REVIEW

Assessment of right ventricular function and its role in clinical practice

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Far more has been published on left ventricular function than on right ventricular function in both congenital and acquired heart disease. Lately, however, more attention has been directed towards right ventricular performance and the problem of right ventricular dysfunction and the imbalance is now being redressed. This is in part related to improved investigative techniques, but it is also coupled to heightened awareness of the functional relevance of the right ventricle in maintaining the circulation. For example it has now been shown that there is significant impairment of right ventricular performance, with pathophysiological consequences for the circulation, in a range of conditions including acute¹⁻³ and chronic⁴⁻⁶ coronary arterial disease, valvar heart disease,⁶ and septicaemic shock.^{7,8} In addition, right ventricular dysfunction influences survival in patients with acute⁹ and chronic¹⁰ left ventricular injury and in patients with congenital heart disease both before and after surgical intervention.¹¹⁻¹³

Why has right ventricular function been ignored until recently?

The right ventricle has been neglected for many reasons, but the chief one is the difficulty of accurately assessing right ventricular size and function, primarily because of its complex shape. Modern imaging techniques, however, have now largely overcome this problem. An important contributory factor though has been the widely held view that the right ventricle is almost unnecessary to the circulation and that attention should be focused on the more important left ventricle. Early experimental studies¹⁴⁻¹⁶ that showed that extensive damage to the right ventricular free wall caused little haemodynamic upset led to the conclusion that the right ventricle was essentially a passive conduit between the systemic veins and the pulmonary artery. Further support for this idea came from the prolonged survival of patients with little or no right ventricular functional contribution (for example, patients with pulmonary pulmonary atresia and intact interventricular septum or tricuspid atresia) and from the success of surgical procedures, such as the Fontan operation, that exclude the right ventricle from the circulation.¹⁷ Later, more sophisticated animal experiments suggested that this concept was incorrect. When the right ven-

tricular free wall, either alone¹⁸ or in combination with the interventricular septum,¹⁹ was replaced by non-contractile material the degree of haemodynamic upset was great, and most animals died within hours of operation.

Evaluation of right ventricular size and function

Three aspects of right ventricular anatomy make it difficult to assess function: (a) Left ventricular volume can be calculated by simple mathematics and a single plane angiogram but the more complex shape of the right ventricle demands orthogonal biplane pictures and computer analysis of the data; (b) heavy trabeculation of the right ventricular free wall complicates edge recognition; (c) with some imaging techniques an overlap between the right ventricle and other cardiac chambers makes it difficult to measure volume reliably.

Contrast ventriculography, echocardiography, and radionuclide ventriculography have largely overcome these problems and all have been used to analyse right ventricular volume and function. More recently, use of rapid computed tomography and gated magnetic resonance imaging has improved image resolution.

CONTRAST VENTRICULOGRAPHY

Contrast ventriculography was the first method used to visualise the right ventricular chamber and it remains the reference standard for volumetric or function measurements.

Reedy and Chapman were the first to attempt right ventricular volume measurement from biplane angiograms;²⁰ they adopted the novel approach of measuring the combined volume of right and left ventricles from simultaneous right and left ventriculograms by using a multiple slice technique and then subtracting the volume of the left ventricle and septum to estimate the volume of the right ventricle. Because of the practical difficulties inherent in simultaneous right and left ventriculography this method was never widely used to measure human right ventricular volume. However, the general principle put forward by Reedy and Chapman of using multiple slices to measure the volume of complex shapes has been adopted as the best method for measurement of right ventricular volume. Multiple slice methods rely on dividing the ventricle into a series of equal parallel

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slices of known thickness. The cross sectional shape of each slice is assumed to be an ellipsoid or rectangle, the lengths of the major and minor axes of which are derived from simultaneous orthogonal angiograms. By the application of Simpson's rule the total volume can be derived from the sum of the volumes of each slice.²¹ One error inherent in this method is that the cross sectional shape of the normal right ventricle may no longer be ellipsoidal if haemodynamics function is abnormal.²² Another potential source of error relates to the number of slices into which the ventricle is divided. Methods that use a fixed slice depth of say 0.5 cm may divide the right ventricle into as few as four or five slices when it is small, and there is some evidence that about 40 slices are required for accurate volume assessment.²³ In addition, any multiple slice method is laborious and time consuming even with computerised analysis. Because of this much effort has gone into attempts to produce an accurate but simpler method to measure right ventricular volume. Most of these methods assume the right ventricle to be a simple geometric shape—for example, a triangular based prism,²⁴ or a triangular based pyramid²⁵—or use a two-chamber technique²⁶ that divides the right ventricle into the body (the volume of which is derived from one of the geometric models above) and outflow tract (which is assumed to have the volume of a cylinder). These techniques are simpler to apply and almost as accurate as applying Simpson's rule in the estimation of the volume of normal right ventricular casts from humans and animals, but they are less reliable when the shape of the right ventricle is abnormal.²⁴

With either technique right ventricular volume can now be measured from biplane angiograms as accurately as left ventricular volume and angiographic right ventricular volume and ejection fraction measurements have now been used to assess right ventricular function in a wide range of congenital and acquired heart disease.

ECHOCARDIOGRAPHY

The complex shape of the right ventricle makes assessment of its function difficult whichever method is used but in addition the position of the normal right ventricle directly beneath the sternum poses specific problems for echocardiography. These problems are compounded by chronic lung disease and previous thoracic surgery, which are common in patients in whom right ventricular function studies are often crucial. Despite these limitations, right ventricular size and function are increasingly estimated by M mode and cross sectional echocardiography.

The earliest attempts to evaluate right ventricular function by M mode echocardiography^{27,28} were limited by the difficulty in delineating the endocardial surfaces and dependence on the correct orientation of the ultrasound beam across the cavity. Cross sectional echocardiography overcame some of the problems of beam orientation²⁹ by using ana-

tomical landmarks to standardise the orientation of the ultrasound beam within the right ventricular cavity. This approach gives acceptable measurements of right ventricular volume and function.

RADIONUCLIDE VENTRICULOGRAPHY

Right ventricular function has been assessed by first pass and equilibrium techniques. The first pass technique has the advantage of rapid data acquisition but assumes homogeneous mixing of the tracer—an assumption that is perhaps optimistic.³⁰ Even if complete mixing of the tracer is assumed, there are other potential problems, particularly separation of the right ventricular image from that of the right atrium, pulmonary arteries, and left ventricle. Sophisticated programs for boundary definition and for background subtraction in more modern equipment have gone some way to minimise this error but it can never be eliminated.³¹

Equilibrium studies use counts recorded during successive beats over 10–15 minutes and are analysed by electrocardiographic gating. The cardiac cycle is divided into a series of 50 ms frames, and frames can be displayed sequentially to measure ejection fraction or to produce a moving image of an “average” cycle in order to examine wall motion. The problems associated with gated blood pool imaging are those common to all radionuclide techniques—that is, border recognition, chamber overlap, etc—but these are even more pronounced in equilibrium studies because radioactivity is emitted from all structures containing blood. It is therefore important to select views of the right ventricle to optimise the separation from surrounding structures.

The importance of the above factors is illustrated by the wide variation in reports of right ventricular ejection fraction measured by different radionuclide techniques; the mean (SD) “normal” right ventricular ejection fraction varies between 23 (12)%³² and 60 (7)%.³³

CONCEPTS OF RIGHT VENTRICULAR FUNCTION ASSESSMENT

Right ventricular systolic and diastolic function can be assessed with some validity by various imaging techniques and calculation methods. As a result function—expressed as a simple index such as ejection fraction—can be easily assessed. The evaluation of right ventricular performance, however, demands an understanding of the interplay between the right ventricle and the rest of the circulation. Like the left ventricle, the function of the right ventricle is modified by the contractile state of the myocardium (contractility); preload; afterload; and to some extent the more minor effects of intrapericardial pressure, left ventricular contractile performance, and the contribution to right ventricular work of the septum. Any analysis of right ventricular performance must therefore take into account this relation between intrinsic and extrinsic factors. Variables such as ejection fraction may not be sufficiently sensitive to evaluate “intrinsic” right ventricular contractile performance even although it seems to change appropriately in disease

states such as acute inferior infarction,³⁴ obstructive airways disease,³⁵ and left-sided heart lesions.³⁶ Certainly the right ventricular ejection fraction is sensitive not only to changes in contractility but also to changes in preload and afterload. It is therefore tempting to study other indices of right ventricular function such as end diastolic and end systolic volume and right ventricular pressure volume relations. Though individual absolute volume measurements are known to be less accurate than estimates of ejection fraction, in many cases they may give a better indication of right ventricular function. For example, right ventricular end systolic volume is dependent mainly on afterload and contractility but not on preload; and in circumstances such as right ventricular volume overload the end systolic volume may be a more useful indicator of contractile state than the ejection fraction.

Construction of right ventricular pressure volume loops may also permit better evaluation of right ventricular function. The study of phase relations between pressure and volume have greatly increased knowledge of left ventricular function, enabling evaluation of (a) phase relations of pressure and volume in the normal and diseased ventricle,³⁷ (b) the energetics of contraction,³⁸ (c) the cycle efficiency of ventricular function,³⁹ and (d) the establishment of an end systolic pressure volume relation⁴⁰ that, although controversial, is commonly used as a load independent measure of contractility. In view of the possible physiological and diagnostic information that can be derived from pressure volume relations, it is suprising how little attention has been paid to the human right ventricular pressure volume relation. In 1984 Friedman *et al* used an equilibrium radionuclide method for right ventricular volume measurements with "simultaneous micromanometer pressure measurements".⁴¹ Unfortunately there were several major weaknesses in this study, particularly in relation to the accurate timing of events. In 1988 Redington *et al* studied and described the normal right ventricular pressure volume relations by recording biplane right angiograms and simultaneous high fidelity pressure recordings⁴² and subsequently reported the changes in this relation that were associated with pressure and volume overload.⁴³ The construction of such loops is of great potential clinical significance because they provide an insight into right ventricular function when used in the detailed assessment of patients with right heart disease.

Clinical importance of the assessment of right ventricular function

It is clear that an accurate measure of right ventricular function is vital in the management of patients with a wide variety of clinical problems, both to plan treatment and to predict prognosis.

The development of right ventricular dysfunction with myocardial infarction is now recognised as a common occurrence. With anterior myocardial infarction there is usually persistent left ventricular regional impairment

and transient global right ventricular impairment, whereas in inferior infarction there is often persistent regional impairment of both the right and left ventricles.¹ The haemodynamic response of the two ventricles to infarction differs, and in patients with extensive right ventricular infarction the development of cardiogenic shock is not uncommon^{44,45} and requires a different therapeutic approach.^{44,46} The degree of right ventricular dysfunction can also be used to assess prognosis. Polak *et al* studied patients with a reduced left ventricular ejection fraction and clinically evident heart failure secondary to coronary artery disease.¹⁰ Those patients surviving two years into the study had a higher right ventricular ejection fraction and less extensive left ventricular dyskinesis. Two year mortality was significantly higher in patients with a lower right ventricular ejection fraction (< 35%) and right ventricular ejection fraction was the single most useful indicator of patient outcome overall.

Right ventricular function is also important in predicting the outcome in patients with ventricular septal defects after myocardial infarction. In a small study of patients with acute ventricular septal defect requiring intra-aortic balloon pumping and open heart surgery Grose *et al* described right ventricular dysfunction as the major cause of death in 25% of cases and a major contributory factor in a further 37% of cases.⁶ In a larger study Radford *et al* followed the course of 41 patients with post-infarction ventricular septal defect.⁴⁷ Cardiogenic shock developed in 55% of their patients and this was unrelated to the site of infarction, the extent of coronary artery disease, the left ventricular ejection fraction, or the pulmonary systemic flow ratio. The mean pulmonary artery pressure, however, was lower in the patients with shock than those without, suggesting that right ventricular impairment was a contributory factor to shock. Survival was better in those patients without shock and with essentially normal right ventricular function, but was not related to the extent of coronary artery disease, left ventricular function, or the size of the left to right shunt.

Right ventricular dysfunction is also common in other shock-like states including septicæmic shock^{7,8} and post-cardiotomy shock,⁹ probably as a result of alterations in right ventricular afterload and contractility.⁸ This is clinically important because interventions that lower right ventricular afterload or increase right ventricular contractility will be more therapeutically appropriate. Patients requiring left ventricular assist devices because of the post-cardiotomy syndrome commonly have biventricular dysfunction and would therefore benefit from biventricular mechanical support.⁹

Assessment of right ventricular function is important in congenital heart disease. Right ventricular dysfunction can be an important predictor of long term outcome as Fuster *et al* showed in a large surgical series of patients with tetralogy of Fallot.¹¹ More recently Redington *et al* studied patients before and after such repair and showed that pressure-volume loops

are a useful indicator of right ventricular dysfunction and pulmonary regurgitation postoperatively. They also analysed right ventricular function by this technique in transposition of the great arteries after an atrial re-routing operation and after anatomical correction by the arterial switch.¹³ This comparative study gave only preliminary observations and conclusions; longer term comparisons of studies of right ventricular function are needed.

The future

At present right ventricular volume and function can both be accurately assessed and more sophisticated and detailed analysis of such function can be obtained from the construction of pressure-volume loops. The use of such techniques in the future should be able to resolve many of the obvious and complex clinical questions about right ventricular dysfunction.

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