in separating from cardiopulmonary bypass in cardiac surgery. Emergent bedside procedures in the ICU, such as the institution of extracorporeal membrane oxygenation or percutaneous LV assist device placement, also are aided by TEE.

Infective endocarditis is a common presenting diagnosis or complication in ICU patients. Infective endocarditis has been reported to be the second most common indication for performance of echocardiography in the ICU (85, 86). Certainly, endocarditis and its complications can be an important cause of heart failure, and the consequences of untreated endocarditis can be devastating. Prompt recognition and treatment is of utmost importance. The typical echocardiographic features of infective endocarditis include: a mobile intracardiac mass on a valve or on a catheter, pacing wire, or other device; new valvular regurgitation; intracardiac abscess; or dehiscence of a prosthetic valve (87). Sensitivity for the echocardiographic diagnosis of infective endocarditis has been reported to be 58% to 62% and 88% to 98% for transthoracic and TEE studies, respectively (88). In the ICU, transthoracic sensitivity for infective endocarditis is often poorer, as images are frequently technically limited. TEE is superior to transthoracic echo in diagnosing complications of endocarditis such as abscess, fistula, and chordal rupture of the mitral valve. TEE in the ICU for evaluation of infective endocarditis is indicated in cases where the clinical suspicion is high and a transthoracic study is nondiagnostic,
where prosthetic valve endocarditis or complications of known endocarditis are suspected, and in the setting of *Staphylococcus aureus* bacteremia with an unknown source or persistent bacteremia on antibiotic therapy (83, 89).

Caveats. There are several important limitations that must be kept in mind when employing TEE in the ICU setting. TEE does not provide all of the same views obtainable from transthoracic imaging. It is often difficult to obtain parallel alignment from which to accurately measure Doppler velocities, particularly through the aortic and pulmonic valves. Stenosis of these valves may therefore be underestimated. It may be preferable (and more diagnostic) to assess the pulmonic valve and LV apex using transthoracic echo, since these structures are in the “far field” of the TEE probe. TEE also is limited in the assessment of hemodynamic variables, because patients are frequently sedated for the procedure, leading to alterations in loading conditions.

Guidelines for TEE competence have been published by the American Society of Echocardiography (90). Generally, TEE is safe when performed by an experienced operator (91, 92). Contraindications to TEE examination include: esophageal stricture or malignancy, recent esophageal ulcer or hemorrhage, Zenker’s diverticulum, unevaluated odynophagia or dysphagia, and altered mental status or an uncooperative patient. In the trauma patient, TEE is not used when there is esophageal oro-facial or oropharyngeal trauma, or other disorders that preclude placement of the TEE probe.

EMERGING TECHNOLOGIES

New Doppler echo techniques have been developed to improve cardiac imaging and may become clinically important for heart failure patients admitted to a critical care unit. Real-time 3-dimensional echocardiography (RT3DE) and hand-carried ultrasound (HCU) technology, in particular, hold promise to improve heart failure patient management in the ICU setting.

Real-time 3-Dimensional Echocardiography

*LV Assessment.* Three-dimensional echocardiography traditionally has been hampered by the requirements for tedious reconstruction of multiple 2-D images. The development of new matrix array transducers allows collection of full volume data sets from a single view (Fig. 6). RT3DE has multiple clinical applications for the heart failure patient, including several studies that have demonstrated increased precision and lower inter- and intraobserver variability in the measurement of LV volumes and LV ejection fraction compared with 2-D echocardiography (93, 94, 95).

The concurrent imaging of all ventricular walls may help improve and automate the detection of wall motion abnormalities. Traditional techniques rely on subjective assessment of wall motion and thickening, but tracking of segmental motion from 3-D data sets allows for generation of regional displacement curves that may result in less variability than conventional wall motion analysis. Dr.
Corsi and colleagues (96) recently have shown the feasibility of an automated 3-D endocardial border detection method that further improves reproducibility of wall motion assessment and volume and ejection fraction calculations.

**Mitrail Valve Assessment.** RT3DE also improves mitral valve assessment. Traditional 2-D evaluation has significant limitations because the mitral valve annulus is saddle-shaped and cannot be fully imaged in a single 2-D plane (97). As a result, mitral regurgitant jets often are inadequately characterized by 2-D imaging, especially when eccentric. The current Doppler and color Doppler methods for calculating regurgitant severity involve geometric assumptions that produce substantial errors in noncentral jets (98,99). Misclassification of mitral regurgitation severity can lead to significant missteps in clinical management, and a deleterious outcome for patients, particularly those in an ICU setting.

Three-dimensional echocardiography can improve the assessment of annular morphology and may prove especially beneficial in facilitating anatomical definition of leaflet prolapse and flail leaflet segments (100,101). RT3DE data sets can be manipulated to show mitral anatomy from an atrial or ventricular perspective, potentially improving preoperative planning, and identify important structural characteristics for cardiac surgeons (102, 103). Semiautomated techniques for the measurement of mitral valve leaflet tenting and annular size may one day predict whether patients will benefit from mitral valve replacement or repair, ventricular reconstruction strategies, or medical therapy alone (104). Three-dimensional imaging of the mitral regurgitant jet may allow more accurate quantification of regurgitation severity (105). RT3DE planimetry of the mitral valve area also may be superior to invasive methods for assessing the severity of mitral stenosis (105,106).

**Limitations.** There are significant limitations to transthoracic RT3DE. The obtainable frame rate, and therefore image quality, is significantly reduced compared with conventional 2-D echocardiography, and tachycardic patients may therefore have reduced image quality. Patients with poor acoustic windows on 2-D imaging are likely to have even poorer 3-D images. Current generation 3-D systems require the integration of several cardiac cycles to produce a full-volume rendering; therefore, arrhythmias and respiratory or translational motion can introduce significant artifacts. The 3-D transducer is considerably larger than conventional 2-D transducers and does not always fit well into intercostal spaces or between tubes and dressings, thereby limiting its applicability for many ICU patients. Further developments in transthoracic RT3DE, including contrast-enhanced RT3DE (107,108) as well as real-time 3-D TEE (109,110), hold significant promise to overcome these difficulties. There will remain, however, an important learning curve for both the sonographer performing RT3DE studies and the physician who interprets them.

**Hand-Carried Ultrasonography**

The recent development of high quality miniaturized echocardiographic platforms has created new ways to apply echocardiography to the detection and management of heart failure in the ICU.

**Applications.** The findings from several studies (111–113) suggest that application of HCU in the ICU setting should be specifically targeted. Attempts to perform full echocardiographic examinations can lead to unacceptable rates of false negatives, especially when assessing valvular function. RV and LV function and effusions can be adequately imaged with HCU in limited, screening examinations. Full feature echocardiography is preferable, when available, but during periods when echo availability might be limited, HCU can extend the ability of the physical examination to define cardiac status and guide important decisions. Furthermore, the repeated use of full-feature echocardiography to track clinical status may not be feasible or cost-effective. HCU has the potential to provide frequent, serial, and rapid noninvasive measures of the response to interventions.

**HCU Operators.** Who performs the targeted HCU exam is of paramount importance. Studies have tested use by operators at many different levels of training—from medical students to attending cardiologists—and parameters from full echocardiographic examinations to limited estimation of right atrial pressure from collapse of the inferior vena cava. While the official recommendations from the American Society of Echocardiography recognize the potential of miniaturized technology to provide adequate image quality to constitute a full examination (if performed and interpreted by appropriately trained imagers [level 2 echocardiographic training = 150 examinations and 300 interpretations]) (114), many experts regard the
The greatest utility of HCU in terms of extension of the physical examination or measurement of specific parameters (115). In other words, HCU does not replace a full echocardiogram, particularly in a complex ICU patient.

The use of sonographers and echocardiographers for frequent, repeated measures of cardiac status in the ICU during off-hour times is not feasible or cost-effective. Intensivists and other physicians have demonstrated acceptable accuracy in the ICU setting, but one study, performed in an outpatient setting, demonstrated acceptable sensitivity for nurses in screening patients for occult LV systolic dysfunction with an HCU device (116). Training in image acquisition and interpretation is a necessity. A carefully performed study that examined a spectrum of training concluded that adequate skill could be obtained following 20 – 40 practice examinations with one-on-one instruction (117).

Limitations. The reduced image quality of HCU devices, especially when operated by nonsonographers, exacerbates the above-mentioned difficulties in obtaining adequate transthoracic images in ICU patients (118). Furthermore, many of the HCU devices lack many important modalities available on standard platforms, including phased array transducers, full color Doppler (instead of power color Doppler), harmonic imaging, pulsed and continuous wave Doppler, M-mode, and the ability to export images in a universally-readable format for off-line analysis. The latest generation devices include most of these features, albeit at considerably increased cost.

Other Emerging Echocardiographic Techniques

Several other novel echo techniques may prove to be useful for heart failure patients in the ICU setting. Intracardiac echocardiography currently is used to guide a variety of percutaneous procedures, from pulmonary vein ablations to mitral valvuloplasties (119). In the ICU setting, intracardiac echocardiography may prove particularly useful for patients in whom TEE is precluded, such as postesophagectomy patients with atrial fibrillation in need of cardioversion. An ongoing study is comparing the accuracy of intracardiac echocardiography to that of TEE for the detection of left atrial appendage thrombi (120).

Recent developments in tissue Doppler imaging and tissue tracking enable the measurement of longitudinal, circumferential, and torsional cardiac mechanics. Tissue Doppler imaging measures the velocity of myocardial motion but is limited by its dependence on a Doppler signal parallel to the direction of myocardial motion. Tissue tracking methods, such as speckle tracking techniques, identify unique speckles within the myocardium and track their motion in three dimensions throughout the cardiac cycle. These techniques are sensitive markers for abnormal wall motion, and can assess the degree of ventricular dysynchrony. These applications may prove particularly useful in the heart failure population, because up to one third of patients fail to respond to biventricular pacing, and many patients demonstrate dysynchrony by echocardiographic criteria but lack a widened QRS complex—a crucial component of the current indications for biventricular pacemaker placement (121). Heart failure patients in the ICU may benefit from echocardiographically guided optimization of pacemaker timing intervals to improve ventricular diastolic filling and cardiac output (122).

CONCLUSION

The use of echocardiography in the ICU setting provides important diagnostic and prognostic information to guide therapy for the heart failure patient. Echo is safe, accurate, portable, and widely available, and continues to have significant advantages over CT and MRI studies for ICU patients. Limitations in image quality in the ICU setting have been largely overcome by the use of harmonic imaging, contrast opacification, and when indicated, transesophageal echocardiography. Newer echo techniques promise to advance the scope and prognostic power of echocardiography, and to expand the portability and availability of this “single most useful” test.

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