Cardiovascular Disease in Williams Syndrome

R. Thomas Collins II, MD

Williams syndrome (WS), also referred to as Williams-Beuren syndrome (Online Mendelian Inheritance in Man 194050), is a congenital, multisystem disorder involving the cardiovascular, connective tissue, and central nervous systems. WS occurs in ≈1 in 10,000 live births as a result of the de novo deletion of ≈1.55 to 1.83 Mb on chromosome 7q11.23. Familial cases can occur but are far less common than de novo cases. The deletion involves 26 to 28 genes, including the ELN gene, which codes for the protein elastin. Hemizygosity of the ELN gene coding for elastin has been demonstrated to be responsible for the vascular pathology in WS. The remaining 25 to 27 deleted genes contribute to the phenotypic findings in patients with WS and have recently been reviewed in detail elsewhere.

In 1961, Williams et al reported their experience with 4 patients with supravalvar aortic stenosis (SVAS), mental retardation, and abnormal facial features. The following year, Beuren and colleagues reported similar findings in 5 patients, and they subsequently reported detailed cardiac and angiographic data from 10 such patients. Their findings, combined with other characteristic features, led both groups to theorize that a previously unrecognized syndrome was the likely origin, a theory that led to the eponym Williams-Beuren syndrome.

Diagnosis

After the reports of Williams et al and Beuren et al were published, the basis for the diagnosis of WS was the presence of a constellation of distinctive phenotypic characteristics. Genetic analysis at that time was limited essentially to karyotyping and microscopic inspection of individual chromosomes, which Beuren et al reported in 3 of their patients. With improved molecular genetics diagnostic techniques, Ewart et al used fluorescent in situ hybridization to demonstrate hemizygosity of the ELN locus in patients with WS. This method is now the standard for establishing the diagnosis of WS (Figure 1).

Clinical Manifestations

As a result of the size of the deletion in WS, the phenotypic features seen commonly are numerous, and a complete discussion of them is beyond the scope of this article. However, several classic features are worthwhile noting.

Before the reports of Williams et al and Beuren et al, several authors had reported on hypercalcemia, mental retardation, and failure to thrive in small groups of patients with elf-like facial features. This gave rise to the moniker "elfin facies syndrome", by which WS was referred. Careful examination of the facial features of 2 patients reported by Bongiovanni et al is consistent with the diagnosis of WS. The constellation of facial features often seen in WS includes a broad forehead; peri orbital fullness; a stellate pattern of the irises; a flattened nasal bridge with an upturned nose; a long philtrum with a wide mouth and full lips; high, rounded cheeks; and a pointed chin (Figure 2).

In addition to typical facial features, patients with WS have a characteristic ebullient personality profile that is classically referred to as the cocktail personality. Patients with WS are hypersocial and garrulous and have a relative verbal strength that belies a mean IQ of 50 to 60. Although their verbal communication skills are relatively strong, 50% to 90% of patients meet diagnostic criteria for anxiety disorder, attention deficit–hyperactivity disorder, or phobic disorder.

Hypercalcemia, which was a prominent feature in the report of Bongiovanni et al, has been reported to occur in up to 50% of patients with WS. This finding is most commonly seen in infancy and typically resolves during childhood.

Cardiovascular Features of Williams Syndrome

Cardiovascular defects are the most common cause of death in patients with WS. Structural cardiovascular abnormalities occur in ≈80% of all WS patients and are present in up to 93% of WS patients presenting in the first year of life. Although a number of cardiovascular abnormalities are common to WS, the majority consist of some form of arterial stenosis.

Pathophysiology of Arterial Stenoses

Elastin constitutes 50% of the dry weight of the normal aorta and is the product of extensively cross-linked tropoelastin monomers. Elastin is characterized by a high degree of reversible distensibility, including the ability to deform significantly with small forces. In the arterial system, this characteristic allows the storage of energy in the form of arterial distension during systole and the subsequent release of the stored energy via vascular recoil during diastole, a principle known as the Windkessel effect, which greatly improves the efficiency of the cardiovascular system.

In the arterial tree, smooth muscle cells produce the large majority of elastin, with some also being produced by endothelial cells and adventitial fibroblasts. Elastin polymers form elastic fibers that are arranged into concentric rings of elastic lamellae around the arterial lumen. Each elastic lamella...
alternates with a ring of smooth muscle, forming a lamellar
unit. The elastic lamellae allow an artery to respond to
the increased hemodynamic stress of cardiac systole and to
maintain sufficient blood pressure during diastole. Patients
with WS and with hemizygosity of ELN lack the elasticity of
the arterial tree provided by normal elastin and thereby have
increased arterial stiffness.

Elastin also serves to regulate phenotypic modulation, pro-
liferation, and migration of vascular smooth muscle cells. In
the absence of elastin, pervasive subendothelial migration and
proliferation of vascular smooth muscle cells occur, resulting
in occlusion of the vascular lumen. Murine models of ELN
haploinsufficiency display marked arterial medial hypertrophy
and subsequent arteriopathy, findings that are strikingly sim-
ilar to those found in patients with WS (Figure 3).

Supravalvar Aortic Stenosis
SV AS was the cardiovascular lesion first reported by Wil-
liams et al and has been found to be the most common car-
diovascular abnormality. The incidence of SV AS has been
reported to be 45% to 75% in patients with WS. Two
types of SV AS are typically seen in patients with WS: a dis-
crete, hourglass narrowing at the sinotubular junction or a
diffuse, long-segment stenosis of the ascending aorta (Fig-
ure 4). The hourglass type of SV AS is the more common of the
two, occurring in ≈ 75% of children. The diffuse type of
SV AS often is associated with stenoses of the brachiocephalic
vessels.

The natural history of SV AS in WS depends on the severity
of the lesion at presentation or follow-up. Historically,
SV AS in patients with WS has been thought to tend to
progress, but this expected observation, as demonstrated in
Table 1, is not in keeping with the majority of publications.
Review of the reports that led to the expectation of
progression of SV AS casts doubt on the accuracy of the
conclusion. Giddins and colleagues first reported that
SV AS might be progressive in a cohort of 10 patients with
WS in 1989. Significant sampling bias was introduced in
that only those patients with SV AS of a severity to warrant
at least 2 cardiac catheterizations were included. In a
cohort of 32 patients with SV AS, Eronen and colleagues
reported that SV AS tended to progress, a conclusion based
on the observation that 3 patients <1 year of age underwent
SV AS intervention compared with 7 patients 1 to 15 years
of age who underwent SV AS intervention. In an incomplete
follow-up sample, Kececioglu et al reported progression
of SV AS severity in 11 of 21 patients. Kim and colleagues
also reported progression of SV AS severity; however,
the study was cross-sectional, not longitudinal, and the
conclusion was based on the finding that the severity of

Figure 1. Laboratory diagnosis of Williams syndrome. Fluorescence in situ hybridization (A) demonstrates 1 normal chromosome 7 with 2 hybridization signals. The presence of the elastin gene (ELN) is marked by a red fluorescence signal (red arrow). The second chromosome 7 shows no evidence of ELN. The green fluorescing signals on each chromosome 7 are control genes (green arrows). A schematic of chromosome 7 (B) from an Agilent 244K microarray demonstrates a cluster of green hybridization consistent with a loss of ≈ 1.5 Mb from the Williams syndrome critical region (WSCR). Reprinted from Pober with permission from the publisher. Copyright © 2010, Massachusetts Medical Society.

Figure 2. Facial characteristics of Williams syndrome. This photograph of a boy with Williams syndrome demonstrates a number of the typical facial features, including a broad forehead, mild periorbital fullness, stellate irises, an upturned nose, a long philtrum, full lips, a small chin, and prominent cheeks. (Informed consent has been obtained from the patient’s legally authorized representative to publish identifying details.)
SVAS was greater in the older patients than in the younger patients (R=0.32). Thus, these studies include significant methodological issues that limit their scientific validity, and they are not in keeping with the majority of studies. Therefore, although SVAS severity can progress, especially in patients with a moderate or severe degrees of stenosis, it remains stable in the majority of patients.

Findings Associated With SVAS

Although SVAS can occur in isolation, it is frequently associated with other cardiovascular lesions. Brown and colleagues reported ≥1 associated congenital cardiac abnormalities in 75% of patients with SVAS. In their report of 242 patients with WS who had undergone cardiac catheterization or surgery, Pham et al reported that SVAS was associated with pulmonary artery stenoses or aortic arch abnormalities in 58% of children. Coronary artery abnormalities, whether ostial stenosis or arterial dilation, are seen in up to 45% of patients with SVAS and likely contribute to sudden death in patients with WS. Aortic valve abnormalities are also seen regularly in the setting of SVAS. These lesions are addressed separately.

Pulmonary Arterial Stenosis

Pulmonary artery stenosis (PAS) is the second most common cardiovascular abnormality in WS. The incidence of PAS in WS depends on the age at the time of presentation; PAS is more common in patients in the first year of life than at older ages. The reported range of incidence of PAS in WS is 37% to 75%, with the majority of studies reporting an incidence of 40%.

The stenoses seen in the pulmonary arterial bed most commonly occur in the branch and peripheral pulmonary arteries. Although discrete stenosis can be seen, diffuse stenoses involving large segments of the pulmonary arterial tree are frequently encountered (Figure 5). Supravalvar pulmonary stenosis is also seen but is less common, occurring in 12% of all patients with WS and 20% of those presenting in the first year of life.

The natural history of PAS in WS is one of improvement, which has been described in multiple studies. This natural history is likely related to the change in arterial medial tension that occurs in the postnatal period. Pulmonary arterial concentrations of elastin normally decrease in the first few months of life, at a time when pulmonary vascular resistance is normalizing. Theoretically, the decrease in pulmonary arterial pressure lessens the arterial medial tension in the pulmonary arteries, decreasing the role of elastin. As a result, there is improvement in the arterial stenoses as the patient grows.
Coronary Artery Abnormalities in SVAS

Coronary artery abnormalities are often associated with congenital SVAS. Some investigators have recommended that every patient with SVAS should be considered at risk for myocardial ischemia. Coronary artery involvement in patients with WS may manifest as coronary ostial stenosis, diffuse coronary artery stenosis, coronary artery dilation, or obstruction to coronary artery inflow by the aortic valve, the sinotubular ridge, or a combination of both (Figure 6).

In recent medical literature, coronary ostial stenosis is the most commonly reported coronary abnormality, occurring in ≈5% of all patients with WS and 9% of those presenting in the first year of life. However, these estimates are likely to be below the true prevalence because the majority of patients in those studies did not have evaluations of the coronary arteries, by either imaging or inspection at surgery. Stamm et al reported a prevalence of coronary ostial stenosis of 45% in their surgical series of patients with SVAS. Ostial stenosis is more frequent in patients with WS and severe vascular disease; in those patients with stenosis of the thoracic aorta (STA), coronary ostial stenosis had a prevalence of ≈19%. The diagnosis of coronary ostial stenosis is difficult to make and is usually made only at the time of cardiac catheterization or surgery when a coronary probe cannot be passed easily into the coronary artery. The increasing use of cardiac magnetic resonance imaging and cardiac computed tomography will likely increase the likelihood of the diagnosis of coronary ostial stenosis, leading to a higher true prevalence than previously reported.

The pathophysiology of coronary ostial stenosis can be complex. Inflow to the coronary arteries can be restricted by adhesion of the aortic leaflet edge to the narrowed sinotubular junction. The coronary ostia may also become narrowed by the overhanging, stenosing SVAS ring, resulting in reduced diastolic coronary arterial flow. Alternatively, high pressure proximal to the SVAS is transmitted to the coronary arteries and may result in severe dysplasia and narrowing of these arteries.

Dilated and tortuous coronary arteries are seen commonly in patients with SVAS. Numerous investigators have reported that dilation of the coronary arteries is seen more frequently than stenosis. van Son and colleagues reported that coronary ostial stenosis was more common than dilation in the left coronary artery, whereas dilation was more common than stenosis in the right coronary artery. Furthermore, Kim et al reported that in those patients with the hourglass type of SVAS, 80% had coronary arterial dilation, whereas those with long-segment stenosis demonstrated coronary ostial stenosis. Marked dilation and aneurysm of the coronary arteries can be seen, with the lumen of the proximal coronary artery being as large as the aorta itself.

The pathophysiology of coronary arterial dilation has been suggested to be the result of the increased pressure and turbulence to which the coronary arteries are subjected by left ventricular ejection into a small, noncompliant chamber (Figure 6B).

Other Systemic Arterial Stenoses

It has become increasingly clear that the elastin haploinsufficiency in WS results in a systemic arteriopathy. This systemic arteriopathy manifests at sites other than the supravalvar aortic region and the pulmonary vascular bed in ≈20%
The frequency of STA is uncertain because the range of incidence from multiple studies is 2% to 70%.15,33,43,39,60,61

About half of the patients with STA will have mild disease, whereas one quarter have moderate stenosis and the remaining one quarter have severe stenosis. The incidence of other systemic arterial stenoses is increased in patients with STA,15,40 indicating that STA is a marker for worsened generalized arteriopathy. Progression of STA can be seen in moderate and severe stenoses, with some patients demonstrating rapid progression over short periods of time. These patients usually manifest progression within the first year of life.62,63

Renal artery stenosis (RAS) has been reported in 7% to 58% of patients with WS.12,15,61,64 RAS is usually found at the origin of the renal arteries. Rose et al39 demonstrated that isolated RAS is rare and is usually seen in combination with STA. In the presence of STA, RAS occurs in 16% of patients.40 Rose and colleagues12 demonstrated that ≈40% of patients with WS with systemic hypertension have RAS. Systemic hypertension is present in ≈50% of adult patients with WS.

Systemic arterial stenoses can be seen at other sites throughout the arterial tree. The remaining most common sites are the neck and limbs, abdominal aorta, mesenteric arteries, and intracranial vessels.15

Other Structural Cardiac Abnormalities

Although arterial stenoses represent the large majority of cardiovascular abnormalities in patients with WS, a number of other structural cardiac abnormalities are seen with regularity. Ventricular septal defects are present in 4% to 9% of all patients with WS15,45 and up to 21% of those presenting in the first year of life.16 The defects are muscular ventricular septal defects in 75% of children, with the remainder often being conoventricular (perimembranous).15,65 Ventricular septal defects in the setting of a complete atrioventricular canal defect46 and tetralogy of Fallot10,67,68 have been reported.

Aortic valve abnormalities have been described in surgical reports in up to 50% of cases of SVAS.48 Adhesion of the leaflets of the aortic valve to the sinotubular junction, which may result in myocardial ischemia as a result of the obstruction of coronary blood flow, is the most common aortic valve abnormality in patients with SVAS,69 occurring in as many as half of patients.34 This fusion, or tethering, of the aortic valve to the sinotubular junction has been reported in association with sudden cardiac death in patients with WS who had SVAS.70 The aortic valve may be thickened in up to 30% of patients with SVAS,39 Bicuspid aortic valve has been reported in 25% to 39% of patients with SVAS71,72 and in 5% to 12% of patients with WS.16,65

Mitral valve abnormalities are also common in patients with WS. Mitral valve prolapse is seen in 9% to 27% of patients45,65,67,73 and is mild in 85% of them. Mitral regurgitation also occurs in ≈15% of patients and is mild in 80% of them.73

In contrast to mitral valve involvement, the tricuspid valve is seldom reported to be involved in patients with WS.74 Ebstein anomaly of the tricuspid valve has been reported rarely.35–37

Sudden Cardiac Death

Sudden cardiac death in a patient with WS was first reported by Rashkind et al.74 The risk of sudden cardiac death is 25 to 100 times greater than that in the general population.44–79

The reason of this increased risk of sudden death is not completely understood. A large number of cardiovascular collapses and deaths in patients with WS have been in the periprocedural and perianesthetic setting.60 The risk of sudden cardiovascular collapse appears to be greater in the presence of bilateral outflow tract obstruction,43 especially with coronary arterial stenosis.44 However, sudden death has been reported in the absence of autopsy evidence of outflow tract or coronary obstruction.33,81 More recently, prolongation of
the corrected QT interval (QTc) on ECG has been shown to be present in 13% of patients with WS and may contribute to the increased risk of sudden death. In addition, ventricular ectopic complexes and arrhythmias have been correlated with the presence of QTc prolongation in patients with WS, which may indicate a role for microvascular ischemia in the QTc prolongation.

**ECG Abnormalities**

Patients with WS often undergo ECGs, but data on the findings of ECGs in these patients are limited. In addition to the abnormalities of cardiac repolarization previously mentioned, ventricular hypertrophy is frequently seen. Right ventricular hypertrophy on ECG will be found in ≈60% of patients, whereas left ventricular hypertrophy on ECG is demonstrated in 40% of patients.

**Screening for Cardiovascular Abnormalities**

Because cardiovascular abnormalities occur in 80% of patients with WS, detailed cardiovascular screening is imperative. Once the diagnosis of WS is made, all patients should undergo an evaluation by a pediatric cardiologist. In addition to a thorough history and physical examination, the initial cardiologic evaluation should include an ECG and complete echocardiogram. If cardiovascular abnormalities are found, individualized follow-up should be dictated by the patient’s age and lesion severity. Because of the increased risk of ventricular ectopic complexes and arrhythmias, arrhythmia screening with 24-hour ambulatory ECG monitoring should be considered.

Four-extremity blood pressure measurements should be obtained on every patient if possible. However, physiologic cal caveats must be considered in this special population. In those patients with SVAS, the Coanda effect, the tendency of a moving fluid to attach itself to a surface and move along it, often produces discrepant blood pressure measurements. In those patients with SVAS, the Coanda effect, the tendency of a moving fluid to attach itself to a surface and move along it, often produces discrepant blood pressure measurements. In those patients with SVAS, the Coanda effect, the tendency of a moving fluid to attach itself to a surface and move along it, often produces discrepant blood pressure measurements.

**Management of Structural Cardiovascular Abnormalities**

**Medical Management**

Depending on the severity of the lesions, a large number of patients can be followed up clinically without immediate intervention. Table 2 outlines the author’s recommended cardiovascular evaluation and follow-up strategy. Those patients who present in the first year of life are at an increased risk of progression of arterial stenoses compared with those who present later.

For this reason, follow-up visits every 3 months during the first year of life are suggested, which is more frequent than the 2001 recommendations of the American Academy of Pediatrics. Patients with moderate to severe degrees of stenoses should be re-evaluated on a more frequent basis because progression can occur rapidly. During follow-up visits, the decision for echocardiographic re-evaluation can be determined on the basis of physical examination findings.

Patients presenting after the first year of life have a decreased, although not absent, likelihood of arterial stenosis progression. Those with severe stenoses are nearly certainly likely to require intervention, whereas those with moderate stenoses are most likely to remain stable. Patients with mild degrees of arterial stenoses are highly unlikely to have progression of arterial stenoses to a degree that would necessitate intervention, and less aggressive cardiovascular follow-up can be undertaken.

Therapeutic options for systemic hypertension in patients with WS must take into consideration the potential presence of RAS. Thus, the use of angiotensin-converting enzyme inhibitors is contraindicated unless RAS has been definitively ruled out. Data-based recommendations for antihypertensive therapies cannot be made. However, calcium channel blockers of the dihydropyridine type are effective medications for the treatment of hypertension in patients with WS. The use of β-blocker therapy for hypertension has the attractive additional benefit of potentially decreasing the risk of ventricular arrhythmia or an increased adrenergic response, as well as sudden death, in patients with prolongation of the QTc.

**Surgical Management**

Approximately 20% of patients with WS will require surgical or transcatheter interventions for cardiovascular abnormalities, the large majority of which will be needed by 15 years of age. The need for intervention is increased to ≈30% in those who present during the first year of life.

Surgical intervention is most commonly undertaken for SVAS, because transcatheter balloon angioplasty has been found to be ineffective. Surgical approaches to SVAS have evolved over time, with the current most common technique being the use of an inverted Y-shaped patch.
Table 2. Cardiovascular Evaluation and Follow-Up of Patients With Williams Syndrome*

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<tr>
<th>Examination every 3 mo during the first year of life, then annually until 5 y of age, and biennially or triennially thereafter</th>
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<td>ECG at each visit to assess QTc</td>
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<tr>
<td>24-h Ambulatory ECG at 1 y of age, annually until 5 y of age, and then biennially</td>
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<tr>
<td>Echocardiography at presentation, at least annually until 5 y of age, and then as needed if heart disease is present</td>
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<tr>
<td>CT or MRI of the aorta if severe SVAS is present; imaging of head and neck vessels should also be considered</td>
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<tr>
<td>Renal ultrasound if hypertensive or if abdominal bruits are auscultated</td>
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<td>Ultrasound of carotids if carotid bruits are present</td>
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CT indicates computed tomography; MRI, magnetic resonance imaging; and SVAS, supravalvar aortic stenosis.

*Cardiovascular management should be performed by a pediatric cardiologist well versed in the care of patients with Williams syndrome.

When augmentation of the ascending aorta is necessary,^42^ the modified Brom (3-sinus) technique has been shown to have excellent midterm outcomes without the need for reintervention^14^ and is increasingly being used. Other techniques such as the apicoaortic conduit^29^ are used less commonly. In a study cohort with 41% WS patients, the overall survival of patients with SVAS was estimated at 90±7%, 84±9%, and 82±10% at 5, 10, and 20 years, respectively.^91^ Freedom from late reoperation in the same cohort was estimated at 97±4%, 93±7%, and 86±10% at 5, 10, and 20 years, respectively. However, in those patients with the diffuse type of SVAS, as many as 35% will require reintervention.^42^

Transcatheter intervention is most commonly used for peripheral PAS.^15^ Geggel et al^46^ have reported that central pulmonary arteries do not respond well to balloon angioplasty. However, the intrapulmonary segments of the pulmonary arteries respond better to balloon dilation, especially when undertaken in a serial manner. A significant issue reported by Geggel and colleagues is pulmonary arterial aneurysm formation after balloon angioplasty. Wessel et al^19^ previously reported that high degrees of PAS are tolerated well without intervention, which, when combined with the high frequency of complications from transcatheter interventions, led Geggel et al^46^ to recommend frequent noninvasive observation in the asymptomatic patient with subsystemic right ventricular pressures. Transcatheter vascular stenting has been used infrequently in patients with WS.^15^ Rapid failure of arterial stenting in patients with WS has been reported, and the resected arterial wall demonstrates extensive fibrosis and intimal and smooth muscle cell proliferation.^22^ In-stent stenosis in patients with WS is likely related to an abnormal arterial response to injury caused by stent implantation in the setting of decreased arterial elastin.^

STA does not require surgical or transcatheter intervention in ~70% of patients with WS. Those patients with STA requiring intervention are highly likely to need intervention before 5 years of age, and the risk of reintervention is >50%.^40^ Furthermore, those who undergo reintervention have an 80% likelihood of undergoing another subsequent reintervention. Because of the decreased likelihood of successful intervention and the attendant risks of the procedures, conservative, noninterventional management of patients with STA should be considered.

Periprocedural Management
As noted previously, sudden cardiovascular collapse during the periprocedural period has been reported multiple times in patients with WS. To date, no studies have evaluated anesthetic regimens in patients with WS, and no data-driven recommendations are available. Medley et al^1^ have recommended preoperative thyroid screening. Those authors also recommended against the use of succinylcholine because of a theoretical risk of a hyperkalemic response and recommended titrating neuromuscular blockade with intraoperative monitoring of train of four. Burch and colleagues^80^ have published anesthetic goals in patients with congenital SVAS, including patients with WS, that can be summarized as follows: maintain sinus rhythm at an age-appropriate heart rate, ensure an adequate preload while avoiding rapid shifts in intravascular volume, avoid anesthetic strategies associated with negative inotropic effects and decreased systemic vascular resistance (ie, propofol, Sodium Pentothal, sevoflurane, isoflurane, and desflurane), and treat hypotension aggressively (phenylephrine, ephedrine, or low-dose epinephrine may be appropriate, depending on the status of the patient).

Medical Management of QTc Prolongation
Because prolongation of the QTc may occur with or without concomitant structural cardiovascular abnormalities, ongoing ECG screening should be considered in all patients with WS on at least a biennial basis. Those whose QTc interval suggests prolongation (≥440 milliseconds) should be referred to a pediatric cardiologist well versed in the care of patients with WS, and consultation with an electrophysiologist is recommended. Assessment should include elucidation of other risk factors for sudden death, review of medications that may contribute to QTc prolongation, and an enhanced adrenergic state. Strong consideration should be given to treatment with β-blocker therapy for those with QTc prolongation, especially before the initiation of attention deficit–hyperactivity disorder medications.^

Furthermore, all patients with WS who are maintained on attention deficit–hyperactivity disorder medications should undergo repeat ECG at appropriate intervals, with or without β-blocker therapy. In patients with long-QT syndrome, a QTc ≥500 milliseconds is a high-risk indicator for sudden death. Genetic testing has been recommended for any asymptomatic patient with QT prolongation in the absence of other clinical conditions that might prolong the QT interval, as defined by a QTc >480 milliseconds (prepuberty) or >500 milliseconds (adults). Because patients with WS have other clinical conditions that might prolong the QT interval, it is the author’s practice to undertake genetic testing for WS patients with a QTc ≥500 milliseconds.

Developing Therapies
Currently, medical therapeutic options for cardiovascular issues in patients with WS are limited primarily to the
treatment of hypertension or dysrhythmias. However, a number of potentially beneficial therapies have been reported in animal studies.

The use of minoxidil has been shown to increase elastin content significantly in the abdominal aorta, superior mesenteric, and renal arteries.\textsuperscript{39} The presumed mechanism of action is via decreased tissue elastase activity. Minoxidil was initially developed as an antihypertensive and could be an attractive therapeutic option for the treatment of hypertension in patients with WS with the possible added effect of increasing arterial elastin content.

Multiple agents affect elastin synthesis regulation and could potentially serve as therapeutic options in patients with WS. Transforming growth factor-β increases the expression of multiple extracellular matrix genes, including elastin, through increases in transcription or stabilization.\textsuperscript{38} Aldosterone increases elastin mRNA levels, tropoelastin synthesis, and elastic fiber deposition in a dose-dependent manner.\textsuperscript{39} The elastogenic effect of aldosterone is mediated via a mineralocorticoid receptor–independent mechanism involving insulin-like growth factor-1 receptor signaling.\textsuperscript{100} Glucocorticoids upregulate tropoelastin expression in the fetal lung,\textsuperscript{101} possibly via a similar corticosteroid pathway. Interestingly, the aldosterone receptor antagonist eplerenone has been shown to increase arterial collagen content in patients with hypertension.\textsuperscript{102} Similarly, eplerenone and spironolactone have been reported to increase elastic fiber formation in dermal layers.\textsuperscript{103}

These results suggest a possible role for aldosterone antagonists in the treatment of the arterial stenoses most commonly present in patients with WS.

Matrix metalloproteinases cause the breakdown of extracellular matrix proteins such as collagen and elastin.\textsuperscript{104} Petricevic et al\textsuperscript{105} have shown in rat models that doxycycline, a matrix metalloproteinase inhibitor, prevents the fragmentation and destruction of elastin. Other investigators have shown in porcine models that the use of matrix metalloproteinase inhibitors results in higher elastin density with less intimal hyperplasia in the vessel wall of treated animals.\textsuperscript{104} In that study, neointimal hyperplasia was significantly reduced in Gore-Tex grafts in animals treated with matrix metalloproteinase inhibitors, a finding that may be translatable to transcatheter stent implantsation.

Tissue-engineered blood vessels are being developed and hold promise for surgical treatment options for significant arterial stenoses.\textsuperscript{105} Elastin-mimetic polypeptides can be fabricated into nonwoven fabrics of fiber networks that mimic native elastin scaffolds. Tubular constructs that could be used as an arterial substitute have been produced by fiber deposition.\textsuperscript{107}

**Summary**

WS is a complex, multisystem disorder with significant cardiovascular manifestations. Arterial stenoses make up the large majority of cardiovascular issues in patients with WS. Although all patients with WS need early and ongoing cardiovascular evaluation and follow-up, most patients will not require cardiovascular interventions. In those patients who do undergo surgical and catheter-based interventions, the results are favorable, although long-segment STA remains very difficult to treat. Sudden death in patients with WS is significantly greater than in the general population, and expert periprocedural care of these patients is paramount. Prolongation of the QTc is common in patients with WS, and conservative management with medications should be considered. The potential for groundbreaking advancements in medical therapies is present in already available pharmaceutical agents; these potential therapies need to be investigated in meaningful ways.

**Disclosures**

None.

**References**

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