

# **Cardiac Testing in Adolescents**

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Diagnostic testing in adolescents and young adults with known or suspected heart disease typically involves the use of electrocardiography, various imaging modalities, and, in some cases, other laboratory investigations. In this chapter the authors discuss common tests that may be ordered by the generalist or cardiologist to evaluate the heart. The emphasis is on indications for ordering a specific test, understanding the strengths and weaknesses of those tests, and basic interpretation of the results. Heart disease in adolescents primarily includes previously diagnosed congenital lesions, undiagnosed defects such as atrial septal defect (ASD) or aortic valve abnormalities that are often asymptomatic in childhood, inherited latent conditions that may first become manifest during the teen years, such as hypertrophic cardiomyopathy (HCM), and acquired disease such as myocarditis. Signs and symptoms of possible heart disease, when present, may include a pathological murmur or heart sound(s), chest pain and shortness of breath, especially when associated with exercise, palpitations or syncope, or signs of heart failure such as a gallop, increased jugular venous distension, hepatomegaly, rales, and peripheral edema. Often, a careful family history may yield important clues to the possibility of inherited cardiac disease. An electrocardiogram is often ordered by the generalist or specialist to evaluate symptoms of possible heart disease or to monitor potential side effects of medications. Most imaging studies, including echocardiography, cardiac MRI and CT, as well as cardiac catheterizations are ordered or performed by the cardiologist to diagnose specific defects or conditions, and catheterizations are increasingly done primarily for intervention purposes.

## **1. ELECTROCARDIOGRAPHY**

The electrocardiogram (ECG) remains an invaluable noninvasive tool to assess the electrical activity of the heart in order to evaluate adolescents with known or suspected cardiovascular disease and may be appropriately ordered by the generalist as part of the investigation of symptoms or monitoring of therapy. The standard 12-lead ECG helps to identify abnormalities of impulse formation (sinus bradycardia, isolated premature atrial, junctional, or ventricular beats, or atrial, junctional, or ventricular arrhythmias) or impulse propagation, such as slowed conduction through the AV node (AV block) and His-Purkinje system (high degree AV block or bundle branch blocks). It can identify those individuals with a short PR interval and delta wave indicating ventricular preexcitation (Wolff-Parkinson-White syndrome). Repolarization syndromes involving abnormal myocardial cell membrane ion channels (long QT syndrome and Brugada syndrome) can also be diagnosed on the standard ECG. Additionally, abnormalities of the ECG associated with myocardial hypertrophy (hypertrophic cardiomyopathy), inflammation (myocarditis or pericarditis), myocardial ischemia (anomalous coronary arteries or premature coronary artery disease) or injury (myocardial infarction) can be detected. Serial ECGs are also commonly used to monitor potential cardiac effects of certain psychotropic medications.

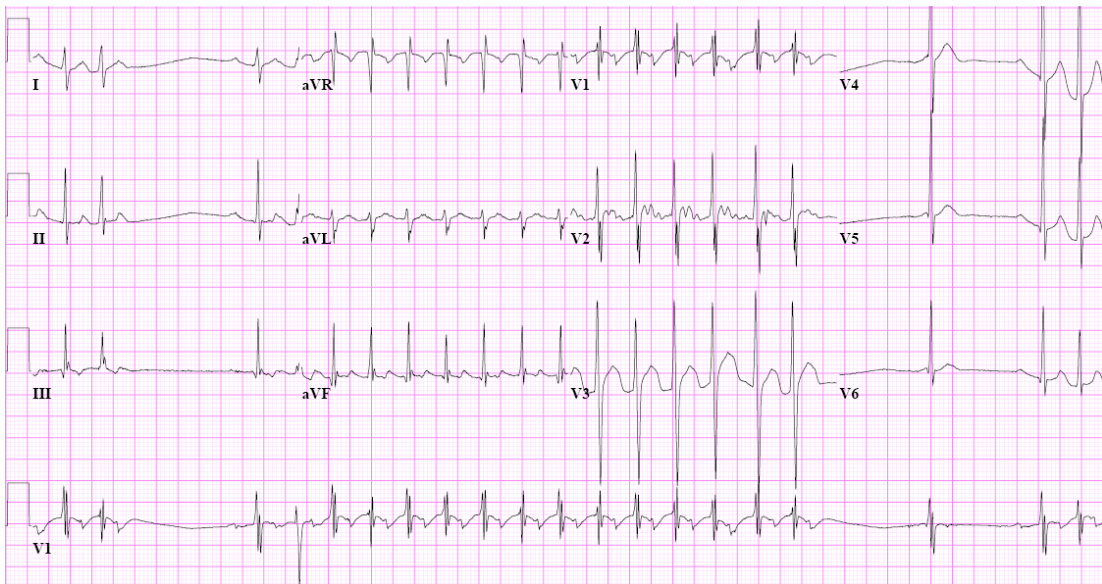
Guidelines for the performance of electrocardiograms were published by the American College of Cardiology and American Heart Association (ACC/AHA) in 1992<sup>1</sup> and have not changed in recent years. These guidelines make recommendations for the use of ECGs in patients with and without cardiovascular disease, which for the most part are applicable to the adolescent population.<sup>2</sup>

Electrocardiography is a quick, inexpensive, and widely-available test that can be administered accurately in a variety of clinical settings with a minimum of training. In addition, detailed automated computer interpretation algorithms can assist in interpretation, though must always be carefully confirmed for accuracy by an experienced reader. Data can be stored digitally and transmitted electronically or by fax for rapid expert interpretation. Artifacts include those due to movement or faulty connections, although many errors in connection can be easily detected (e.g., by checking for consistency between lead I versus V6 pattern). The ECG is less helpful for diagnosing specific structural abnormalities and has a high false positive rate for detecting left ventricular hypertrophy, particularly in athletes or those with thin body habitus.

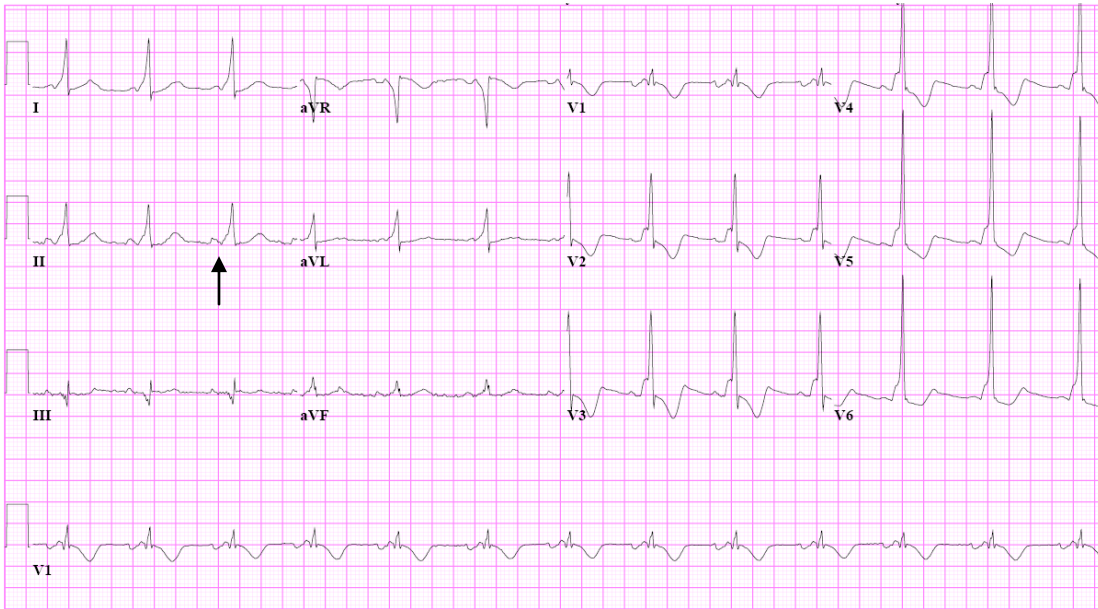
### Interpretation of abnormal heart rate and rhythm

Sinus tachycardia, characterized by heart rate greater than the 98%tile for age (usually >120 but less than ~200 beats per minute with P waves of normal axis (0-90 degrees) preceding each QRS complex, is by far the most common tachyarrhythmia and is often due to an underlying hypersympathetic state such as fever, pain, anxiety, anemia, dehydration, substance abuse or withdrawal, or hyperthyroidism. Other forms of narrow complex tachycardia represent primary cardiac disorders of either increased automaticity or reentry pathways. When the atrial activity (P wave) occurs shortly *after* the QRS complex, an atrio-ventricular bypass tract is the most likely mechanism (Fig 1). The baseline (non tachycardic) ECG in patients with Wolff-Parkinson-White syndrome (WPW) has the typical short PR interval with an upstroke (delta wave) from the end of the P wave to the beginning of the QRS (Fig 2). When a regular, narrow complex tachycardia is present with no visible P waves, simultaneous depolarization of the atria and ventricles with the P wave “hidden” in the QRS complex is more likely, indicating an AV nodal re-entry tachycardia. When P waves are prior to the QRS but have an abnormal axis (i.e., other than 0-90 degrees), automatic or ectopic atrial tachycardia is more likely. When the 12-lead ECG demonstrates a wide complex tachycardia (QRS duration > 120 msec), the differential diagnosis includes ventricular tachycardia, supraventricular tachycardia with aberrant conduction between the atria and ventricles, or a fixed bundle branch block.

**Figure 1.** ECG of a 13 year old boy showing supraventricular tachycardia alternating with bradycardia.

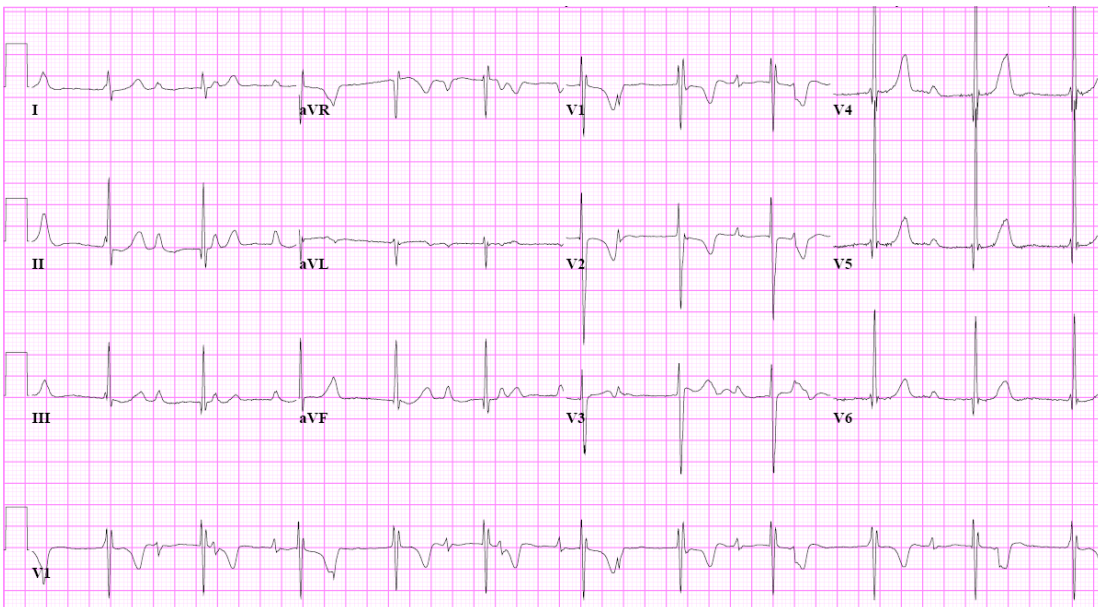


**Figure 2.** ECG of 20 year old female with WPW. Note the short PR interval and the upstroke (delta wave) from the end of the P wave to the beginning of the QRS complex (arrow).



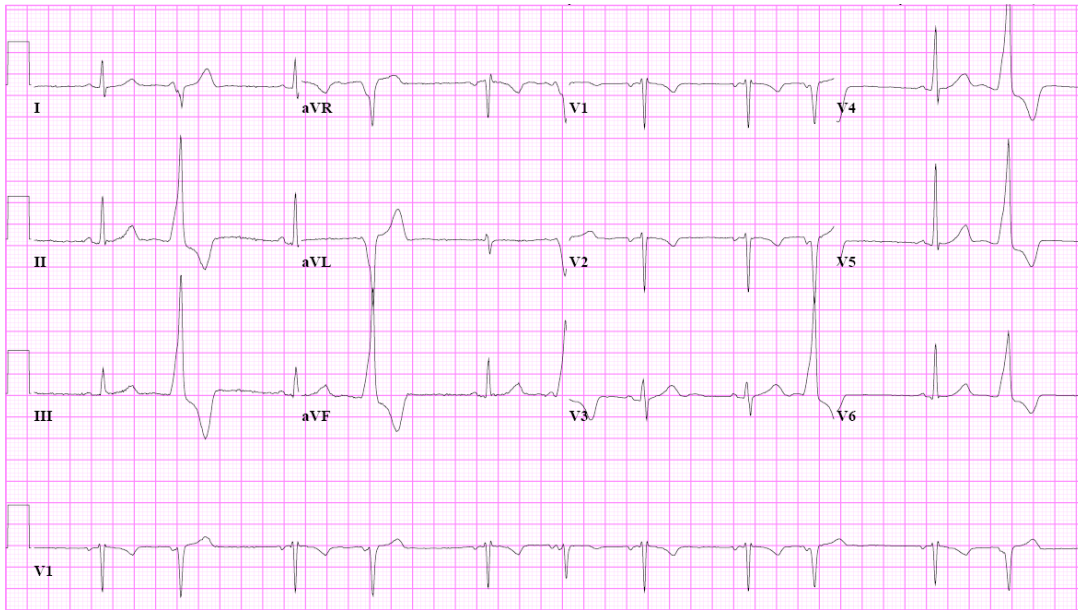
Bradycardia in the adolescent is encountered in competitive athletes or individuals with eating disorders (Anorexia Nervosa) and most commonly manifested on ECG as sinus bradycardia (defined as sinus rhythm with a heart rate <2%tile for age, usually < 60 beats per minute). Other causes of sinus bradycardia include hypoxia, hypothyroidism, hypothermia, hypercalcemia, hyperkalemia, hypoglycemia, and increased intracranial pressure. In addition, bradycardia may be seen in congenital long QT syndrome. In patients with complete heart block (CHB), the ventricular rate is slower and dissociated from the atrial rate (Fig 3). CHB occurs congenitally in infants born to mothers with lupus or may be acquired following certain infections (e.g., Lyme disease).

**Figure 3.** ECG of 18 year old female with complete heart block. The P waves regularly march out at a higher rate than the QRS complexes.



Adolescents evaluated for palpitations or syncope should have an ECG performed as a simple, inexpensive, and non-invasive diagnostic tool. Ideally a 12-lead ECG should be recorded during an episode of symptoms, though this is often not feasible. Roughly, up to 50% of patients evaluated for syncope will have an abnormal but non-diagnostic ECG.<sup>3</sup> The presence of ventricular pre-excitation, ectopic atrial or ventricular beats, ventricular hypertrophy, long QT interval, bradycardia, or sustained tachycardia suggest a plausible cause of syncope. Premature ventricular beats (PVCs) (Fig 4) are common findings and usually do not require further investigation. If they occur with increased frequency a Holter monitor aids in quantification, and an echocardiogram is useful to exclude ventricular dysfunction.

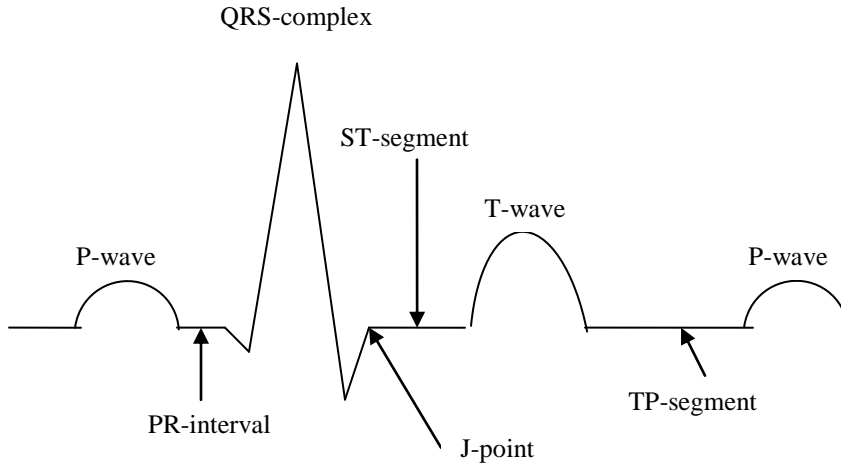
**Figure 4.** ECG in a 14-year old adolescent demonstrating frequent PVCs.



### **Evaluation of chest pain**

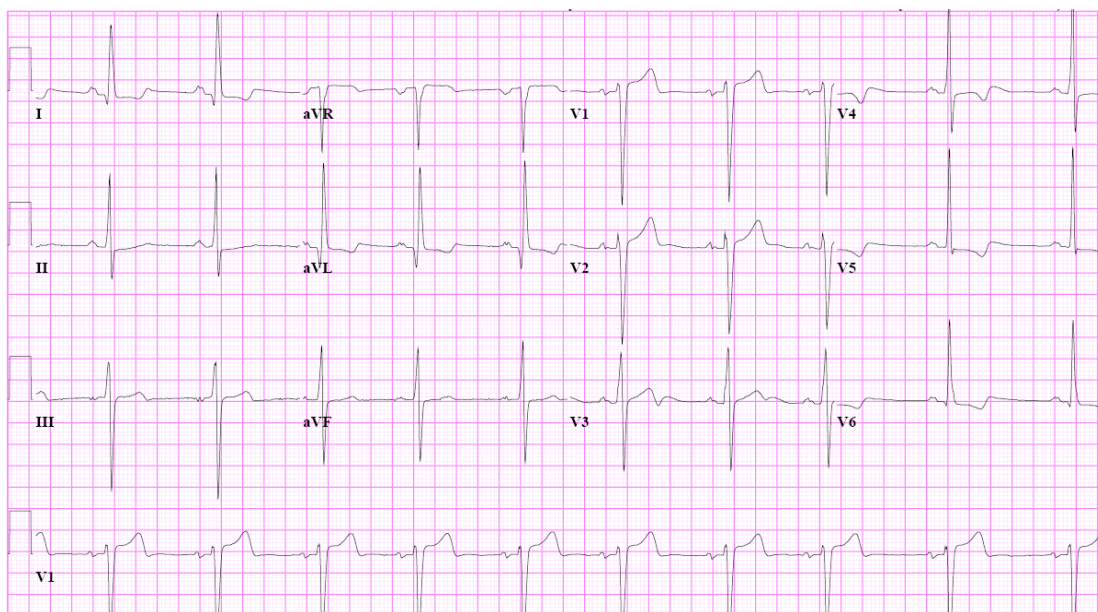
An ECG is indicated as part of the initial evaluation of adolescents with non reproducible, exertional chest pain. Although chest pain is often of great concern to the patient and family, the majority of adolescents with this symptom do not have a cardiac etiology. ECG changes that warrant further investigation, such as ST segment deviation, T wave changes, ventricular hypertrophy, or conduction abnormalities are easily detected. In patients evaluated for chest pain, deviations of the ST segment from baseline may indicate myocardial ischemia, injury, other pathological processes, or represent a normal variant. Comparison to an old ECG is often helpful, however not always available. The ST segment is identified as the portion between the end of the QRS complex (ventricular depolarization) and beginning of T wave (repolarization). The normal ST segment is usually isoelectric relative to the TP segment. The end of the QRS complex is marked by the junction to the ST segment (J point) (Fig 5).

**Fig 5.** Normal ECG

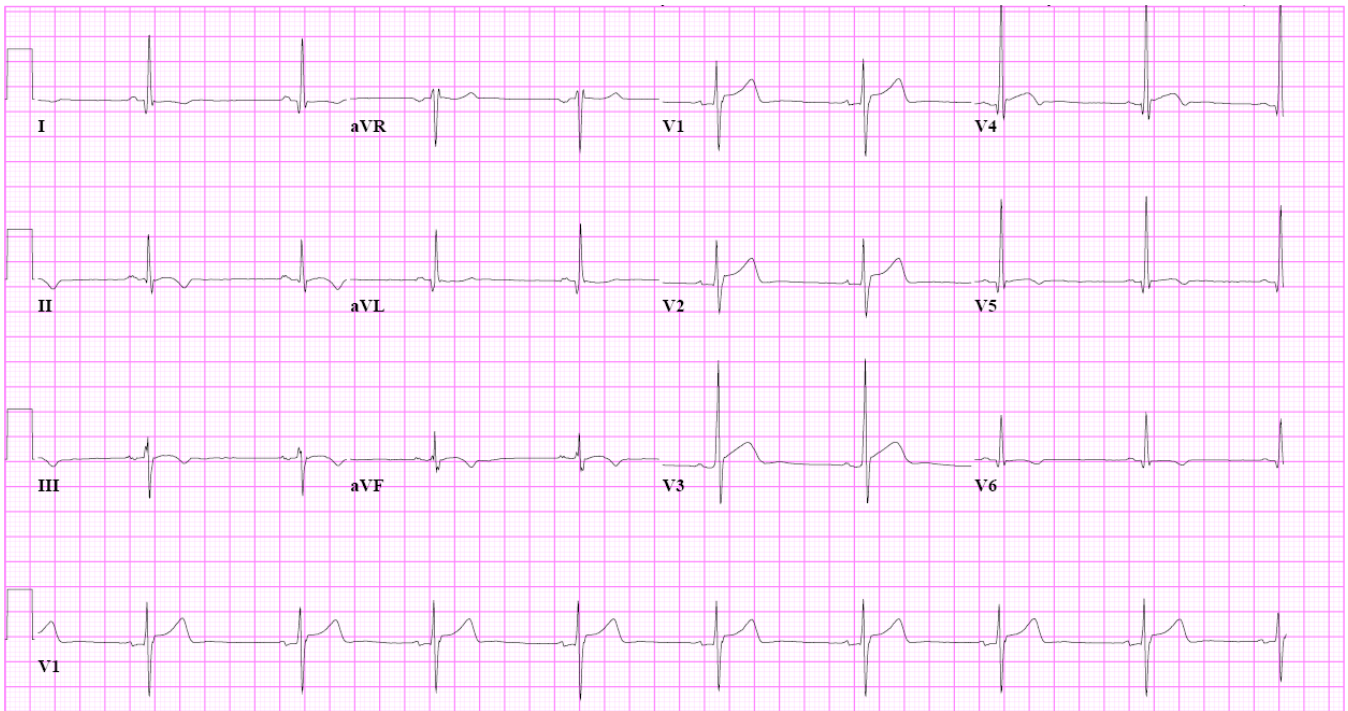


Variations occur in the ST pattern. It is important to recognize them because they can be mistaken for abnormalities. ST-T patterns can be affected by changes in autonomic tone, variations in body position, hyperventilation, drinking cold water, and performing Valsalva maneuvers. ST segment elevation in adolescents may represent benign “early repolarization”, or be seen in pericarditis, acute myocardial infarction (e.g., in the setting of cocaine use), commotio cordis, left ventricular hypertrophy, left bundle branch block, hyperkalemia, and critical illness (including neurologic conditions such as subarachnoid hemorrhage). Up to 90% of patients with hypertrophic cardiomyopathy (HCM) have some abnormality of the resting ECG,<sup>4</sup> often either ST segment abnormalities or T wave changes (Fig 6). Whereas infarction and ischemia are uncommon in adolescents the term “early repolarization” is applied when it is associated with ST elevation, most easily appreciated in the anterior and mid-precordial leads (V2-V4) (Fig 7). The term is a misnomer (as repolarization normally begins before depolarization ends), the associated elevation of the ST segment may be due to the normal age-dependent changes of ST segment potentials. It can especially mimic changes seen in pericarditis. J point elevation due to early repolarization often disappears with exercise. Table 1 summarizes common ECG features in myocardial ischemia or injury, pericarditis, and early repolarization.

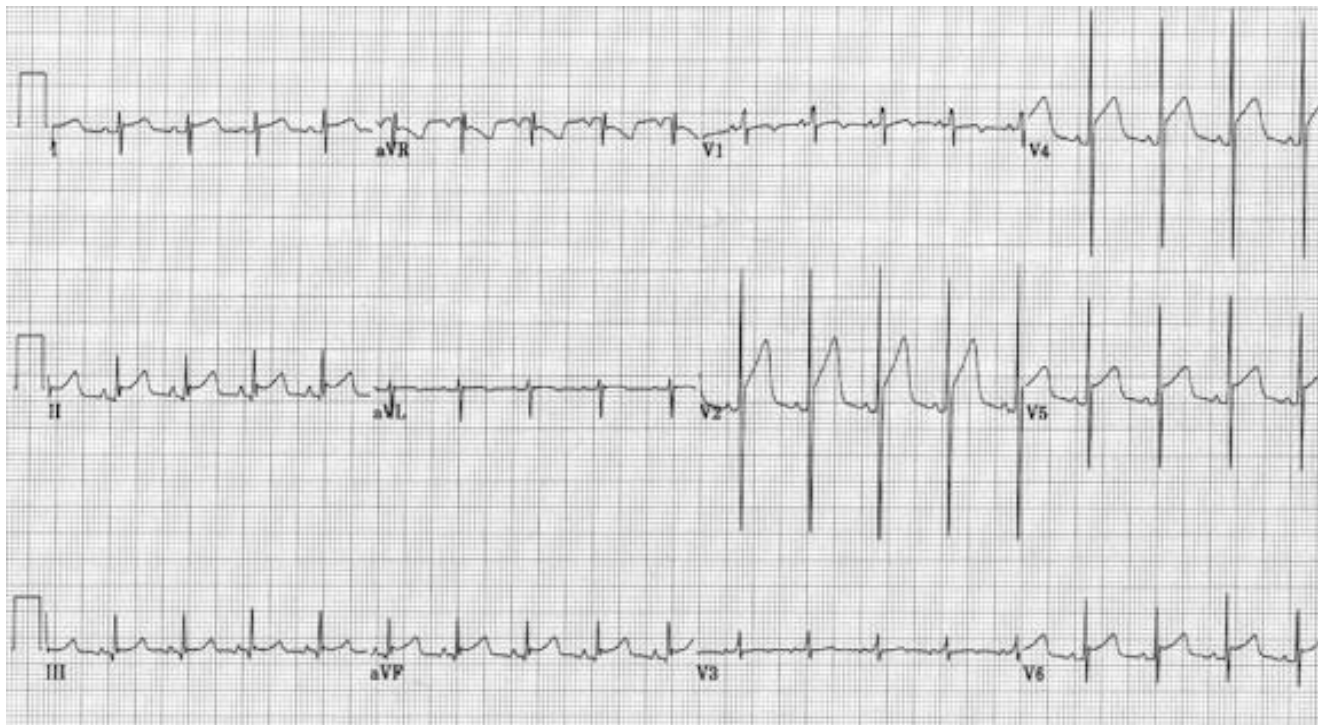
**Figure 6.** ECG in a 19 year old male with hypertrophic cardiomyopathy demonstrating changes consistent with left ventricular hypertrophy.



**Figure 7.** ECG in a 15 year old boy with chest pain demonstrating changes consistent with early repolarization. J-point elevation is appreciated in leads V1-V4

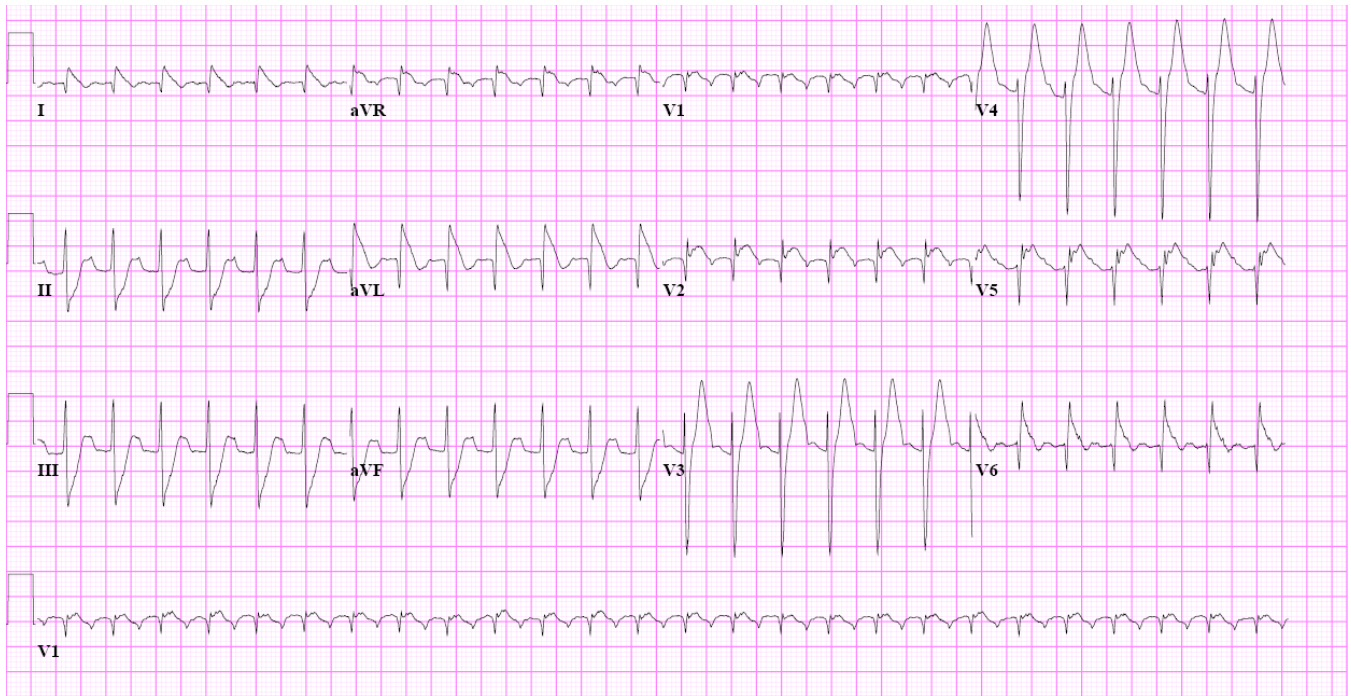


Pericarditis is the most common cause of ST segment elevation in children other than early repolarization (Fig 8).<sup>5</sup> Initially, the ST segment is elevated with a normal T wave, followed by normalization of the ST segment and T wave inversion. PR segment depression may also be seen. Usually findings differ from ischemic changes because they involve all leads.<sup>6</sup> Myocarditis can result in ST segment deviation or conduction abnormalities but most commonly presents with flattened or inverted T waves and low voltage QRS patterns (<0.5 mV QRS amplitude in the limb leads and <1.0 mV in the precordial leads).<sup>2</sup> Fulminant myocarditis, the more hemodynamically severe form of the acute disease, often has ventricular ectopy and tachycardia.

**Figure 8.** ECG in a 15 year old girl with pericarditis. Widespread ST elevation is seen.

Myocardial ischemia is rarely seen in the adolescent population. It can occur in the setting of congenital abnormalities of the coronary arteries (Fig 9), as part of the sequelae of prior cardiac surgery or Kawasaki disease, in premature coronary atherosclerosis in patients with familial hypercholesterolemia, as late sequelae in adolescents post heart transplant, or with use of anabolic steroids or cocaine. Ischemic ECG changes manifest as ST segment elevation or depression (a horizontal or downsloping ST segment is generally indicative of ischemia, an upsloping ST segment is a poor indicator of ischemia) or T wave inversion. The ST segment is compared to the TP segment at 60-80 ms after the J point. ST depression  $> 2$  mm or T wave inversion in the lateral precordial leads (V5-6) represent significant changes (Fig 10). Differential diagnosis includes subendocardial ischemia, hypertrophy with strain, or therapeutic digitalis use. T wave inversion may be seen in ischemia, hyperventilation,<sup>7</sup> electrolyte abnormalities, intracranial pathology, and normal variants such as persistent juvenile pattern (T wave inversion without ST elevation in V1-3 with normal R wave progression) or “benign T wave inversion”. Comparison to an old ECG can be of benefit.

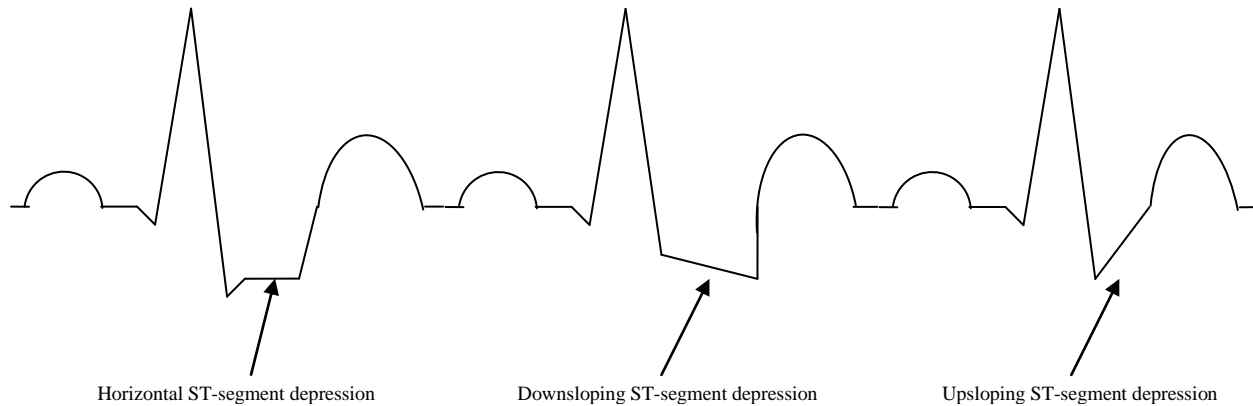
**Figure 9.** 14 year old boy, with sudden collapse while playing basketball, found to have anomalous origin of left main coronary artery. ECG demonstrating widespread ischemic changes.



**Table 1.** ECG features differentiating “Early repolarization” from Pericarditis and Myocardial Ischemia or Infarction

	<b>Myocardial ischemia or infarction</b>	<b>Pericarditis</b>	<b>“Early repolarization”</b>
<b>PR depression</b>	Rare	Frequent	Absent
<b>Q waves</b>	May be present	Absent	Absent
<b>ST elevation</b>	Convex and localized to area of related artery	Concave and widespread	Concave and localized (Most prominent in leads V2-4)
<b>Reciprocal ST depression</b>	May be present	Absent	Absent
<b>T wave</b>	Inverted when ST segments are still elevated	Inverted after ST segments have normalized	Normal or prominent
<b>AV block, ventricular arrhythmias</b>	Common	Absent	Absent



**Figure 10.** Various forms of ST-segment depression.

Chest pain may be evaluated by either continuous or patient-activated ECG monitoring (see below). However, on ambulatory ECG (AECG) a cardiac cause of chest pain is identified in <5% of pediatric patients<sup>8</sup> and most ambulatory ECG (AECG) studies in pediatric patients have reported no yield in the evaluation of chest pain. The primary role of AECG monitoring in pediatric patients with chest pain may be to exclude rather than to diagnose a cardiac cause.

### Evaluation of the QT interval

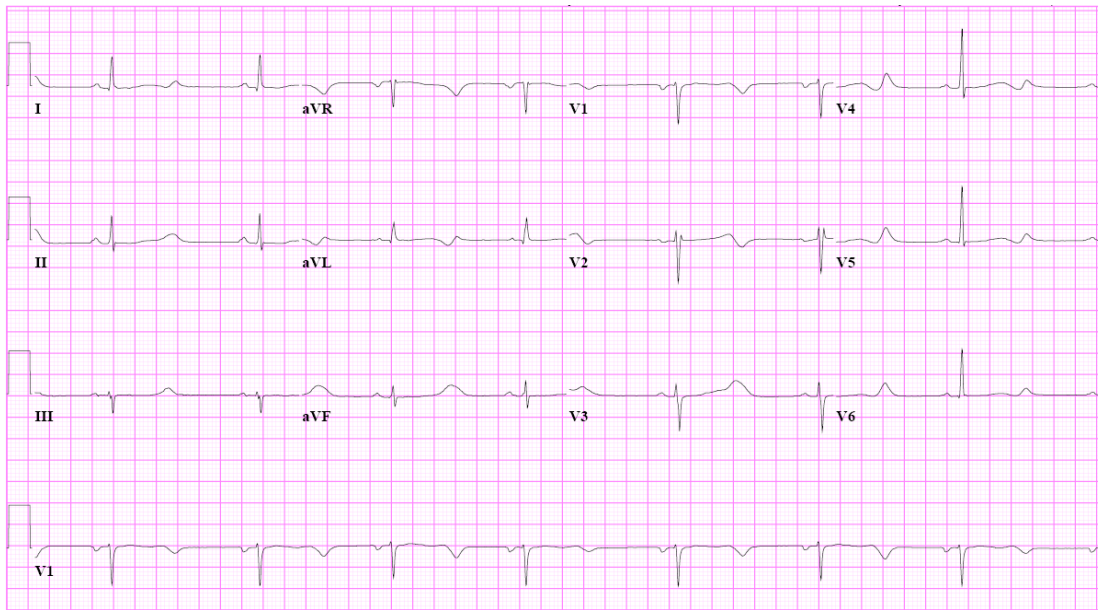
A final interval of the ECG waveform is the QT interval. The QT segment represents the period between ventricular depolarization and repolarization, the length of which is influenced by ion movement through myocardial cell membrane channels. Abnormal ion movement can occur due to certain medications, automatic states, and genetically determined channel abnormalities. The QT interval is measured from the beginning of the QRS complex to the end of the T wave in the lead with the longest interval and without a prominent U wave.<sup>9</sup> The best measurement of the QT interval is in lead II and V5.<sup>10</sup> The duration of the QT interval decreases with increasing heart rates. Thus, the normal range for the QT interval is rate dependent. The QT interval duration varies from lead to lead and with age.<sup>11</sup> The corrected QT interval (QTc) relates the QT interval to heart rate in the formula developed by Bazett:  $QTc = QT/(R-R)^{1/2}$ . The R-R interval preceding the measured QT interval is used for the calculation. The Bazett's formula is not linear, overcorrecting for heart rates < 60 bpm and undercorrecting at high rates.<sup>10</sup> A large recent study shows that the 98%tile for the QTc (averaged across all age groups) is 449 ms for males and 460 ms for females.<sup>12</sup> For ages 10-19 years, the upper limit of normal is 448 ms for boys, and 457 ms for girls. For ages 20-29 years, the upper limit is 436 ms for men, 454 ms for women.

The length of the QTc interval has been associated with the risk of sudden death after myocardial infarction and the long QT syndrome (LQTS) (Fig 11).<sup>13</sup> Familial long QT syndrome is characterized by an abnormally prolonged QTc interval associated with T wave abnormalities and ventricular arrhythmias (polymorphic ventricular tachycardia and torsade de pointes). Patients typically present with syncope, seizures, or sudden death, often triggered by physical or emotional stress or loud noise. Disorders are inherited as an autosomal dominant pattern with variable penetrance (Romano-Ward syndrome) or less frequently as an autosomal recessive pattern (Jervell-Lange-Nielsen syndrome), which is also associated with deafness.<sup>14</sup> Sporadic cases without a known family history have also been described. Mutations in the genes encoding ion channel proteins that control repolarization have been identified as underlying causes. The diagnosis is made using a scoring system combining data obtained from clinical and family histories and ECG.<sup>15</sup> Serial ECGs provide the greatest opportunity to make an accurate diagnosis, since there is variability in the QT interval.<sup>16</sup> In ~25% of genetically proven cases the QT interval actually falls into the normal range.<sup>17</sup> Exercise testing is also used to evaluate the absolute changes of the QT interval (normally the QT interval shortens with exercise due to increased heart rate, however it can abnormally lengthen). Available genetic testing is believed to currently identify ~70-75% of the

mutations that cause LQTS.<sup>10</sup> When the question of LQTS is raised in an adolescent, first degree relatives should also be screened.

Prolongation of the QT interval is an undesired effect of many medications, and in the context of a patient with congenital prolongation of the QT interval, can lead to life-threatening arrhythmias. There are a number of drugs (especially in combination) that prolong the QT interval (typically class 1A antiarrhythmics, macrolide and fluoroquinolone antibiotics, antimalarials, antifungal agents, selected antihistamines, tricyclic antidepressants, antipsychotics, and opioid analgesics). They must be used with caution in individuals with a history suggestive of long QT syndrome, such as syncope or a family history of syncope, deafness or sudden death. Factors predisposing to development of torsade de pointes include bradycardia, hypokalemia, and hypomagnesemia. Serial ECGs are commonly used to monitor potential cardiac effects of certain psychotropic medications.<sup>18</sup> Adolescents receiving tricyclic antidepressants or antipsychotics/neuroleptics should be monitored for ECG changes (PR > 200 ms, QRS > 120 ms, QTc > 460 ms), in which case alternative therapy may need to be considered along with further evaluation by a pediatric cardiologist. A follow-up ECG after therapeutic levels are reached should be obtained.

**Figure 11.** Prolonged QT interval. The QTc measures approximately 630 ms.



### Use of ECG in sports participations screening

The ECG has relatively low specificity as a screening test in athletic populations largely because of the high frequency of ECG alterations associated with the normal physiological adaptations of the trained athlete's heart.<sup>19</sup> Under current recommendations the AHA panel does not recommend the routine use of tests such as 12-lead ECG or echocardiography in the context of mass, universal screening. This view is based on the substantial size of the athlete cohort to be screened, the relatively low prevalence of cardiovascular conditions responsible for sports-related deaths, the limited resources presently available for allocation, but particularly the absence of a physician-examiner cadre prepared and available to perform and interpret these examinations.

## 2. HOLTER AND EVENT MONITORING

Holter, or ambulatory ECG (AECG) monitoring in the adolescent patient is indicated for evaluation of symptoms that may be arrhythmia related, risk assessment in patients with cardiovascular disease, with or without symptoms of an arrhythmia, and evaluation of cardiac rhythm after an intervention such as drug therapy or device implantation.

In adolescents with frequent symptoms possibly related to an arrhythmia such as palpitations, presyncope, syncope, dizziness, or chest pain, AECG is an excellent tool in helping to correlate an arrhythmia with symptoms.<sup>20</sup> In contrast to the standard 12-lead ECG, which captures a brief period of time (a few seconds), the ambulatory monitor records the cardiac rhythm over a prolonged period of time, usually 24-48 hours. It is an ideal test for patients with frequent (at least daily) arrhythmias and provides information on the frequency of occurrence, related symptoms, and potential exacerbating factors. An activity diary can aid in correlating symptoms to ECG findings. Between 25-50% of patients will have complaints of symptoms during the time wearing a Holter monitor. Of these patients 2-15% will have a causal arrhythmia.<sup>20,21</sup> The second type of ambulatory monitoring is the event recorder. There are multiple technologies available. They can be broadly categorized as event recorders, loop recorders, or implantable long-term recorders. The event recorder typically records the electrogram on a continuous tape. Only the last 30-90 seconds are available for playback. When symptoms occur, the patient can stop the tape by pressing a button and transmit the information on the tape via telephone. This type of testing is best ordered for relatively infrequent symptoms that have been difficult to document. This monitor is carried for an extended period of time (usually several weeks), until a symptomatic episode is captured. More sophisticated loop devices can store presymptomatic, symptomatic, and postsymptomatic arrhythmias for a period of several minutes when activated. The diagnostic yield of such recorders is up to 60% in individuals with intermittent symptoms. The third option is an implantable rhythm monitor, a tiny micro-processor based device placed under the skin, which has the ability to record a patient's ECG for weeks to months. The information can be downloaded periodically and reviewed. This type of device is usually ordered and implanted by electrophysiologists.

A patient-activated recorder is generally recommended for the evaluation of palpitations because of the paroxysmal nature of the symptom. An arrhythmia, usually supraventricular tachycardia, has been reported to correlate with palpitation in 10-15% of young patients, whereas ventricular ectopy or bradycardia is demonstrated in another 2-5%. Sinus tachycardia is identified in nearly 50% of young patients with symptoms of palpitation during ambulatory monitoring, whereas 30-40% of patients have no symptoms during monitoring.<sup>20</sup> One of the primary uses of ambulatory ECG monitoring in adolescents is to exclude an arrhythmia as the cause of palpitation. The intermittent nature of symptoms results in a low efficacy of 24-48 hours of continuous ECG monitoring; conversely, temporary patient incapacitation usually precludes patient-activated recording. Continuous ECG monitoring is primarily indicated in pediatric patients with exertional symptoms or those with known heart disease, in whom the presence and significance of an arrhythmia may be increased.

Ambulatory ECG monitoring is commonly used in the periodic evaluation of pediatric patients with heart disease (Fig 12), with or without symptoms of an arrhythmia. The rationale for this testing is the evolution of disease processes (such as long QT syndromes or hypertrophic cardiomyopathies), growth of patients and the need to adjust medication dosages, and the progressive onset of late arrhythmias after surgery for congenital heart defects. The use of AECG monitoring for periodic evaluation of patients with prior surgical treatment of congenital heart disease must be based on consideration of the type of defect, ventricular function, and risk of late postoperative arrhythmias. For example, uncomplicated repairs of atrial or ventricular septal defects are associated with low incidence of late postoperative

arrhythmias. Complex repairs or those with residual hemodynamic abnormalities have a higher incidence of late-onset atrial and ventricular arrhythmias. Although the significance of arrhythmias in these patients remains controversial, high-grade ambulatory ventricular ectopy associated with ventricular dysfunction does appear to identify patients at an increased risk of late sudden death. Complex arrhythmias detected in these patients by AECG may indicate the need for further investigation or intervention, even in the absence of overt symptoms.

Figure 12. Holter monitor in a 13 year old adolescent with history of myocarditis, ventricular tachycardia, and status post implantable cardioverter defibrillator showing recurrent ventricular tachycardia.



Periodic AECG monitoring for young patients with hypertrophic or dilated cardiomyopathies or the long QT syndromes is recommended because of the progression of these diseases and the need to adjust medication doses with growth. The risk of sudden death with these diseases is much greater in pediatric patients than adults, with sudden death as first symptom in 9-15% of patients.<sup>22,23</sup> One primary role of AECG monitoring is to identify occult arrhythmias, which may indicate the need for reevaluation of therapy in an asymptomatic patient. However, the absence of an arrhythmia during monitoring does not necessarily indicate a low risk of sudden death. AECG monitoring has a limited role for establishing a diagnosis of long QT syndrome in patients with borderline QT prolongation.

AECG monitoring may be used to identify asymptomatic patients with congenital complete AV block at increased risk for sudden arrhythmic events and who thus may benefit from prophylactic pacemaker implantation. Routine AECG evaluation of asymptomatic patients with preexcitation syndromes (Wolff-Parkinson-White) has not been demonstrated to define patients at risk for sudden arrhythmic death.

Arrhythmias have become increasingly recognized in young patients with a number of diverse medical conditions. These include Duchenne or Becker muscular dystrophy, myotonic dystrophy, and patients who are survivors of childhood malignancies. AECG monitoring may be indicated in these patients in the presence of symptoms compatible with an arrhythmia because of the potential for both ventricular arrhythmias and progressive conduction system disease.

AECG monitoring is useful to evaluate both beneficial and potentially adverse responses to pharmacological therapy in pediatric patients. Additional indications for AECG monitoring include the evaluation of symptoms in patients with pacemakers or after radiofrequency catheter ablation or heart

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surgery, particularly when complicated by transient AV block. AECG monitoring is also indicated for the evaluation of cardiac rhythm after treatment of incessant tachyarrhythmias, which have been associated with progressive ventricular dysfunction.

### **3. STRESS TESTING**

Reasons for stress testing in the young include investigating exercise-related symptoms, evaluating the stress of exercise on known cardiac conditions, and assessing the effectiveness of medications (e.g., beta blockade effect on heart rate). In general, these studies are most appropriately ordered and supervised by the cardiologist with expertise in adolescent heart disease. Exercise testing is rarely needed to look for occult coronary obstructions in the pediatric population. Exercise capacity is diminished in some adolescents with heart disease, and measurement is often useful in evaluating subjective limitations.<sup>24</sup> Exercise testing of children and adolescents has a very low risk compared with testing of adults. Complications of pediatric exercise testing are extremely infrequent, even when testing is done in populations of children with congenital cardiac defects and arrhythmias. Indications for exercise stress testing have been published in specific guidelines.<sup>24,25</sup>

Several different methods of stress testing are available including treadmill or bicycle exercise with ECG monitoring, imaging by echocardiography during or just after exercise, or pharmacologic simulation of stress (e.g., using dobutamine infusion) with imaging by echo or nuclear methods. Treadmill protocols are relatively simple for the patient, simulate typical activities engaged in (representing a more physiological stress), and provide important information about peak endurance, respiratory health, overall fitness, blood pressure response, as well as cardiac electrical activity. However, confounders may include lack of cooperation, poor coordination, or unfamiliarity with the procedure, especially in younger patients. Stress tests should be ordered in consideration of the pretest probability of the presence of a specific disease process, since sensitivity and specificity will need to be interpreted in this context.

#### **Evaluation of exercise-induced symptoms**

Though chest pain is common in children and adolescents, the history and physical examination are generally adequate to exclude serious pathology and provide reassurance to patient and family. Non cardiac chest pain is usually described as a brief stabbing or shooting pain that occurs with or without exercise. Pleuritic pain is common. Typical etiologies include gastroesophageal reflux, exercise-induced reactive airways disease, costochondritis, or anxiety. Routine use of exercise testing for evaluation of chest pain in children and adolescents is not required. Exercise testing is appropriate for evaluation of the uncommon child with chest pain that is typical angina by description and consistently related to exercise. Exercise-induced bronchospasm is best identified by pulmonary function tests.

Exercise testing is an important component of evaluation of adolescents who have unexplained syncope related to physical exertion. Features of syncope that suggest a potentially life-threatening cardiac event include an abrupt loss of consciousness (as opposed to a prodrome or aura), injury on impact (as opposed to a gradual “slump”), and syncope related to physical activity. Evaluation for possible arrhythmia, left ventricular outflow obstruction, and cardiomyopathy is appropriate. Neurally-mediated hypotension may rarely manifest primarily as exercise-induced syncope, most often with symptoms occurring immediately upon cessation of the activity.

Premature atrial contractions are common and benign in young persons. Exercise test evaluation of premature atrial contractions in adolescents is not required. Exercise testing helps in evaluation of selected cases in which the history suggests an exercise-related tachycardia. The majority of children with supraventricular tachycardia however will not have exercise-induced tachycardia.

Isolated premature ventricular depolarizations in asymptomatic children and adolescents usually disappear with the higher heart rates associated with exercise. It is not necessary to perform formal laboratory testing to demonstrate this. Exercise testing is often of value in diagnosing ventricular tachycardia (VT) and assessing the efficacy of treatment. VT with exercise is often observed in children with no structural heart abnormality as well as in children with myocarditis, cardiomyopathy, or a congenital cardiac malformation. Arrhythmogenic right ventricular dysplasia (ARVD) is an inherited cardiomyopathy particularly related to development of VT with exercise. Measurement of shortening or prolongation of the corrected QT interval to exercise has been used as an adjunct in the diagnosis of long QT syndromes.

#### **4. TILT TABLE TESTING**

Tilt table testing is used primarily to diagnose or confirm suspicion of neurally-mediated hypotension in patients with syncope or near syncope. The test, while relatively simple to perform, is somewhat uncomfortable for the patient and is thus usually reserved for situations in which the diagnosis is unclear from history and physical exam alone, or in which response to empiric therapy has been limited. Although protocols used in performing tilt table testing vary among centers, most laboratories tilt patients for 15-45 minutes at an angle of 60-85 degrees. After baseline parameters are measured the patient is secured to a table and tilted. Normally, individuals compensate for such a tilt by increasing both  $\alpha$ - and  $\beta$ -adrenergic tone as a result of baroreceptor stimulation, thus compensating for the decrease in venous return. In susceptible individuals, these compensatory mechanisms eventually collapse, and venous return is never completely compensated. As a result sympathetic tone increases producing vigorous ventricular contractions of a relatively empty heart. This results in recruitment of cardiac C fibers, which causes stimulation of the medullary vasodepressor region. The result is a sudden withdrawal of sympathetic tone, a sudden increase in vagal tone, vasodilation, and syncope. If the test is negative, the table is lowered in the original horizontal position, and an intravenous infusion of isoproterenol started and the dose adjusted to increase the baseline heart rate to  $> 20\%$ . The tilt table test is repeated for 15-20 minutes. Syncopal episodes have been shown to be preceded by a catecholamine surge. The addition of isoproterenol increases the sensitivity of the tilt table test.

Questions about the sensitivity, specificity, diagnostic yield, and day-to-day reproducibility of tilt table testing have been raised in the most recent AHA/ACCF scientific statement on the evaluation of syncope.<sup>26</sup> The reported sensitivity and specificity of tilt table testing depend on the technique used. Sensitivity ranges from 26-80%, and specificity is approximately 90%. The statement argues that in patients with a negative evaluation, (i.e. no evidence of ischemia and a structurally normal heart), the pretest probability that the diagnosis is neurocardiogenic syncope is high; hence head-up tilt table testing contributes little to establishing the diagnosis.

#### **Evaluation of syncope**

Syncope is common in adolescents as up to 47% of college students report having fainted.<sup>27</sup> Syncope is a disabling condition that requires attention, but is generally not life-threatening. It can be frightening to patients, families, and primary care providers. If cardiac or neurologic abnormalities are not apparent after a thorough history and physical examination has been performed, and blood work, ECG, and echocardiogram are normal, tilt table testing is often used as an aid in establishing the diagnosis of neurally mediated hypotension (NMH) and postural orthostatic tachycardia syndrome (POTS).

NMH is defined by a drop in systolic blood pressure of  $> 25$  mmHg (compared to the BP measured when the person lies flat) during standing or upright tilt table testing.<sup>28</sup> POTS is defined by an exaggerated increase in heart rate with standing. A healthy teenager usually has a slight increase in heart rate by about 10-15 beats per minute within the first 10 minutes of standing. POTS is considered present

if the HR increases > 30 beats per minute (or if it reaches 120 beats per minute or higher) over the first 10 minutes of standing.<sup>29</sup> Some patients with POTS in the first 10 minutes of standing or tilt testing will go on to develop NMH if the test is continued. Different response patterns to tilt table testing in normal individuals, as well as in NMH, POTS, dysautonomia, and psychogenic syncope are listed in Table 2 (Adapted form Feinberg).<sup>27</sup>

**Table 2.** Response Patterns to Tilt Table Test

<b>Pattern</b>	<b>Blood Pressure</b>	<b>Pulse</b>	<b>Response</b>
Normal	No change, or slight increase	No change, or slight increase	No symptoms
NMH	Rapid decrease	Decrease	Presyncope/Syncope
POTS	No change or decrease	Increase	Presyncope
Dysautonomia	Gradual decrease	No change or increase	Presyncope/Syncope
Psychogenic	No change, or slight increase	No change, or slight increase	Presyncope/Syncope

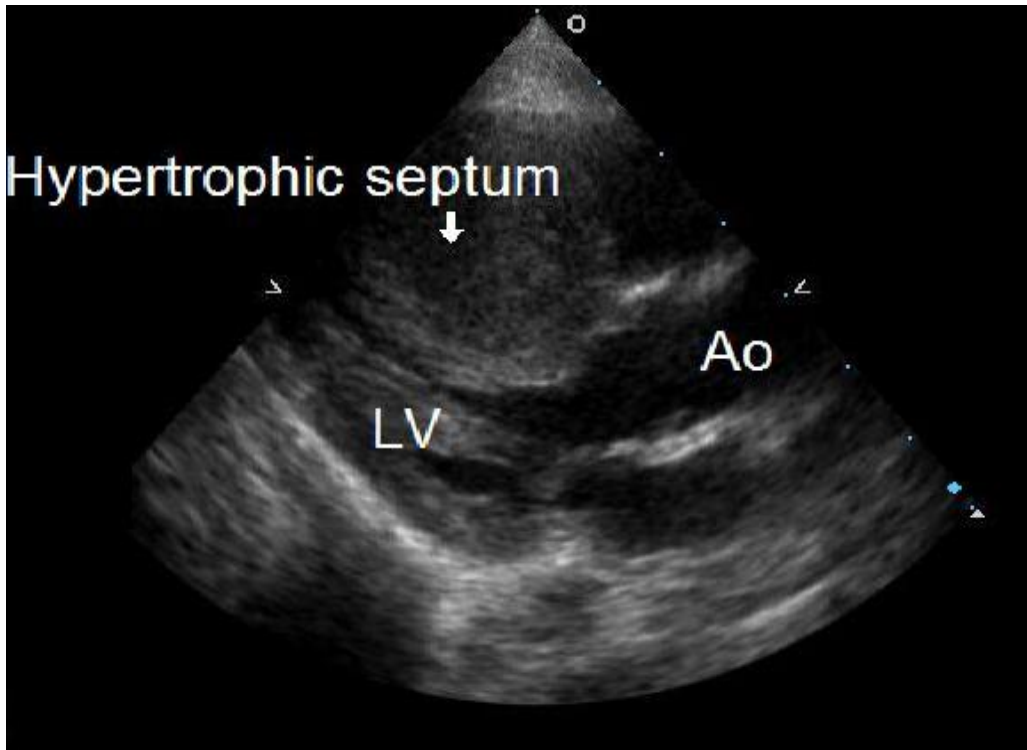
## 5. ECHOCARDIOGRAPHY

Echocardiography is the primary tool of the cardiologist for diagnosing structural heart disease and is highly accurate when performed and interpreted in an experienced laboratory. However, screening for heart disease, especially in the adolescent and young adult, is still more appropriately done by careful history and physical examination. The more important role for echocardiography in an adolescent is in fully characterizing a cardiac lesion once an abnormality is suspected. It also provides essential information concerning the natural history of the abnormality and responses to medical and surgical management. Transthoracic echocardiogram is a reliable and versatile tool for the assessment of cardiac structure, function, and pathophysiology. It is associated with little if any patient discomfort, and no risks. Because it depends on obtaining satisfactory examining windows from the body surface to the cardiovascular structures, there may be limitations to its use. In the obese adolescent, the interposition of adipose tissue between body surface and the heart can limit image quality, and complete examination may not be possible. Echocardiographic contrast agents (administered through a peripheral access line) that can pass through the pulmonary circulation and opacify the left heart have been developed and become a useful aid in the evaluation of obese patients. For specific indications (i.e. evaluation for endocarditis or intracardiac thrombus), transesophageal echocardiography is an excellent tool for further assessment. The echocardiographic transducer is mounted on a flexible endoscope and passed into the esophagus and stomach. However, this technique is invasive and requires sedation and intubation.

Indications for the performance of an adolescent echocardiogram span a wide range of symptoms and signs, including exercise induced chest pain or syncope, murmurs, respiratory distress, abnormal arterial pulses, and cardiomegaly, which may suggest structural heart disease. An echocardiogram is indicated for the evaluation of acquired heart diseases in children, including rheumatic fever and carditis, infective endocarditis, HIV infection, myocarditis, pericarditis, follow-up for Kawasaki disease, all forms of cardiomyopathies (Fig 13), systemic lupus erythematosus, renal disease, and connective tissue diseases with known cardiovascular manifestations (Marfan's syndrome, Loeys-Dietz syndrome). Patients receiving anthracycline or other cardiotoxic agents should have baseline and reevaluation follow-up studies. Pediatric echocardiography is indicated in the assessment of potential cardiac or cardiopulmonary transplant donors and transplant recipients. Echocardiography has been recommended in all children who are newly diagnosed with systemic hypertension.<sup>30</sup> Noncardiac disease states affecting the heart such as pulmonary hypertension constitute an important indication for serial pediatric echocardiograms. Echocardiography may also be indicated in adolescents with thromboembolic events (i.e. sickle cell disease). Elevated right ventricular and pulmonary artery pressure, as estimated by echo-Doppler evaluation of tricuspid regurgitation correlates with increase mortality risk in patients with sickle cell disease.<sup>31</sup> Children with arrhythmias may have previously undiagnosed structural cardiac disease such as congenitally corrected transposition, Ebstein's anomaly of the tricuspid valve, or

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cardiomyopathy, which may be associated with subtle clinical findings and are best evaluated using echocardiography. Sustained arrhythmias or antiarrhythmic medications may lead to functional impairment of the heart that may only be detectable by echocardiography and have important implications for management.

**Figure 13.** Echocardiogram of a 19 year young adult demonstrating hypertrophic cardiomyopathy (Ao = aorta, LV=left ventricle).



Practice guidelines for the clinical application of echocardiography have been published by the ACC/AHA.<sup>32,33,34,35</sup>

Cardiovascular disease in the adolescent includes anomalies of cardiac anatomy, function, and rhythm. While problems often present as an asymptomatic heart murmur, the cardiac murmurs of this age group are more commonly functional than pathological. The contribution of echocardiography to the evaluation of an asymptomatic patient with this finding on routine examination by an experienced clinician is limited. History and skilled physical examination are usually sufficient to distinguish functional from pathological murmurs and are more cost-effective than referral for an echocardiogram.<sup>36</sup> However, in the presence of ambiguous clinical findings, echocardiography can demonstrate the presence or absence of abnormalities such as an interatrial septal defect, bicuspid aortic valve, mildly obstructive subaortic stenosis, mitral valve prolapse, aortic aneurysm, or functionally occult cardiomyopathy.

## 6. CXR/MRI/CT/PET

The chest x-ray is an important clinical tool in the cardiovascular evaluation. In many cases heart disease is associated with cardiomegaly. A quantitative estimate of heart size may be obtained by determining the cardiothoracic ratio, which is calculated by dividing the maximal transverse diameter of the heart in the postero-anterior view by the width of the thoracic cavity. As a general rule, the heart is enlarged if the cardiothoracic ratio is greater than 0.5. Whereas the cardiothoracic ratio is useful in the

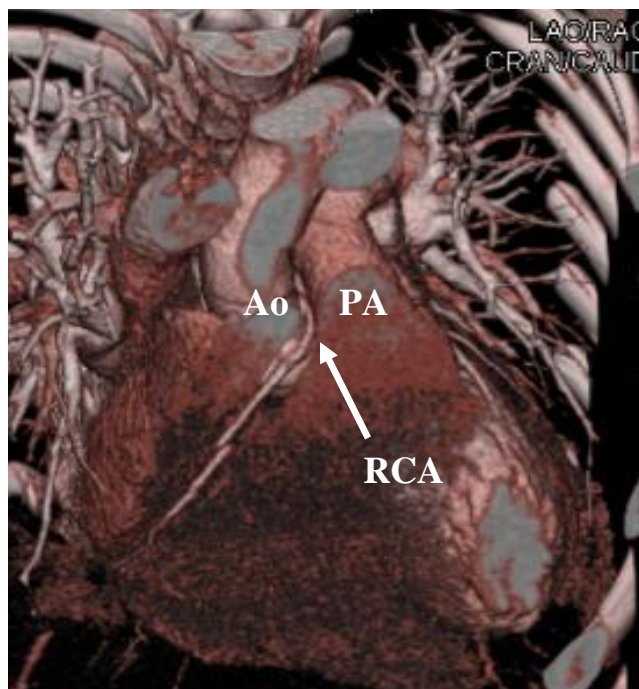


detection of cardiomegaly in cases of left ventricular enlargement or pericardial effusion, it is not as sensitive in the assessment of right ventricular enlargement.

Cardiovascular magnetic resonant imaging (MRI) is a well established diagnostic imaging technique with emerging roles in the evaluation of cardiovascular disease. Its ability to acquire high-resolution images in virtually any plane, to make accurate measurements of blood velocity flow and cardiac volumes, to perform noninvasive angiography, and to assess myocardial mechanics and perfusion, all in the absence of ionizing radiation, promotes its versatility. Indications include, but are not limited to evaluation of congenital heart disease, evaluation of aortic disease, assessment of intrinsic non-ischemic myocardial disease, assessment of ischemic heart disease, assessment of valvular heart disease, evaluation of the pericardium, evaluation of cardiac masses, and assessment of pulmonary arteries. Contraindications to the use of this technique are mainly related to electrically, magnetically, or mechanically active implants in the patient's body.

Indications for cardiovascular computed tomography (CT) have rapidly expanded over the last years, mainly secondary to technical improvements allowing faster scanning with increased spatial resolution. Clinical indications range from assessment of the great vessels to noninvasive imaging of the coronary arteries (Fig 14). Cardiac CT is a non-invasive alternative test to cardiac catheterization. Current technologies include electron beam CT (EBCT) and multiple detector CT (MDCT). EBCT involves the use of a rapidly oscillating electron beam reflected onto a stationary target. It has a high temporal resolution and the slice thickness is 1.5-3 mm, covering the entire heart in one or two breath-hold periods. MDCT involves the use of a mechanically rotated x-ray tube at high speed. This type of scanner is used for non-cardiac and cardiac imaging with minimal slice thickness of 0.75-1 mm, covering the entire heart in a single breath-hold. Clinical indications include coronary artery assessment (calcium scoring, CT angiography), cardiac chamber assessment, evaluation of the great vessels, evaluation of congenital heart disease, and assessment of pericardial disease. The downside of this technique remains the need for radiation. Whereas the average risk for radiation-induced cancer in the general population is estimated at 5% per 1 Sv (Sievert), in children and adolescents the risk is predicted to be up to 2-3 times higher than in adults (as high as 15% per 1 Sv).<sup>37</sup> The typical effective radiation dose for a cardiac CT angiography is estimated to be in the order of 10-25 mSv. In comparison, the typical effective radiation dose for a chest x-ray equals 0.1-0.2 mSv.<sup>38</sup>

**Fig 14.** Cardiac CT in an adolescent boy demonstrating anomalous origin of the right coronary artery (RCA) from the left coronary sinus and traversing between the aorta (Ao) and pulmonary artery (PA).



Positron-emitting tracers (PET) can be used to study myocardial blood flow, glucose and fatty acid metabolism, and oxygen consumption. The PET scan is an established method in the evaluation of myocardial viability in adults with ischemic heart disease. In pediatrics, the application of PET has been limited. Potential applications include the evaluation of ischemic changes that may occur in different diseases of the coronary arteries (congenital anomalies, Kawasaki's disease, and certain postoperative repairs such as the arterial switch procedure).

## 7. CARDIAC CATHETERIZATION AND ELECTROPHYSIOLOGY STUDY

The development of excellent non-invasive techniques has allowed many patients with heart disease to be diagnosed and treated. Nevertheless, cardiac catheterization remains a vital tool in the evaluation and treatment of adolescents with congenital or acquired heart disease. Cardiac catheterization prior to cardiac surgery is indicated when a full anatomic diagnosis or necessary hemodynamic measurements cannot be made by noninvasive tests or when the clinical picture is inconsistent with the patient's presumptive diagnosis. Cardiac catheterization is used to evaluate patients prior to heart transplantation and perform surveillance biopsies to evaluate for subclinical rejection post cardiac transplantation. Cardiac biopsy obtained at catheterization is used to diagnose myocarditis. Furthermore during cardiac catheterization patients can be evaluated for pulmonary hypertension and their response to drug therapy assessed. Detailed indications for specific cardiac lesions are beyond the scope of this review. The field of therapeutic cardiac catheterization continues to expand. Percutaneous device closures of atrial septal defect, patent foramen ovale, patent ductus arteriosus, or stent enlargement of coarctation of the aorta are only a few examples. Overall, the risk associated with this technique is low. It should also be kept in mind that cardiac catheterizations are among the radiological x-ray procedures with the highest patient radiation dose, which remains a source of great concern in the pediatric population. For an average diagnostic cardiac catheterization a median effective radiation dose of 4.6 mSv was found. Therapeutic procedures result in a higher median effective radiation dose of 6.0 mSv.<sup>39</sup>

The electrophysiology study is a specialized form of cardiac catheterization that can be helpful in evaluating a broad spectrum of cardiac arrhythmias. It can assess the function of the sinus node, the atrioventricular node, and the His-Purkinje system. It can also determine the mechanism and characteristics of tachyarrhythmias and locate reentrant circuits (accessory pathways). Finally, it can evaluate the efficacy of antiarrhythmic medication and devices. During the procedure multiple electrodes are placed in the heart recording the electrical signals from the atria, atrioventricular node, and ventricles. Pacing from localized areas within the heart is used to induce the arrhythmia to be studied. If an amenable tachycardia is identified, an ablation procedure can be performed, thus interrupting the aberrant electrical pathways. Ablation techniques use heat (radio-frequency) or cold (cryoablation) to produce thermal damage to the myocardial tissue. Procedures can be repeated for recurrences. Specific guidelines for intracardiac electrophysiological and catheter ablation procedures have been published.<sup>40</sup>

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