World Journal of Cardiovascular Surgery, 2022, 12, 264-279
https://www.scirp.org/journal/wjcs
ISSN Online: 2164-3210
ISSN Print: 2164-3202

To What Extent Can Transcatheter Devices Replace Open-Heart Surgery in the Treatment of Cardiac Septal Defects?

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How to cite this paper: Somanathan, A.S. (2022) To What Extent Can Transcatheter Devices Replace Open-Heart Surgery in the Treatment of Cardiac Septal Defects? *World Journal of Cardiovascular Surgery*, **12**, 264-279.
https://doi.org/10.4236/wjcs.2022.1210024

Received: August 31, 2022
Accepted: October 28, 2022
Published: October 31, 2022

Abstract

Transcatheter treatments are widespread, having the advantages of being less invasive than surgery with quicker recovery times and reduced physical and psychological consequences. However correct patient selection is vital to optimise outcomes. In the case of an isolated atrial septal defect (ASD), transcatheter closure is preferred. Whilst multiple or large ASDs or ventricular septal defects (VSDs) are best treated through the transthoracic approach. Furthermore, the development of the transcatheter approach has yielded devices that can be used in the transthoracic approach resulting in hybrid techniques. This article aims to evaluate both transcatheter devices and open-heart surgery in the treatment of cardiac septal defects. A brief discussion follows on from the causes and history of cardiac defect treatments.

Keywords

Cardiac Septal Defect, Atrial, Transthoracic, Transcatheter, Septal Occluder, Hybrid

1. Introduction

The heart is comprised of 4 separate chambers, 2 atria and 2 ventricles. The purposes of the ventricles and atria with their intervening septae are to separately pump deoxygenated blood on the right-hand side (pulmonary circulation) and oxygenated blood on the left-hand side (systemic circulation). This is shown in Figure 1 [1] below. Allowing these two separated types of blood to mix (like in an atrial septal defect) can cause problems such as deoxygenated blood being pumped to organs and muscles with these being unable to carry out respiration due to a lack of oxygen. This can result in fatigue and stunted growth in children. This is shown in Figure 2 [1] below.

2. Categorisation of Septal Defects into ASD and VSD

Cardiac septal defects can be categorised into two main types, atrial and ventricular.

An atrial septal defect (ASD) is caused by a hole in the septum which separates the two atria of the heart. There are four different types of atrial septal defects, and these depend on the position of the hole in the septum, as shown by Figure 3 [2].

A ventricular septal defect (VSD) is when the same occurs in the septum dividing the left and right ventricles. Similar to ASDs the type of VSD depends on its location in the septum. Despite both having similar characteristics the causes of ASDs and VSDs are different but both can lead to serious complications as they allow unregulated blood flow, as shown by Figure 4 [2].

The heart septum contains many nerve bundles, and any defect can result in damage to or absence of these nerves which will result in a lack of nerve impulse conduction, resulting in abnormal heart contraction and blood flow.

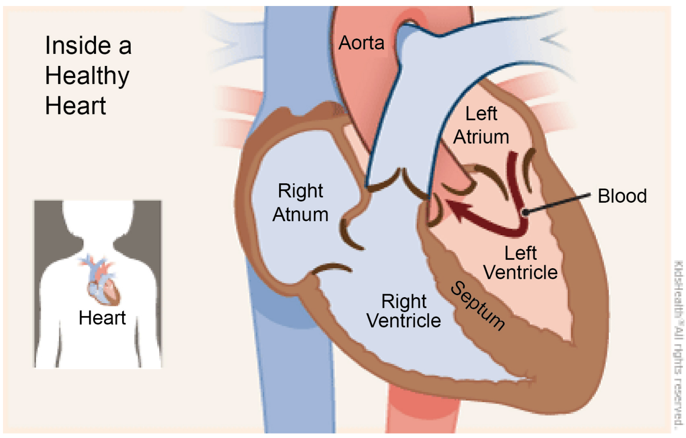

Figure 1. Blood flow in a normal heart.

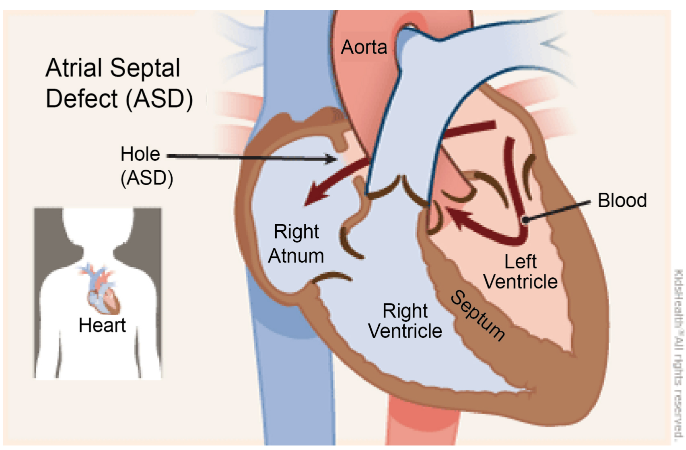

Figure 2. Blood flow in Atrial Septal Defect heart.

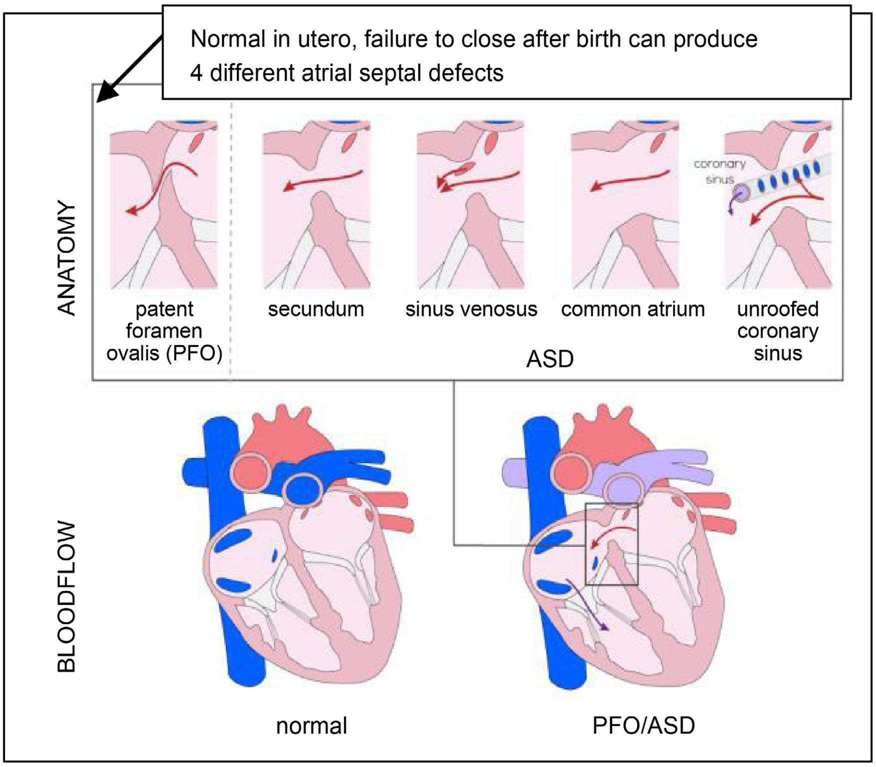

Figure 3. Atrial septal defects.

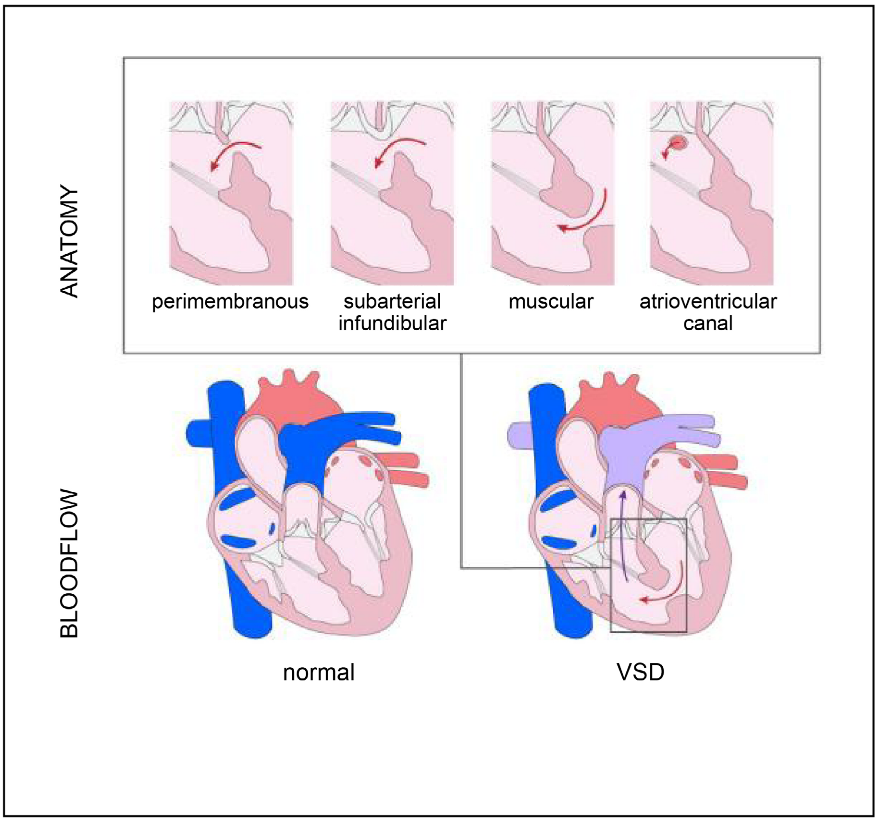

Figure 4. Ventricular septal defects.

The septum dividing the two atria of the heart has been studied and of interest since the 1800s. The first time an ASD came to interest was when a "paradoxical embolism" passed from the pulmonary circulation through an intracardiac defect into the systemic circulation. It is paradoxical as there is normally no direct communication between the two circulations. This was first discovered by Julius Cohnheim a German pathologist in 1877 [3].

This article aims to evaluate transcatheter devices in the treatment of ASDs and VSDs and analyse whether this type of treatment would be more suitable and effective than the more widely used treatment of open-heart surgery.

It is necessary to evaluate both types of treatment to reduce patient morbidity and mortality. These improvements will have positive effects elsewhere, for example societal impacts. Improving the well-being of patients quickly allows them to get back to their job and allows them to provide to society and the economy, by paying tax and not claiming benefits. A longer hospital stay is funded by tax and takes up space which could be taken by another patient. Furthermore, it can have adverse psychological impacts such as depression. Short stays also reduce NHS costs and expenditure; these savings can be used in other areas such as research into the treatment of other conditions.

3. Causes

3.1. Genetic and Environmental

ASDs and VSDs are prevalent among newborn babies. In the womb babies' hearts have several openings in the septa, allowing foetal blood to bypass the non-functioning lungs. This allows oxygenated blood from the placenta to be pumped to the other vital organs. However, these openings are meant to close during pregnancy or shortly after birth when these do not close ASDs and VSDs can persist into life causing problems.

Cardiac septal defects often coexist with other inherited conditions like Downs or Eisenmengers syndromes, as there is a greater likelihood of chromosomal mutations.

These defects occur due to congenital problems or environmental factors. Defects can be random but evidence has shown that families where multiple members suffer from ASDs, these were caused by mutations to genes (e.g. TLL1 gene found on the long arm of chromosome 4) [4]. However, there are many different genetic causes for ASDs. A family history of heart defects is often due to inherited mutations within specific gene sequences, most often found within the long arm of chromosomes5 or 6 [4] resulting in a greater likelihood of VSD forming in children from birth.

Well known environmental causes include excess alcohol consumption during pregnancy resulting in foetal alcohol spectrum disorder [5], as well as Rubella [6] (German measles). Both disrupt normal organ formation and increase the likelihood of atrial or ventricular septal defects.

VSDs are more likely to occur in women, senior people, those with high blood pressure or chronic kidney disease and those who have a family history of heart defects. Acquired VSD can be caused by a myocardial infarction (death of heart muscle due to lack of blood supply) and these are often fatal. This is caused when the septum is starved of blood and the tissue within the septum begins to weaken and die and thus a hole can form in the septum due to the high pressure. This will then lead to the tissue within the septum turning into scar tissue. This tissue will have nerve bundles which are unable to conduct impulses, and this causes heart failure and death as conduction problems cause the heart to be unable to contract properly.

3.2. Acquired Causes

A teratogen is any agent that acts during embryonic or foetal development to produce an alteration of form or function. In this sense alcohol and Rubella act as teratogens.

Paroxetine (an anti-depressant) used in early pregnancy (first trimester) can cause a greater likelihood of development of ASDs and VSDs [7]. This is because during the first trimester formation of the foetuses organs occurs, and thus drugs such as Paroxetine can hinder correct organ formation resulting in defects.

Downs Syndrome children in whom the mother has not taken folic acid supplements during pregnancy have a greater likelihood of ASDs [8].

3.3. Symptoms and Presentation of Illness

Many babies do not display symptoms or signs of ASDs. However, when present, symptoms include a bluish colour around the mouth or on the lips and tongue, poor appetite, tiredness resulting in poor feeding, shortness of breath and frequent lung infections. These will all result in stunted growth. It is these symptoms which bring the patient into hospital allowing the defect to be diagnosed.

After detecting the heart murmur that suggests a cardiac defect, typical investigations include, a chest X-ray (an image of the heart and surrounding organs), anelectrocardiogram (ECG—a record of the heart's electrical activity) and an echocardiogram (a picture of the heart and the blood flow through its chambers using ultrasound). This is often the primary tool used to diagnose a defect.

If symptoms go unnoticed when growing up into adulthood these can develop more seriously.

These include shortness of breath during exercise, fatigue, swelling of legs and abdomen and an irregular heartbeat.

There is no variation of symptoms with congenital or acquired defects.

3.4. Geographic and Demographic Distribution

There is a positive correlation between altitude and incidence of ASDs, as shown by **Figure 5** [9]. As altitude increases so does the pressure within the right

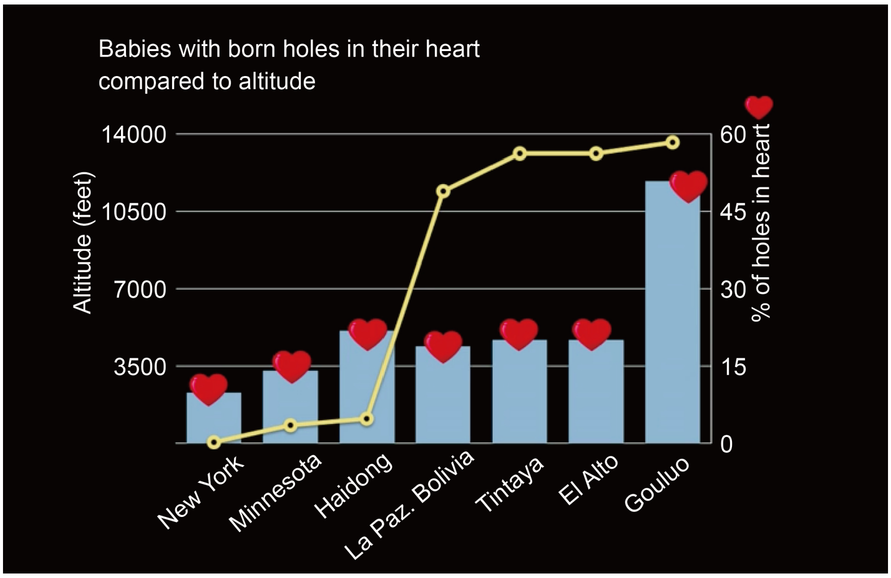

Figure 5. Babies with born holes in their heart compared to altitude.

atrium, leading to tissue weakening and a greater likelihood of an ASD occurring or persisting (not closing after birth). With higher altitudes the size of the ASD will be much larger than normal due to the higher pressure.

Studies on congenital heart defects, which include ASD and VSD, showed that there was a higher prevalence in Asian and Black ethnic groups compared to white ethnic groups. Furthermore, non-white ethnic groups lived in more deprived areas compared to white children. This can result in pregnant mothers-making poorer lifestyle choices such as poor diet, lack of exercise, alcohol consumption and smoking. It is essential that healthcare provision mitigates ethnic disparity, including through timely identification of defects at screening, allowing effective interventions. Future research should explore the factors underlying ethnic variation and impact on longer-term outcomes [10].

3.5. Evaluation of Treatments

In 1947 Cohn tried to block the atrial septal defect through extracardiac surgery by invaginating (push in from outside) the atrial wall in dogs. However, in 1948 Murray tried this atrial wall invagination in a 12-year-old girl. This was proved to be unsuccessful through further catheterization of the heart. This involves injecting X-ray opaque dye into the heart and tracking its progress. The first successful clinical operation of an atrial septal defect was by Santy *et al.* in 1949. This procedure involved using the atrial appendage, a sac of tissue on the side of the atrium, to invaginate the atrium and thus block the atrial septal defect. Other procedures involved the use of polythene buttons by Swan *et al.* in 1950, as shown in **Figure 6** [11], to invaginate the atrial appendage and block the atrial septal defect with transatrial sutures [3]. In 1976, King *et al.* attempted the first transcatheter closure of an ASD in human beings.

Figure 7 [12] shows the passage of a transcatheter device from the femoral

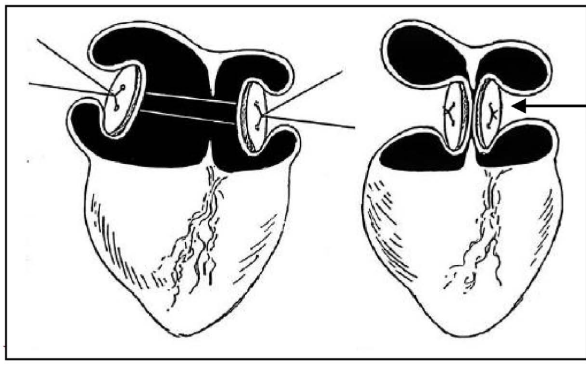

Figure 6. Swan *et al.* atrial septal defect closure.

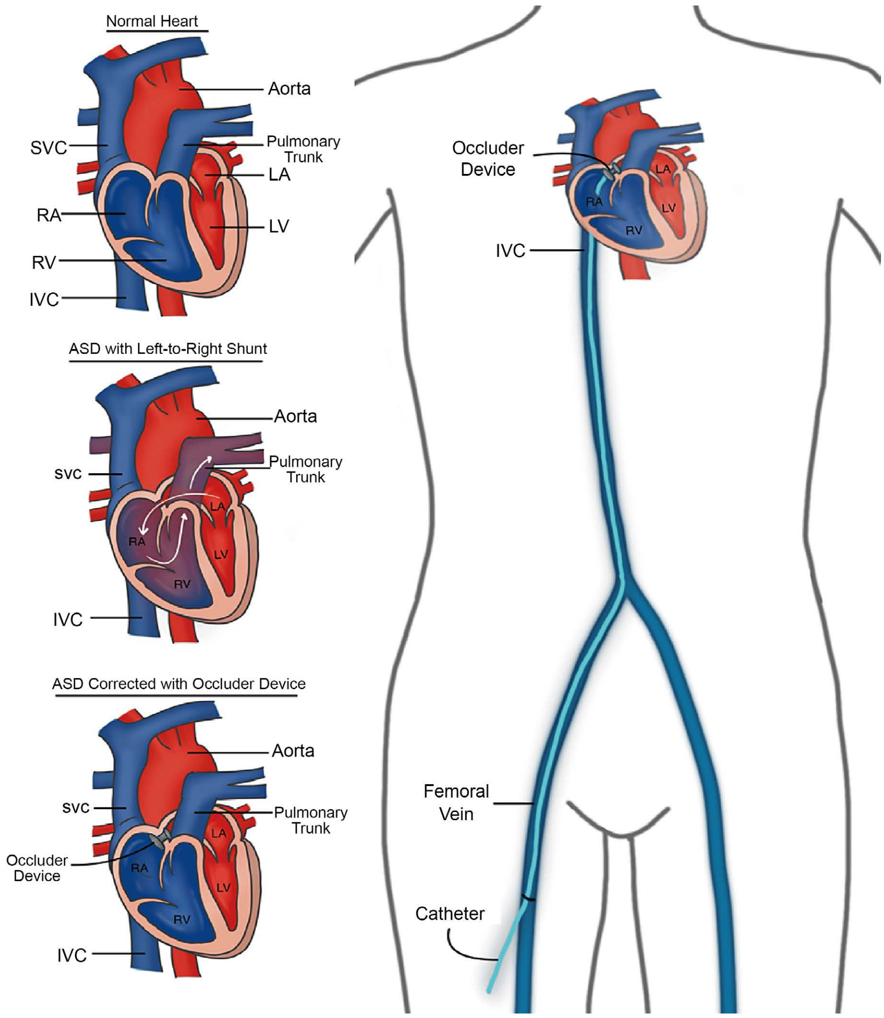

Figure 7. Passage of a transcatheter device from the femoral vein to the heart.

vein to the cardiac defect.

3.6. Open Heart Surgery

The different types of transthoracic (opening the chest wall to gain access to the heart) closure involve different types of incisions. This can be done by a median sternotomy 1, right anterolateral thoractomy 4, and right axillary thoractomy 5. The number of each cut matches that on **Figure 8** [13]. These different cuts are dependent on the patient's opinion, height, weight, and sex. All patients when undergoing this procedure will be under cardiopulmonary bypass (CPB) as the heart must be stopped for the operation. Different materials can be used to block defects including pericardial (a tissue layer surrounding the heart) patches. This is then followed up with transatrial sutures.

Transthoracic closure of septal defects allows greater flexibility into the size of the defect repaired, as transcatheter devices require modification and must be specific to each type of hole. This explains why transthoracic closure is more widely used in areas at higher altitudes as the defects present tend to be much larger.

The transthoracic approach is a very successful procedure with little to no complications after closure. The transcatheter procedure has a lower success rate due to dislodgment of the device.

Transcatheter devices require highly skilled operators and a large amount of training and practice. While transthoracic closure is a much simpler procedure.

If multiple defects are present within a patient, the transthoracic approach is a much more effective procedure as it is easier to close them and does not require multiple devices. In addition to this when detecting defects within the heart, transthoracic echocardiogram can be unreliable due to the multiple layers between the skin and the heart interfering with the formation of a clear picture. Thus, defects can go unnoticed. Transthoracic closure allows undiagnosed defects to be closed during the procedure while the same is not true for transcatheter procedures.

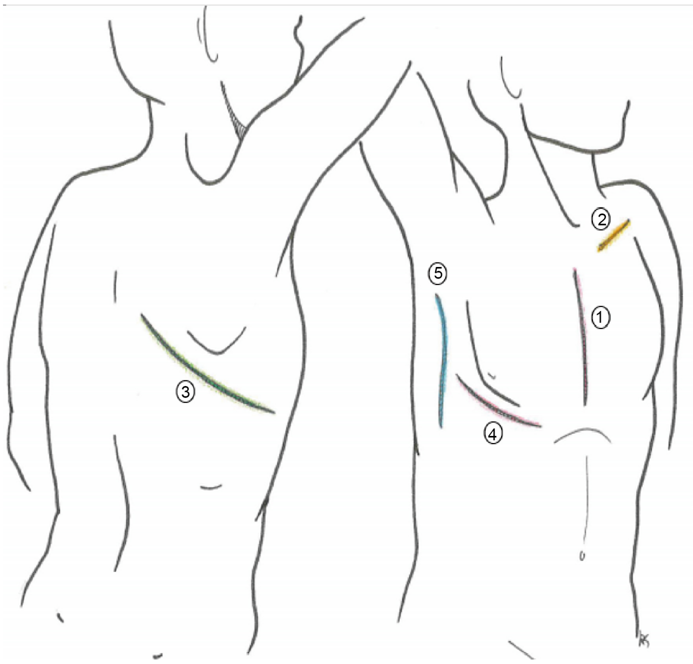

Figure 8. Different types of surgical cuts to treat cardiac septal defects.

The transthoracic approach involves large cuts and scarring. As this defect is prevalent in young infants these scars can often have a large psychological impact when growing up as the cosmetic effect of the scar can be unpleasant for the patient, as the scar is large and in an obvious place it can't be hidden. Transcatheter requires a small cut near the groin area which is much more discrete with much less of a cosmetic effect and psychological toll on patient.

Transthoracic closures involve longer stays in hospital and intensive care due to the morbidity of a traumatic procedure that requires CPB. This has a knock-on effect as this causes patients, or the parents of child patients to be away from their jobs for longer, preventing them from working and contributing to society and the economy. Also staying in hospital for long periods of time prevents admission of other patients and increases the likelihood of hospital-acquired illnesses like chest infections. Longer hospital stays also put a larger strain on the NHS with more money spent on beds and rooms which could be spent on other patients or research into other diseases.

While mortality rates for this procedure are very low there are high rates of postoperative pulmonary infections. Patient selection is key when deciding upon whether they will be fit enough to undergo this traumatic procedure.

Transthoracic closure is a much more expensive procedure compared to transcatheter as cardiopulmonary bypass machines are required which can be extremely costly, in addition to the multiple highly trained staff required during and after the procedure and the theatre, ITU bed and other resources (e.g., blood and drugs) also needed.

3.7. Transcatheter Procedures

The most common type of septal occluder is the Amplatzer ASD device, as shown in **Figure 9** [14]. This is used in both transcatheter and intraoperative closures. This is made of an alloy of Nickel and Titanium and consists of a sheath and a pushing rod. When inserted into the defect the device can be left within the patient for the rest of their life and the wire mesh allows tissue to grow over the device allowing it to become part of the heart muscle, shown in **Figure 10** [15].

There is research into biodegradable devices such as BioSTAR which is made of collagen and is fully replaced by host tissue during recovery. This can also prevent problems associated with rejection due to nickel allergy.

Patients undergoing transcatheter closures only require to be in hospital for 1 day, with no ICU stay, which is a much shorter time than transthoracic closure thus the morbidity and societal impacts are much less using this method.

Cosmetically transcatheter procedure requires a needle stick into the groin in order to enter the femoral vein, and thus there are no large scars or psychological impacts left on the patients.

There are also fewer complications from this procedure as transthoracic closure can result in a greater likelihood of postoperative pulmonary infections. Transcatheter closure also results in much less postoperative pain.

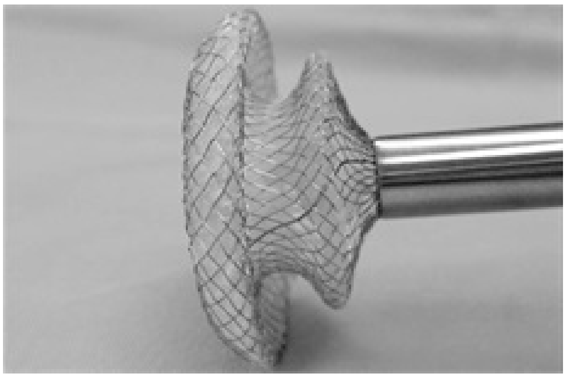

Figure 9. A typical transcatheter device.

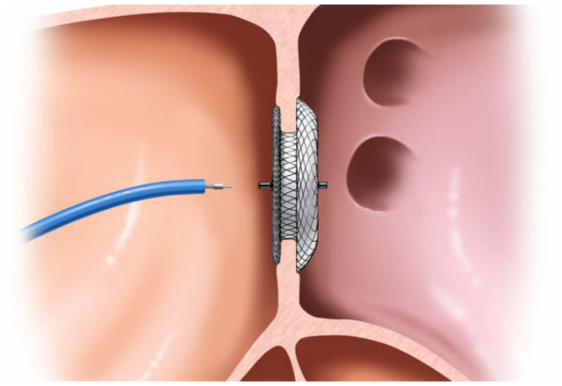

Figure 10. Transcatheter device in place closing an ASD.

Patient selection for transcatheter closure is less important as this procedure does not lead to large amounts of trauma and thus most patients will be fit enough.

There is no general anaesthesia required—this carries its own risks such as infection, allergy, post-anaesthetic vomiting with the risk of aspiration and hallucinations.

In some instances, dislodgement of transcatheter devices can occur, resulting in embolisation and severe complications, like a pulmonary embolism or a stroke. This will require emergency surgery resulting in increased morbidity, mortality and cost.

Use of transcatheter devices only work when there is a rim around the defect in order for the device to latch onto the septum properly. Thus, larger defects with a deficient rim commonly result in dislodgment of the device, preventing use of transcatheter closure.

Some devices may need to be modified and made larger in order to fill the whole defect.

This device can often cause an immune response as rejection occurs due to nickel allergy or other factors. The device can also irritate the septum if not placed properly and can result in aortic erosion.

Blood thinners such as Heparin must be used in order to prevent clots forming and allow the device to travel safely from vein to heart without being blocked. This carries the risk of internal bleeding.

If multiple defects are present requiring multiple devices, it is more efficient to use transthoracic closure. Transthoracic echocardiogram can be unreliable at times when diagnosing lesions thus transcatheter closure can be extremely risky if more than one defect is present or the defect location has been incorrectly identified.

Transcatheter closures require skilled and experienced operators to use the device effectively and close the defect. As this procedure is not extremely common there will be few operators who are well enough trained.

3.8. Hybrid Techniques

These involve a combination of transthoracic incisions and closure using a transcatheter device. Smaller incisions are needed, 2 - 3 cm in hybrid and 6 - 9 cm in transthoracic. Smaller incisions result in less cosmetic issues and less psychological impact on the patient. Right axillary thoractomy is often used in hybrid techniques while transthoracic mainly uses median sternotomy which is much less discrete and a larger scar. Disadvantages are the same as for transcatheter and transthoracic techniques

3.9. Overall Outcomes and Cost-Benefit Analysis

Transcatheter closure of ASD using an Amplatzer septal occluder has a mean cost of around $11,541 while closure of the same type of ASD can cost around $21,780 by transthoracic surgery [16].

With transcatheter patients having to spend overall 1 day in hospital for the procedure followed by no stay in ICU, while on the other hand transthoracic closure involves a much longer stay in hospital and ICU, this has a much larger impact in terms of psychology, morbidity and on society due to patients being away from jobs, claiming benefits and taking up NHS time, space and resources.

Furthermore, prolonged stays in hospital from transthoracic closure can result in greater morbidity due to hospital acquired illnesses affecting these patients. With treatment for ASDs by transthoracic closure postoperative pulmonary infections are common while this is not the case for transcatheter procedures.

Thus, in many instances the transcatheter approach is preferred.

3.10. Future Improvements

There are 3 different types of transcatheter device: Amplatzer device (ASO), OcclutechFigulla Flex-II (OFF-II), BIOStar occluder.

ASO (**Figure 11**) [17]—the most common type of device, made from an alloy of Nickel and Aluminium. The main issues associated with this are Nickel allergy and general irritation causing possible septal erosion. There is also the problem of defect size and presence of a sufficient rim which is needed for the device to properly attach otherwise dislodgement can occur.

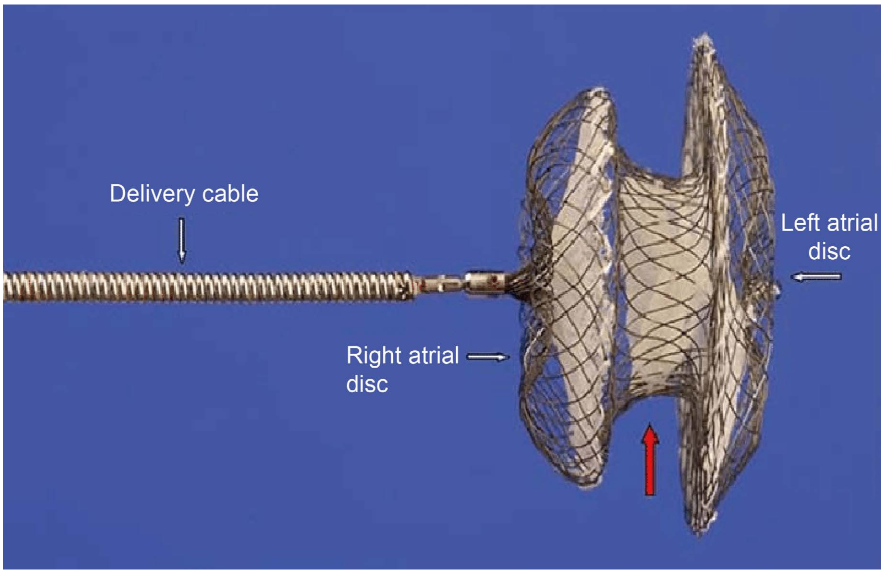

Figure 11. ASO closure device.

OFF-II (Figure 12 [18])—This device is very similar to ASO with a few differences. It is made of Nitinol mesh (Nickel and Aluminium alloy) but is covered with aluminium oxide to prevent Nickel release and general rejection by the immune system. Furthermore, ASO has a microscrew in its left atrial disc making it more rigid and less likely to become detached, while OFF-II has a ball and socket attachment which increases the flexibility and softness of the device, thus allowing it to be more flexible and attach to larger defects with deficient rims. This greater flexibility increases the time taken for the device to align with the defect thus increasing overall mean procedure time when compared to using ASO. OFF-II contains Spun bonded PET patches (a high mechanical strength non-woven fabric) behind its mesh, which allows faster tissue growth upon the device and quicker tissue closure of the septal defect [19].

BIOStar (Figure 13 [20])—this involves using a septal occluder made from collagen taken from porcine submucosa (collagen within tissue of pigs' small intestines) coated in heparin (blood thinner) This device can be used as it decreases the likelihood of rejection as no foreign bodies are injected. This device is the first septal occluder to be completely reabsorbed and covered by the host tissue. Thus, accurately conforming to the internal shape of the heart and improving its functionality.

3.11. Robotic Surgery

Da Vinci robotsare often used in the treatment of septal defects with pericardial patches. While the initial expense of robotic surgery can be high, over time it can prove extremely useful and decrease the cost of transthoracic surgeries due to the fewer number of staff required during the procedure. This is shown in Figure 14 [21].

Patient reported outcomes have shown to be better with transcatheter closure

Figure 12. OFF-II closure device.

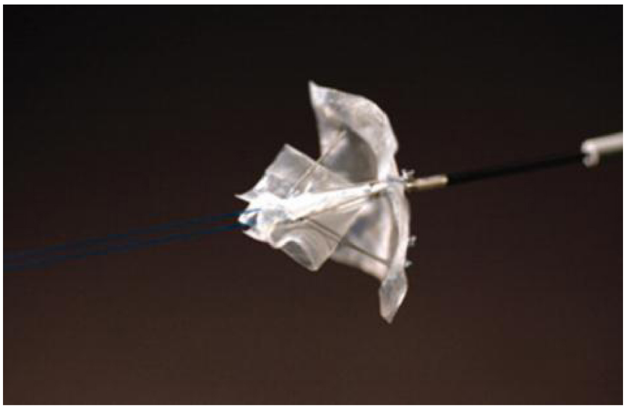

Figure 13. BIOStar closure device.

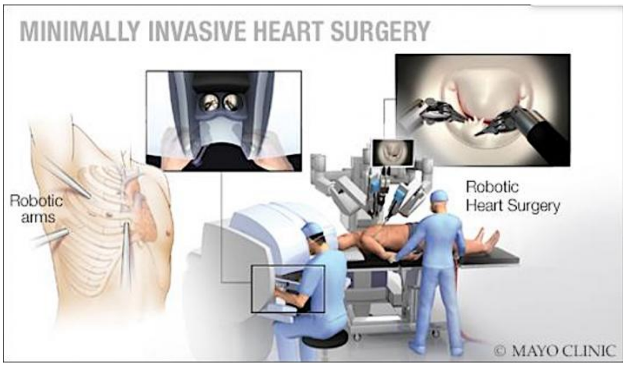

Figure 14. Robotic surgery treating cardiac septal defects.

compared to transthoracic. This is due to the cosmetic effects each procedure has. Transcatheter devices have little to no cosmetic effect on the patient as the procedure involves a needle prick near the groin region which is extremely discrete and unnoticeable. While on the other hand transthoracic or hybrid procedures require cuts from 2 - 9 cm in size which can be in very obvious areas of the body. As this defect is prevalent in young children this can result in high psychological impacts and thus patient reported outcomes favour the use of transcatheter closure.

3.12. Better Protocols for Better Outcomes?

Both transthoracic and transcatheter closures are better suited to different types of septal defects. For example, in most instances of large defects with deficient rims, transthoracic closure is more suited as transcatheter can result in dislodgement. Thus, the larger defect present at higher altitude favours transthoracic treatment.

With multiple defects transthoracic closure is better suited and less expensive as multiple devices are required for transcatheter treatment.

Patients with viscous blood or too thin blood may not favour transcatheter devices due to complications resulting from device transfer from the femoral vein to the heart. Patients with large fatty deposits in blood vessels face similar problems.

VSDs do not suit transcatheter techniques as the beating heart prevents the catheter passing through atrio-ventricular valves which are constantly opening and closing.

4. Conclusions

Following the discovery of ASDs, invagination of the atrial appendage secured by transatrial sutures became the first successful therapeutic procedure. This progressed to the successful use of pericardial patches using a transthoracic approach, now the mainstay of treatment. With the advancement of technology, less invasive transcatheter approaches have also been developed.

Whilst each approach has its own advantages and disadvantages, in general, the transcatheter approach is the first choice for an isolated ASD, the hybrid approach the second choice, and surgical repair the last resort. In cases of large ASDs, multiple ASDs, or VSDs, transthoracic surgery is favoured.

Correct patient selection is essential for a successful outcome and will dictate the approach used.

The development of transcatheter devices has produced novel methods of repairing different-sized defects. This includes techniques used in open-heart surgery, resulting in a hybrid approach. Furthermore, the advent of biodegradable devices allows incorporation of native tissue by acting as a scaffold, thus minimising the likelihood of rejection.

Whilst the transcatheter approach has a significant role to play in the treatment of cardiac septal defects, its use is limited by the various factors previously mentioned—defect location (ASD vs VSD), number, size, patient stability and operator experience.

On the other hand, minimally invasive robotic surgery allows successful repair of defects on a beating heart with minimal use of CPB and a reduction of its associated postoperative morbidity.

Ultimately the future of this field will depend upon the appropriate use of all these techniques involving a multi-disciplinary approach such that the best possible outcome for the patient is achieved.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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