Special Article

Questions Remaining About the Surgical Correction of Tetralogy of Fallot

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Tetralogy of Fallot is the most common cyanotic congenital heart lesion. Its anatomical features were first described by Stenson in 1672.[1] In 1888 Fallot[2] published his clinical observations, linking the four elements he considered to be the main anatomical abnormalities (interventricular septal defect, stenosis of the right ventricular outflow tract, right ventricular hypertrophy and an aorta that straddles the ventricular septum) with the clinical syndrome of progressively increasing cyanosis. Much later, Van Praagh[3] introduced the term tetralogy to describe the incomplete development and hypoplasia of the infundibulum, namely the right ventricular outflow tract. From a pathophysiological point of view, though, the most important elements of tetralogy of Fallot are the existence of a non-restrictive ventricular septal defect and the degree of obstruction of the right ventricular outflow tract. The spectrum of this classical form of the tetralogy is a wide one, with some patients having only mild obstruction (acyanotic tetralogy of Fallot) and occasionally pulmonary hypercirculation, while others have severe hypoplasia of the infundibulum, hypoplasia of the pulmonary annulus and the pulmonary trunk and/or stenosis in the main trunk as well as along the branches of the pulmonary artery. Even though there are often many small collateral vessels leading to the lungs, the existence of major aortopulmonary collateral arteries (MAPCAs) is rather rare in the classical tetralogy with pulmonary stenosis. In a small percentage of patients (3%) a second interventricular shunt is encountered in the muscular ventricular septum, while also in 3% a significant abnormality in the coronary vessels may coexist (usually the anterior descending branch originating from the right coronary artery and crossing the anterior surface of the right ventricular outflow tract). Other forms of tetralogy with different embryology, pathophysiology and quite different surgical treatment are as follows:

a. Tetralogy of Fallot with pulmonary atresia and dependence of the pulmonary circulation upon the patent ductus arteriosus.

b. Tetralogy of Fallot with pulmonary atresia, hypoplastic pulmonary arteries, pulmonary arterial branching abnormalities and the presence of MAPCAs.

c. Tetralogy of Fallot with concomitant complete atrioventricular canal.

d. Tetralogy of Fallot with absent pulmonary valve.

e. Tetralogy of Fallot with anomalous origin of one pulmonary artery from the aorta (hemitruncus).

These subcategories of tetralogy will not be considered in the present article.

Historical review

Surgical treatment of tetralogy of Fallot was first performed by Blalock and Taussig[4] in 1945, using the palliative procedure

known as the Blalock-Taussig shunt: anastomosis of the subclavian artery to the pulmonary artery. In 1946, Potts[5] introduced anastomosis between the descending aorta and the left pulmonary artery and in 1962 Waterston[6] performed anastomosis of the ascending aorta to the right pulmonary artery. Modification of the Blalock-Taussig shunt using a prosthetic graft was introduced in 1962 by Klinner[7] and taken further by de Leval.[8] While all these palliative procedures improve the level of oxygenation in the blood, prevent the appearance of hypercyanotic crises, and allow the patient's development with total correction at a later stage, the modified Blalock-Taussig shunt using a polytetrafluoroethylene (PTFE) graft is the most common palliative procedure today. This method avoids to a large degree the problems of deforming the branches of the pulmonary artery (at the points of anastomosis, as often happens in Potts and Waterson anastomoses), it allows controlled flow in the pulmonary circulation and presents no difficulties in removal of the graft. The modified Blalock-Taussig shunt is placed either through a lateral thoracotomy or via sternotomy (in the latter case the central anastomosis is to the innominate artery). Sometimes a central shunt is used via sternotomy with the central anastomosis to the ascending aorta.

The first total correction of a tetralogy of Fallot was achieved in April 1954 by Lillehei,[9] using the "cross circulation" technique in a patient aged ten months, and subsequently in another ten patients of whom six were under two years of age. The first patient survived and is still living today. The first successful correction of a tetralogy of Fallot using extracorporeal circulation was carried out by Kirklin in 1955.[10] However, in spite of the initial successes in the correction of tetralogy of Fallot in infancy by pioneering cardiac surgeons such as Shumway,[11] further attempts had disappointingly high mortality, and this led to the universal acceptance of correction in two stages, with an initial palliative procedure and total correction at a greater age.[12,13] Barratt-Boyes[14] in 1969 and Castaneda[15] in 1972 reintroduced the correction of tetralogy of Fallot in one stage during infancy, and the results gradually improved,[16] especially after 1990.[17-26] At the same time, however, the discovery that correction in early infancy, especially with the classical transventricular technique (in which the right ventriculotomy is usually extended through the pulmonary annulus to the pulmonary artery trunk, with concomitant broad enlargement of the right ventricular outflow tract) leads to significant pulmonary valve insufficiency and is often accompanied by increased mortality and perioperative complications, led to the introduction of an alternative surgical technique called transatrial/transpulmonary correction. This technique, which was first introduced by Hudspeth[27] and Edmunds[28] and was later promulgated by Kawashima,[29] Pacifico[30] and Mee,[31] does not use right ventriculotomy. It is associated with lower mortality and morbidity and has been used mainly in infants and more recently in neonates. Thus, many recent surgical series have reported successful outcomes with a mortality rate <5%, with a tendency for the procedure to be performed at younger and younger ages.

However, along with this spectacular improvement in the surgical results that has been achieved in the last decade, there has been a growing awareness, based on the long-term follow up of patients who have undergone successful correction, that an appreciable percentage (ranging from 5-25%) show significant problems later on, such as enlargement and reduced functionality of the right ventricle with pulmonary valve insufficiency, tricuspid regurgitation, symptomatic heart failure, need for reoperation, severe arrhythmias and even sudden death.[38-52] The realization of the increasing frequency of these problems gave a powerful motive to the search for the most suitable strategy aimed at the prevention and treatment of these unfavorable long-term complications. The formation of such a strategy requires that answers be found to certain important questions on which a uniform consensus has still to be reached, focused not so much on perioperative mortality (which in general still remains within low levels) but rather on the long-term results, the best possible quality of life and the reduction of the incidence of reoperation and other complications. The questions that remain unanswered until now may be summarized as follows:

1. What is the ideal age for surgical correction?
   a. Neonatal correction for all patients regardless of symptoms?
   b. Correction in early infancy for all patients regardless of symptoms or anatomy?
   c. Selective correction in two stages, where the first stage is a palliative procedure in certain categories of patients (e.g. neonatal age, or with hypoplastic annulus, or with hypoplastic pulmonary arteries, or other accompanying diseases) and later total correction in a second stage?
2. What is the ideal surgical technique?
   a. Classical transventricular correction?
   b. Transatrial/transpulmonary correction at the age of one year?

c. Transatrial/transpulmonary correction in the neonatal period or in early infancy?

Ultimately, of course, perhaps the most important question is this: which strategy, that is, which combination of time and correction method, will lead to the best long-term results?

As regards the question about the most appropriate timing of the procedure, the potential benefits of neonatal correction of the tetralogy or of correction in every case in early infancy include the following:[53-58]

1. It avoids the risks and complications of a palliative aortopulmonary shunt, such as increased pulmonary flow and cardiac volume overload, or the creation of pulmonary arterial stenoses.
2. It eliminates early in life the danger arising from the mingling of venous blood in the systemic circulation (cerebral embolism).
3. The small patch needed for closure of the interventricular shunt in a small heart will be a relatively insignificant non-contractile part of the interventricular septum after maturity.
4. It avoids the creation of right ventricular hypertrophy, which could have long-term unfavorable consequences (e.g. arrhythmias).
5. It precludes possible unfavorable consequences in the development of the pulmonary vessel and brain because of deficient pulmonary circulation and cyanosis.

These theoretical advantages, however, especially in the case of neonatal correction, have not been confirmed clinically. On the other hand, it is clear that correction at neonatal age is associated both with higher mortality (ranging in the best modern series from 5-6%) and with significant morbidity and complications. In addition –and this is perhaps more important– in neonatal correction a transannular patch is used almost universally, leading to the creation of a significant degree of pulmonary valve insufficiency. Thus neonatal correction (which is mostly performed using the classical transventricular method) is associated with reoperation in 10-15% of cases, 5-10 years after the initial operation, while in the long term even more questions remain about right ventricular function and the occurrence of arrhythmias. These real problems may balance out the theoretical advantages of neonatal correction. On the other hand, in the modern age a palliative procedure (shunting) may be performed with very low mortality and little risk of pulmonary artery deformation. Thus, in selected symptomatic patients with severe cyanosis and other factors making total correction difficult (such as low body weight, neonatal age, hypoplastic pulmonary annulus, hypoplastic pulmonary vessels, or other non-cardiac congenital anomalies in neonates, such as esophageal atresia), the problem of hypoxemia is relieved, allowing a corrective procedure to be carried out at an older age and under much better circumstances. As a consequence, the strategy of neonatal correction in all patients cannot be supported without reservation, although there is perhaps a convergence of views concerning correction in infancy, with the selective use of shunting, in certain patients.

As regards the more important question about the ideal surgical technique, it must be noted that perhaps the most important development in the surgical treatment of the tetralogy over the last decade has resulted from the spread of the transatrial/transpulmonary method.[59] In that technique, correction of the tetralogy is carried out without any need for the creation of a large ventriculotomy in the anterior surface of the right ventricle, via which the interventricular septum is closed in the classical treatment. In contrast, the ventricular septal defect is closed transatrially, while the division of the abnormal muscular trabeculae in the right ventricular outflow tract, the pulmonary valvotomy, as well as any necessary widening of the pulmonary annulus, are performed transatrially and transpulmonarily, most probably with only a small pulmonary arteriotomy a few millimeters into the right ventricular outflow tract. This method, therefore, places special emphasis on protection of the function of the right ventricle and pulmonary valve and should theoretically be associated with lower mortality, fewer complications and a better long-term result. In practice, it has been confirmed that the surgical mortality of this method is very low, ranging from 0-2%, while the complication rate is also rather low, as is the percentage of cases that need reoperation (around 5%). However, in some series there has been a high incidence of residual stenosis in the right ventricular outflow tract. Transatrial/transpulmonary correction should ideally be reserved for older infants, and so most supporters of the method use initial palliative shunting selectively in symptomatic neonatal patients. Despite the excellent results of this new method that have been reported by various centers, it should be noted that there have been no randomized prospective studies that have made a comparative evaluation of transatrial/transpulmonary versus classical transventricular correction, or of neonatal correction in all patients versus two-stage correction in selected patients. In the absence of such studies, which do not seem feasible in practice, the answer to the question of

which is the better strategy for improving long-term results will come from the long-term follow up and careful evaluation of the clinical condition and cardiac function of patients who have undergone total correction based on a specific surgical protocol. Of course, the central point of this evaluation will be an assessment of right ventricular function. It has been noted that a number of patients with corrected tetralogy of Fallot exhibit right ventricular diastolic dysfunction,[60-62] probably related to the hypertrophy that accompanies the condition or to some degree of residual stenosis of the right ventricular outflow tract. In any case, diastolic dysfunction may to some extent serve a protective function against pulmonary valve insufficiency, contributing to better exercise tolerance. Apart from an echocardiographic examination, the functional assessment of the right ventricle and cardiopulmonary system should ideally include magnetic resonance imaging, stress testing with ergometry and possibly respiratory testing.

For some years this author has preferred the transatrial/transpulmonary surgical method for correction of tetralogy of Fallot, used in asymptomatic patients aged around twelve months and in symptomatic patients in infancy (given suitable anatomy), or in relatively rare cases as a second stage following an initial palliative shunting procedure at neonatal age. The early surgical results have been excellent,[37] with zero mortality, while from the start detailed prospective monitoring of the patients has included an assessment of right ventricular function over time. The results of that evaluation following the use of the above method in our department have been extremely favorable and are analyzed in a paper published in this issue of the Hellenic Journal of Cardiology.[63]

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