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The Role of Robotic Surgery in Defining Pathogenesis, Diagnosis, and Modern Treatment of Thoracic Outlet Syndrome

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Abstract

Robotic surgery has been a transformative force in minimally invasive thoracic surgery. Robotic surgical technology has impacted surgery of the lung, mediastinum, esophagus, and the sympathetic chain. However, in one area of thoracic surgery, surgery for Thoracic Outlet Syndrome, robotics has not only impacted the minimally invasive surgical approach to the resection of the first rib, but it has allowed for a better understanding of the pathogenesis of the disease. Historically, the only consistent aspects of Thoracic Outlet Syndrome (TOS) have been the confusion among medical practitioners, difficulty in making the diagnosis, and poor results with surgical intervention. The present understanding of TOS is that it is the manifestation of a congenital malformation of the first rib where an abnormal boney tubercle at the costo-sternal joint results in compression of the subclavian vein (SV) at its junction with the innominate vein. The compression of the SV leads to a spectrum of diseases, which range from neurologic symptoms resulting from venous congestion of the upper extremity nerves to thrombosis of the SV with prolonged compression. Robotic technology allows for the precise removal of the "offending portion" of the first rib. This technique is associated with the best-reported results in patients with TOS.

Keywords

Thoracic Outlet Syndrome, TOS, Paget Schroetter Syndrome, Robotic Surgery, First Rib Resection, Robotic First Rib Resection

1. Introduction

Robotic surgery has been a transformative force in minimally invasive thoracic surgery. Robotic surgical technology has impacted surgery of the lung, mediastinum, esophagus, and the sympathetic chain. However, in one area of thoracic surgery, surgery for Thoracic Outlet Syndrome, robotics has not only impacted the minimally invasive surgical approach to the resection of the first rib, but it has allowed for a better understanding of the pathogenesis of the disease. This manuscript outlines the transformative role of robotics in clarifying the pathogenesis and treatment of a disease that had long been an enigma in thoracic surgery.

2. The Index Case: The "Eureka Moment"

Legend has it that Archimedes shouted "Eureka", Greek for "I have got it" when he jumped naked from his bath and exclaimed the discovery of the relationship between water displacement and the weight of an object. Through the years, a number of circumstances surrounding this moment have given rise to the Legend of Archimedes. Some have attributed this exclamation to solving the problem of the purity of the Crown of the Syracuse King, Heiro II. Others have recounted it in terms of Archimedes' ability to build a ship that was the largest in the ancient World, Syracusia, using the principle of buoyancy that he discovered while in a bath. No matter which story is the root of the exclamation "Eureka", what is certain is that a "eureka moment" has come to represent the discovery of a hereto unknown and totally unexpected phenomenon. Such a moment was brought about when the surgical robot was applied to the enigma, which is Thoracic Outlet Syndrome (TOS).

Our group at the George Washington University Medical Center was one of the first adopters of robotics for thoracic surgery. The first robotic thoracic surgical procedure was performed by our group in 2003. Shortly thereafter, a 47-year-old man presented for a robotic surgical approach to right-sided lung pathology. Of significance, this patient had previously undergone a right transthoracic first rib resection for Neurogenic TOS. Unfortunately, the patient's upper extremity neurologic symptoms persisted after the surgery. A chest radiograph and computerized axial tomography of the chest clearly showed the absence of the first rib. As has been reported in so many patients who have persistent symptoms following first rib resection for "neurogenic" TOS, this patient was placed in the recurrent category. During the robotic lung surgery, we observed that the costosternal joint between the first rib and the sternum was intact. This observation was facilitated by the high-resolution three-dimensional camera of the surgical robot that could be driven right up to the costosternal junction. The rib had been transected just distal or lateral to the joint. There were venous collaterals denoting backflow from the subclavian vein. However, prior to the rib resection, the patient had no symptoms of venous thoracic outlet syndrome. Following the recovery from the lung surgery, the patient underwent a dynamic venogram of the right upper extremity, which clearly showed extrinsic compression of the subclavian vein at its junction with the innominate vein. As will be outlined further in this manuscript, venous congestion has been found to be a significant etiologic factor in nerve pain, absent any nerve or perineural pathology. It was hypothesized that the patient's persistent neurologic symptoms following first rib resection may have been attributable to venous congestion and secondary neurologic symptoms resulting from extrinsic compression of the subclavian innominate junction by a bony abnormality at the costosternal joint. On a research protocol, the patient underwent a robotic transthoracic disarticulation of the costosternal joint. In the operating room, the venous collaterals decompressed, and pulsation was returned to the subclavian vein. Postoperatively, the patient had total resolution of his upper extremity neurologic symptoms. This index case gave rise to the "eureka moment" for TOS. It was hypothesized that perhaps the neurologic symptoms in the largest group of patients with TOS were the result of venous congestion with secondary neurologic symptoms as opposed to direct nerve compression. The "eureka moment" began a journey of discovery that culminated in defining the pathogenesis and the modern robotic surgical approach to TOS. What follows is "the Rest of the S Key Words: Thoracic Outlet Syndrome, TOS, Paget Schroetter Syndrome, Robotic Surgery, First Rib Resection, Robotic First Rib Resection Tory."

In 1956, the term "Thoracic Outlet Syndrome" (TOS) was first proposed for the purpose of unifying the symptoms associated with several related upper extremity neurovascular compression syndromes [1]. Since that report, it has been surmised that TOS results from compression of the neurovascular bundle in the "Thoracic Outlet" [1]-[5]. The thoracic outlet has been divided into three narrow spaces where there is the potential for compression of the brachial plexus, subclavian artery, or subclavian vein [1]-[3]. The first of these compartments is the Scalene Triangle, which is formed by the upper border of the first rib, the anterior scalene, and the middle scalene muscles. The second compartment is the costoclavicular space which is bordered by the medial aspect of the first rib at the costosternal joint, the sternum, and the clavicle. Finally, the third compartment is under the tendon of the pectoralis muscle and the coracoid space.

These three spaces, especially the costoclavicular space, become even more constricted when the arm is elevated above the shoulder.

3. Classification of Thoracic Outlet Syndrome

Since the report by Peet, there has been significant inconsistency in the classification and diagnosis of TOS [4] [5]. TOS has been categorized according to symptoms, the compressed component, the space in the thoracic outlet being narrowed, or the etiology of compression [2] [4] [5].

The most widely used classification of TOS is based on the component of the neurovascular bundle that is being compressed. These are the subclavian artery, the subclavian vein, or the brachial plexus. As a result, TOS has been classified as Arterial TOS (A-TOS), Venous TOS (V-TOS) and Neurogenic TOS (N-TOS). The latter class is frequently subdivided into true NTOS (TNTOS) and disputed NTOS (DNTOS) according to the presence or absence of objective findings related to nerve compression [4] [5].

Some authors have advocated recognizing TNTOS and DNTOS as entirely separate entities and have proposed that TOS should be classified into 5 categories [4].

Neurogenic TOS: Neurogenic TOS accounts for over 95% of the cases, followed by venous (3% - 5%) and arterial (1% - 2%) [2]. Neurogenic TOS has been classified as "True" or "Disputed". True NTOS has been reported in the literature as "Classic TOS" or "cervical rib and band syndrome" [3]-[9]. In these patients, the predominant etiology is a fibrous band that extends from the first thoracic rib to a bony anomaly of the last cervical vertebra, which is either a cervical rib or an elongated transverse process. This results in compression of the lower band of the brachial plexus, which elicits very explicit symptoms of nerve compression [10]. In these patients, a cervical x-ray shows the bony abnormality, a neurologic exam is lateralizing and consistent with nerve compression, and nerve conduction studies are diagnostic. Although cervical rib disease is the first etiologic process that is entertained by most practitioners who face the possibility of the diagnosis of TOS, in fact, this is truly the least likely cause. The prevalence of this subtype of NTOS is estimated at around 1 per 1,000,000 people, and it represents only 1% of NTOS cases [11]. The modern understanding of TOS advocates for more accurately classifying cervical rib or cervical bands as Cervical Rib Syndrome [10].

The majority of patients with symptomatic NTOS have non-specific findings on physical examination, and almost all present with negative nerve conduction velocity (NCV) studies. In the 1980s, Wilbourne asserted that a positive NCV study should be a sine qua non for the diagnosis of neurogenic TOS. Wilbourne further reasoned that patients with an identical clinical picture, but without a positive NCV study should be considered as having 'Disputed' NTOS ("D" NTOS). NCS is highly specific for the diagnosis of brachial plexus compression in the cervical region. On the other hand, NCS is not at all specific or sensitive in diagnosing patients with neurologic symptoms of the upper extremity who would be classified as "disputed TOS".

Disputed NTOS accounts for 95% - 99% of NTOS [12]-[17]. There have been reports in the literature that the incidence of DNTOS in the general population is as high as 8% [12]-[17].

Even though disputed NTOS is recognized as a clinical entity, the actual details of its pathogenesis are controversial. Some researchers support that it results from pressure on the brachial plexus, whereas others advocate that it comprises a vascular disorder where the subclavian vein is compressed in the thoracic outlet. The intermittent positional obstruction of the subclavian vein in the thoracic outlet, in the absence of thrombosis, which has been called McCleery syndrome, maybe a significant etiologic factor in patients with DTOS.

Notwithstanding impressive evidence over decades that NCV demonstrates little sensitivity or specificity in patients with NTOS, some physicians still consider all cases of NTOS as "disputed." Therefore, historically, in patients with "Disputed" NTOS, surgery has been used as a last resort in order to establish the diagnosis. Using surgery as both a diagnostic and therapeutic modality in patients with "DNTOS" has resulted in a high rate of false positive findings, a heterogenous patient population, poor surgical results, and a high rate of complications [4] [5]. Furthermore, this approach has added to the confusion in diagnosing NTOS in general.

Venous TOS (VTOS): VTOS is considered a rare form of the syndrome that occurs due to thrombosis of the subclavian or axillary vein following prolonged compression. It has also been referred to as effort thrombosis or Paget-Schroetter syndrome. VTOS predominantly affects men on their dominant hand because of repetitive use of the upper extremity, and it accounts for 5% of all TOS cases. VTOS, which presents as Paget Schroetter syndrome, is easier to recognize. This has resulted in recent reports that have asserted that its incidence might actually be higher at around 20% - 30% of all cases of TOS.

Arterial TOS: The ATOS is the rarest form of TOS and results from subclavian or axillary artery compression. It appears to affect both genders across all age groups. Arterial TOS is associated with cervical rib disorders and does not result from compression in the thoracic outlet. Arterial compression leads to intravascular turbulent flow and damage of the intima, which predisposes to clot formation, distal emboli, local dilation of the artery, and aneurysm formation.

In recent publications, following findings from modern dynamic imaging, Gharagozloo *et al.* have suggested that the pathophysiology and classification of TOS should be reconsidered [18]-[23]. They have asserted that neurogenic and venous TOS symptoms are clinical manifestations of the same underlying pathology, which occurs primarily from compression of the subclavian vein. Furthermore, they have proposed that any form of compression to the neurovascular bundle from cervical ribs or any other cervical vertebra abnormality (fibrous bands, bone anomalies, or incompletely formed cervical ribs) should not be considered part of TOS but instead should be classified as an independent syndrome: Cervical Rib Disease.

4. Modern Understanding of the Pathogenesis of Thoracic Outlet Syndrome

4.1. Venous TOS or Paget Schroetter Syndrome

Recently, examination of the medial aspect of the resected first ribs in patients with PSS has demonstrated the presence of a congenitally malformed bony tubercle which forms a tighter and wider joint at the junction of the first rib and the sternum [7]. In a number of patients with a wider tubercle, there is even a second pseudarthrosis in the head of the clavicle. It has been observed that the wider and less mobile cost-sternal joint "locks" the medial aspect of the first rib into place and results in extrinsic compression of the boney tubercle onto the SV at its junction with the innominate vein. Therefore, the abnormal medial aspect of the first rib compresses the SV at the "thoracic outlet". This abnormal tubercle on the medial aspect of the first rib can be seen in three-dimensional (3D) reconstruction of computerized axial tomograms in patients with PSS (**Figure 1**). In addition, the extrinsic compression of the SV by the tubercle at the medial aspect of the first rib can be demonstrated on dynamic magnetic resonance angiography (MRA) with maneuvers and dynamic venography (Figure 2). Furthermore, these studies clearly demonstrate that the SV compression increases with elevation of the arm above the shoulder. It can be surmised that without the benefit of sophisticated modern imaging and relying only on intraoperative observations, it is likely that historically, surgeons have erroneously referred to this tubercle as the hypertrophied costoclavicular ligament, and the hypertrophied scaleneus anticus tubercle. In patients with PSS, Gharagozloo *et al.* have demonstrated that disarticulation of the costo-sternal (SC) joint and resection of the "offending portion" of the first rib (portion of the rib medial to the SA) results in decompression of the SV [8]-[10].

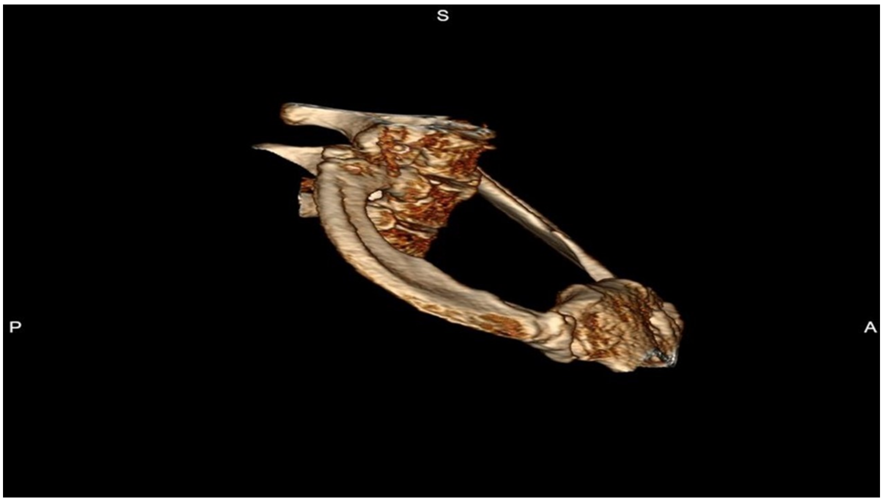

Figure 1. Three-dimensional CT reconstruction of the first rib in a patient with TOS. The abnormal costosternal joint is clearly demonstrated.

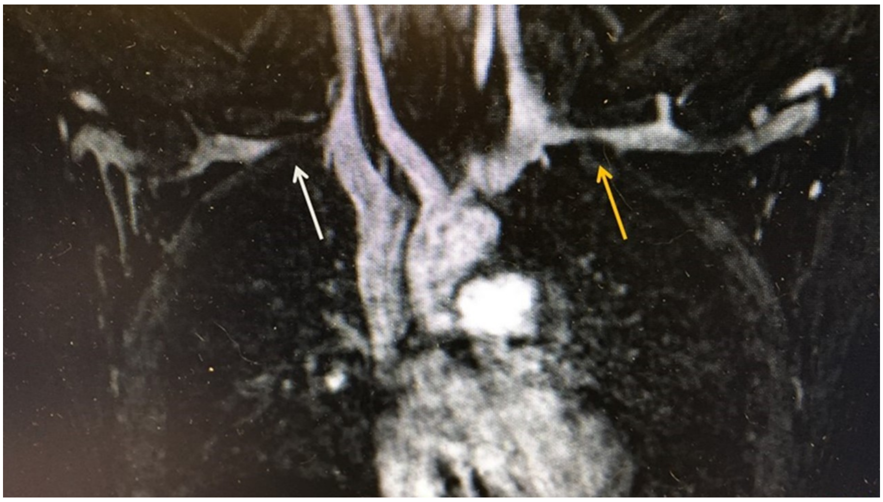

Figure 2. Magnetic resonance angiogram shows extrinsic compression of the left subclavian vein at its junction with the innominate vein by an abnormally developed first rib (yellow arrow). The disease is present on the right side (white arrow), demonstrating the bilateral nature of the disease.

In a recent study, Eighty-three patients underwent transthoracic robotic first rib resection for PSS. There were 49 men and 34 women. The mean age was (24 ± 8.5) years. 27/83 patients (31%) required endovascular venoplasty to completely open SV after the relief of the extrinsic compression. At 3, 6, 12, and 24 months, in all patients, MRA with maneuvers showed relief of extrinsic compression and patency of the SV. Two years after robotic resection of the offending portion of the first rib and obtaining patency of the SV, all patients remained asymptomatic and had full function of the affected upper extremity [10]. Furthermore, these authors have reported that preoperative dynamic MRA has been demonstrated to have a predictive value of 100% for surgical success in patients with PSS. They have suggested that the medial aspect of the first rib, which compresses the SV at its junction with the innominate vein, should be called the "offending portion" of the first rib, and this syndrome should be referred to as "subclavian vein compression syndrome".

In addition, dynamic MRA in patients with PSS has demonstrated the presence of bilateral disease in the head of the first rib (**Figure 3**). This observation further clarifies reports of PSS affecting the contralateral extremity and supports the congenital pathogenesis of the disease. Therefore, it has been suggested that PSS results from a congenital malformation of the first rib, which compresses the SV in the thoracic outlet, and with prolonged compression stemming from activities that elevate the arm above the shoulder, result in thrombosis of the vein.

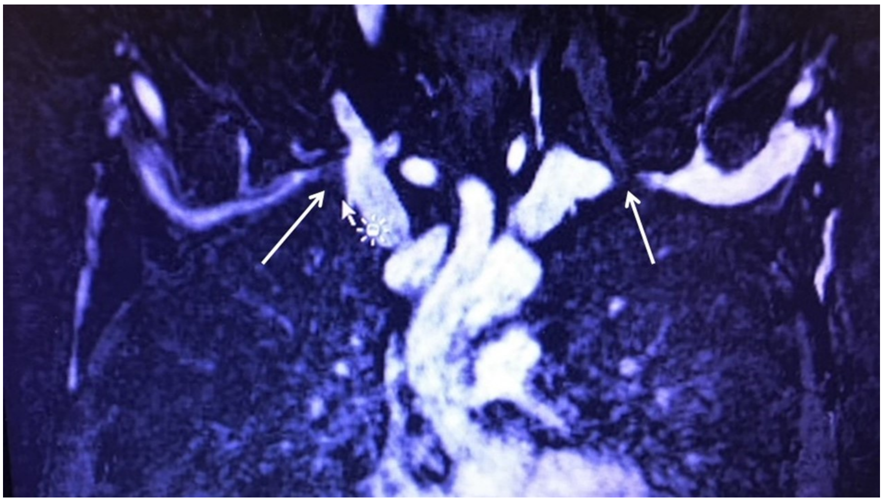

Figure 3. Magnetic resonance angiogram shows bilateral extrinsic compression of the subclavian vein at its junction with the innominate vein by an abnormally developed first rib (white arrows).

4.2. "Neurogenic" TOS

A study of patients with neurogenic TOS who experienced persistent upper extremity pain following first rib resection by the transaxillary and supraclavicular approaches revealed persistent extrinsic compression of the subclavian innominate junction on dynamic MRA. These patients underwent robotic video-assisted exploration of the chest, which showed a persistent SC joint despite evidence for prior removal of the first rib. Robotic disarticulation of the cost-sternal joint and removal of the remaining portion of the first rib, which bore a tubercle similar to that which had been previously described in patients with PSS, alleviated the extrinsic compression of the subclavian-innominate vein junction on postoperative dynamic MRA and resulted in relief of Neurogenic symptoms in all patients [3]. Based on this observation, it was hypothesized that neurogenic TOS may be the manifestation of nerve pain that results from venous compression and venous ischemia of the nerves in the upper extremity. This hypothesis is based on the fact that the upper extremity is fed by a single artery and vein as an "end organ". In such a setting, studies have demonstrated that the blood-nerve barrier in the nerve root was more easily broken by venous congestion than by arterial ischemia. Venous congestion may be an essential factor precipitating circulatory disturbance in nerve roots and inducing neurogenic intermittent claudication [5]. Therefore, compression of the SV at its junction with the innominate vein may result in elevation of venous pressure, a decrease in arterial flow, and relative ischemia of the nerves of the upper extremity. Venous ischemia of the upper extremity nerves may manifest as pain, tingling, paresthesia, numbness, and varying degrees of neurogenic intermittent claudication, depending on the degree and duration of venous compression. Elevation of the extremity above the shoulder may result in greater compression of the SV, further venous congestion, further decrease in arterial flow, greater degree of ischemia of the upper extremity nerves, and exacerbation of symptoms. This phenomenon is demonstrated in dynamic magnetic resonance imaging (MRI) and venography. The pathophysiology of nerve pain in this setting has been likened to symptoms that result from "crossing one leg over the knee".

Only 5% of patients with the diagnosis of neurogenic TOS are found to have a cervical rib and are best classified as Cervical Rib Syndrome. Ninety-five percent of patients with the diagnosis of neurogenic TOS are believed to have neurologic manifestations of upper extremity ischemia and compression of the SV by an abnormal first rib at the thoracic outlet. Therefore, it was hypothesized that robotic transthoracic resection of the medial aspect of the first rib at the SC junction in patients of neurogenic TOS diagnosed by MRA will result in relief of symptoms.

In a proof of concept study, surgical outcomes in patients diagnosed with neurogenic TOS who underwent robotic first rib resection were reviewed. Diagnosis was made by history, physical exam, MRI of C-spine, orthopedic and neurologic examination, nerve conduction studies, and MRA of the thoracic outlet with maneuvers. Patients with cervical ribs or cervical bands were excluded [5]. Patients with compression of the SV by the medial aspect of the first rib ("the "offending portion") underwent robotic resection of the first rib. Subjective symptoms were assessed by Disabilities of the Arm, Shoulder, and Hand Questionnaire Score (Quick DASH) at 1 week, 1 month, and 6 months. The Quick DASH is an abbreviated version of the original DASH outcome measure. In comparison to the original 30 items DASH outcome measure, the Quick DASH only contains 11 items. It is a questionnaire that measures an individual's ability to complete tasks, absorb forces, and severity of symptoms. The Quick DASH tool uses a 5-point Likert scale from which the patient can select an appropriate number corresponding to his/her severity level/function level [6]. The extrinsic compression of the SV on postoperative MRA and angiogram with maneuvers was assessed at 1 month. In this proof of concept study, patients with Neurologic symptoms of the upper extremity who were classified as "neurogenic TOS" had complete relief of symptoms with relief of compression of the SV after robotic resection of the medial aspect of the first rib and disarticulation of the SC joint. Removal of the medial aspect of the first rib and decompression of the thoracic outlet resulted in relief of upper extremity neurovascular symptoms in greater than 97% of patients who presented with neurogenic symptoms in the upper extremity.

These observations have led these investigators to propose the "ischemic" versus the "compressive" mechanism for neurogenic TOS. They have likened neurogenic TOS in the upper extremity to the well-known phenomenon of paresthesia, numbness, and pain, which results from crossing one leg over the other at the knee. Despite the commonly held belief that "crossing leg" syndrome results from compression of the peroneal nerve, it has been shown that, in fact, it is the result of the compression of the popliteal vein by the contralateral knee.

The present understanding of TOS is that it is the manifestation of a congenital malformation of the first rib. The congenital malformation is in the form of a pronounced tubercle, which results in an abnormal costoclavicular-sternal joint and the compression of the SV at its junction with the innominate vein. The congenital disease is bilateral, with variable symptomatic expression. The compression of the SV in the thoracic outlet results in a spectrum of disease which ranges from neurologic symptoms resulting from venous ischemia of the upper extremity nerves (Peet's neurogenic TOS) to thrombosis of the SV with prolonged compression (Paget-Schroetter or Peet's venous TOS). Neurogenic and venous TOS appear to be caused by the same pathophysiologic process which compresses the SV at its junction with the innominate vein. They represent different clinical manifestations of the same disease and represent the spectrum from pain to venous thrombosis. It is suggested that these conditions are best classified as "subclavian vein compression syndrome".

5. Proposed Classification of TOS: Based on the Modern Understanding of the Pathogenesis of the Disease

Peet's classification of TOS was based on anatomic rather than symptomatic presentation of the disease. Based on recent studies, in order to decrease confusion and improve therapeutic results with TOS, it is proposed that the disease should be classified based on the underlying pathologic entity. Acquired and traumatic abnormalities of the clavicle and first rib should be classified separately.

Clearly, after the more common and objectively supported diagnoses of conditions that result in neurovascular symptoms of the upper extremity, such as cervical spine disease, carpal tunnel disease, and nerve entrapment syndromes, have been ruled out, there remains a group of patients who are suspected of having TOS. In these patients, rather than the historic classification such as arterial, venous, or neurogenic, the more accurate approach from a diagnostic and therapeutic approach is to classify them as:

(I) Cervical Rib Disease (CRD): In these patients, an abnormal cervical rib or the associated bands that are inserted into the first rib result in compression and displacement of the nerves or vessels in the neck. These patients can present with neurologic or vascular compromise. Patients with CRD can have complications relating to compression of the SA and the brachial plexus secondary to a well-formed cervical rib or to an incompletely formed first rib, fibrous band associated with a rudimentary cervical rib, or a giant transverse process of C7. Although in the past, these patients have been classified as TOS, the separation of these patients into CRD allows for a more precise diagnostic and therapeutic strategy and, perhaps more importantly, clears the way to a better understanding of diseases that result from anomalies of the first rib.

(II) Thoracic Outlet Disease: In these patients, an abnormal first rib at the costosternal joint results in compression of the SV at the subclavian-innominate junction. Compression of the vein results in venous hypertension in the upper extremity and resultant neurologic symptoms. With prolonged compression of the subclavian-innominate junction, the vein clots give rise to PSS. Therefore, patients who have been previously classified as neurogenic and venous TOS represent a variable symptomatic presentation of the same pathologic entity that affects the SV. The term arterial TOS should be abandoned as these patients are better classified under cervical rib disease or under traumatic causes. On the other hand, neurogenic and venous TOS appear to be caused by the same pathophysiologic process which compresses the SV at its junction with the innominate vein. They represent different clinical manifestations of the same disease and represent the spectrum from pain to venous thrombosis. It is suggested that these conditions are best classified as "subclavian vein compression syndrome". [11]

This classification of TOS has resulted in a dramatic change in the success of first rib resection.

6. Clinical Presentation and Diagnosis of Thoracic Outlet Syndrome

Historically, a number of physical findings and indirect diagnostic tests have been used. These have included Adson's Test, Wright's Test, Neck radiographs, Pulse volume recording, Cervical and Supraclavicular Dopplers, Computerized tomography of the neck and chest, MRI of the cervical spine, Nerve Conduction studies, Angiography, and MRA of the thoracic inlet with upper extremity maneuvers. As a general rule, except for angiography and MRA of the thoracic outlet with arm maneuvers, the other tests have been inconclusive and are of historical value.

Clinical symptoms of TOS vary according to the underlying etiology [8]. As reported earlier, the small subset of NTOS patients with cervical rib abnormalities or cervical bands present with classic and clear clinical findings. Yet, in patients with Disputed Neurogenic TOS, the clinical findings are highly nonspecific and are associated with low specificity. On the other hand, VTOS and ATOS present with classical clinical findings that are related to venous or arterial obstruction.

During the physical exam, maneuvers such as Adson's Test and Wright's Test have been used. Although the perception among the general medical community is that these are diagnostic for TOS, the data shows that they are associated with low specificity, sensitivity, and predictive value.

Based on the published guidelines from the American College of Radiology (ACR), chest radiography is the only strongly recommended imaging across all TOS classifications [24]. MRI and MRA of the chest are recommended for NTOS and ATOS, respectively. On the other hand, MRV is potentially appropriate for VTOS investigation. CT imaging is not of great benefit in the diagnosis of TOS. In patients with VTOS and ATOS, Doppler studies and angiography are appropriate.

Without a clear understanding of the pathogenesis of DTOS, there have been recommendations for the selection of patients for surgery by societies such as the Society of Vascular Surgery [25]. According to these recommendations, NTOS can be diagnosed after meeting at least three out of four criteria:

- signs and symptoms occurring at the thoracic outlet;
- peripheral findings (including distal neurologic changes, often worse with provocative maneuvers);
- absence of other pathology predominantly explaining the symptoms (cervical disk disease, shoulder disease, carpal tunnel syndrome, chronic regional pain syndrome, brachial neuritis);
- positive response to a properly performed scalene muscle test injection.

Invariably, the tests have been inconclusive, and surgery has been used as a means of ruling out TOS. Obviously, such a strategy is deeply flawed.

Gharagozloo *et al.* studied the Predictive value of Multiphase Magnetic Resonance Angiography of the Thoracic Outlet with Maneuvers (MMRA) in predicting surgical success in patients who are classified as DNTOS [23]. The diagnosis of NTOS was made in patients whose specific localizing and diagnostic orthopedic and neurologic conditions were ruled out. Preoperative diagnostic tests included a comprehensive history and physical exam, Chest X-ray, Chest CT, MRI of the cervical spine, Nerve conduction studies, and Multiphase Magnetic Resonance angiography of the Thoracic outlet with arm maneuvers (MMRA). The success of the first rib resection in patients with "Disputed" NTOS was defined by the complete resolution of symptoms. For each of the tests, the Positive Predictive Value of predicting the success of the operation was calculated. There were 157 patients (58 men and 99 women). Mean age was 32 +/− 10.5 years. Operative time was 84 minutes +/− 11.3 minutes. There were no intraoperative complications. There was no injury to the subclavian vessels during the dissection. There were no neurovascular complications. There were no 30 or 90-day mortality. Quick DASH Scores (Mean +/− SEM) decreased from 50.3 +/− 1.1 preoperatively to 4.2 +/− 1.3 in the immediate postoperative period and 1.5 +/− 1.1 at 6 months ($P < 0.001$). Immediate relief of symptoms was seen in all patients (100%). Complete relief of symptoms was seen in 153/157 (97.5%) of patients. Follow-up was complete in all patients. The median follow-up was 6 months. At the time of follow-up, 97.5% of patients had complete relief from symptoms. The predictive value of MMRA for predicting surgical success in patients with "Disputed" NTOS was 153/157 = 97.5%. Multiphase Magnetic Resonance Angiography of the Thoracic Outlet with Maneuvers (MMRA) had a Predictive Value of 97.5 in predicting surgical success in patients with "Disputed" NTOS. The results suggest that his test should be performed in all patients with "Disputed" NTOS prior to consideration of surgery.

Presently, MRA of the thoracic outlet with arm maneuvers is the test of choice for patients suspected of having TOS. This test shows the abnormal bony tubercle on the first rib with extrinsic compression of the subclavian innominate junction, which is exacerbated by the elevation of the arm above the shoulder. The predictive value of the surgical success of this test in patients with Paget-Schroetter presentation is 100%, and in patients with neurologic presentation is 97.3% [12].

Our present approach to the diagnosis of TOS is to rule out cervical rib disease and other conditions that can result in neurovascular symptoms of the upper extremity. We then used MRA with maneuvers to look for compression of the junction of the subclavian vein with the innominate vein by an abnormal tubercle at the cost sternal junction.

Surgical Approach:

There is no universally accepted surgical approach for resection of the first rib (FRR). The techniques have been open, video-assisted, and robotic-assisted [26]-[33].

The traditional approach for FFR has been posterior thoracotomy, transaxillary, and supra- or infra-clavicular approaches.

The supraclavicular approach provides direct visualization of the brachial plexus and, therefore, has been preferred in cases of NTOS. From this approach, the operating surgeon gains access to the thoracic outlet from above and can perform detailed neurolysis and scalenectomy with ease. However, resecting the first rib, especially its medial third and costoclavicular ligament or, more accurately, the costosternal joint, is difficult and impossible via this approach. The infraclavicular incision provides good exposure of the subclavian vein for patients with VTOS, but the posterior part of the first rib cannot be easily excised from under the clavicle. The transaxillary approach to resection of the first rib was first published in 1966. Although this is the most widely used approach, it is hampered by difficulty with visualization and exposure due to the "tunnel effect" of the approach. Also, this procedure requires that the shoulder girdle and the scapula be elevated from the chest wall. This places traction on the ling thoracic nerve. Even if the nerve is not directly injured during the procedure, the traction provided by a well-meaning but overzealous assistant results in injury of the long thoracic nerve and the consequent condition of a winged scapula.

All these techniques were conceptualized and established as the standard of practice prior to the development of video-assistance. Even in the face of poor exposure and the many neurovascular complications associated with these techniques, the proponents cite some advantages. Usually, the patients do not require chest drain insertion since the chest wall is not opened. The post-operative pain is less because the intercostal spaces are not entered. These procedures are less expensive in terms of equipment. Finally, the surgeons do not require minimally invasive or robotic surgical training. These arguments are obscured by the fact that these techniques violate the principle of exposure for excellent surgical results. Resection of the first rib using these techniques is rarely complete, is technically challenging, is associated with a steep learning curve, and requires tissue dissection and mobilization around the brachial plexus, subclavian, and axillary vasculature. Injury to these structures can lead to severe complications that far exceed any perceived advantages of these techniques.

The thoracoscopic approach to first rib resection was introduced by Ohtsuka *et al.* in 1999 [34]. The concept was that an approach through the chest using video-assisted thoracoscopic surgery (VATS) avoided the extrathoracic neurovascular bundle. Using VATS, the surgeon approaches the first rib from a caudo-cephalad direction and has an excellent view of the ribs from within the chest. This offers safer tissue dissection and prevents any injuries to the intercostobrachial cutaneous nerve and components of the neurovascular bundle. The transthoracic thoracoscopic technique represented a minimally invasive approach to the first rib that could potentially obviate retraction of the neurovascular structures necessitated by the extrathoracic approaches. However, although this procedure was based on sound reasoning, it was limited by the shortcomings of the conventional endoscopic instruments and two-dimensional (2D) visualization.

In 1985, Martinez *et al.* published their experience with transaxillary endoscopically-assisted FRR [33]. They argued for the safest procedure to decompress the tension on the neurovascular bundle in patients with TOS compared to existing open techniques. From 2003 and onwards, they used the da Vinci Surgical System (Intuitive Surgical, Inc, Sunnyvale, CA) to perform transaxillary FRR. In their most recent publications, they described their transition from video-assisted to robotic-assisted FRR in patients with TOS. Based on their experience, the authors support the superiority of the robot and explore its potential in specific patient categories.

The first RATS procedure for FRR was described in 2012 by Gharagozloo *et al.* [18]. They initially reported 5 cases of Paget-Schroetter syndrome who had robotic first rib resection (R-FRR) and supported that several attributes of RATS offered significant benefits for FRR. These included the improved maneuverability of the instruments in narrow spaces, offering high-definition magnification and overall better-quality visualization of the operating field. Therefore, Gharagozloo *et al.* introduced a procedure that combines the benefits of robotic-assisted surgery with the benefits of thoracoscopic surgery for FRR.

Robotic surgical systems allow for high-definition, magnified, 3D visualization of the operative field, are associated with accurate instrument maneuverability in a confined space, and may overcome the potential shortcomings of the conventional thoracoscopic approach.

Undoubtedly, the use of robotic technology adds more ports and results in greater short-term operative morbidity, longer hospitalization, longer operative times, and greater cost. However, these shortcomings seem to be obviated by the greater accuracy of robotic dissection, the lower incidence of neurovascular complications, excellent relief of symptoms in patients with "neurogenic TOS", and excellent long-term patency of the SV and arm function in patients with PSS.

7. Robotic Surgical Technique

Video of the operation can be accessed on CTS net.org. [31]

The robot is used to dissect the first rib, disarticulate the SC joint, and divide the scalene muscles. General anesthesia with single lung ventilation is used, and patients are placed in the lateral decubitus position with the affected side up.

7.1. Phase I—VATS Setup

Three 2 cm, non-trocar incisions are made. In the right chest, Incision #1 is made at the 5th intercostal (IC) space at the midaxillary line. Incision #2 is made in the 4th IC space at the anterior axillary line. Incision #3 is made in the 4th IC space at the posterior axillary line. It is important that the port incisions be made as high as possible. Placing the port incisions through a lower intercostal space will result in the collision of the robotic instruments and the camera at the apex of the chest. A 1 cm incision (#4) is made in the 6th IC space at the anterior axillary line.

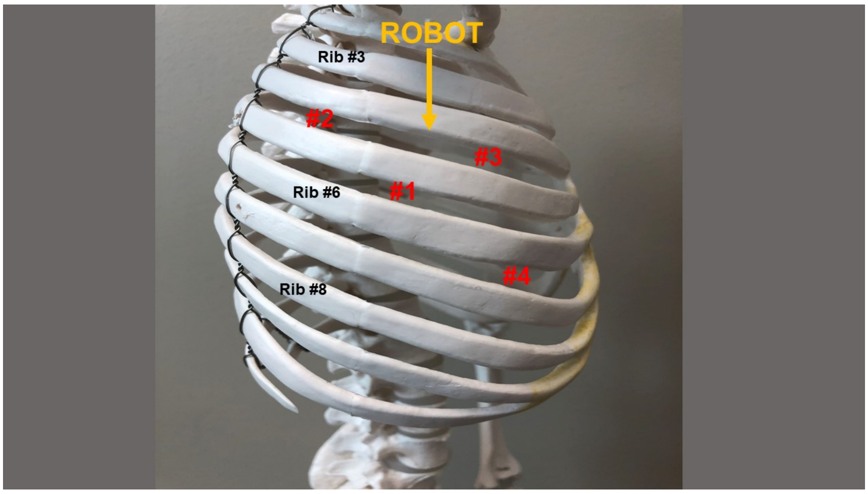

Figure 4. Port placement right chest. The left chest port placement is a mirror image.

The placement of incisions is in a mirror image configuration for the left chest (Figure 4). A retractor (Endopaddle Retract; Auto Suture, Covidien incorporated, Mansfield, MA, USA) is introduced through this incision and used to retract the lung inferiorly. At the end of the procedure, a chest drain is inserted through this incision.

7.2. Phase II—Robot Positioning and Robotic Dissection of the First Rib

The surgical robot (da Vinci, Intuitive Surgical, Inc., Sunnyvale, CA, USA) is positioned over the head of the patient. The camera is placed in incision #1. For the placement of instruments, a 30-degree down-viewing camera is used. The right robotic arm with a hook cautery is positioned in incision #2. The left robotic arm with a grasper overlying the first rib is dissected. The edges of the rib are identified, as is the SC joint. Dissection of the pleura is carried just lateral to the SA (Figure 5). The lateral and posterior aspects of the rib with the associated neurologic structure are left intact.

Figure 5. Intraoperative photograph shows the right first rib with a 30-degree up-viewing scope. The dissection begins by clearing the pleura overlying the first rib and clearly identifying the edges of the rib and the costosternal joint.

7.3. Phase III—Division of the First Rib Using VATS Instruments

Next, the robotic arms are withdrawn. A 30-degree VATS camera is introduced, and the rib under the SA is divided using a 6 mm thoracoscopic Kerrison bone cutter (Depuy Inc., Raynham, MA, USA) (Figure 6). This area represents the thinnest portion of the first rib and is most suitable for an osteotomy. The division of the rib at its midpoint allows for the rib to be pivoted on the SC and costovertebral joints in a trap door configuration.

7.4. Phase IV—Robotic Dissection of the First Rib and Disarticulation of the SC Joint

The robotic arms are replaced in the same ports. A 30-degree down viewing

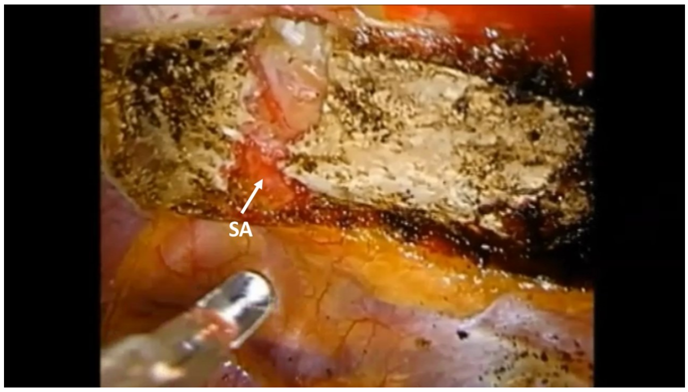

Figure 6. Intraoperative photograph shows the right first rib with a 30-degree thoracoscope introduced through the anterior incision. The first rib is divided at its thinnest point, which is located under the subclavian artery (SA), using a Kerrison instrument.

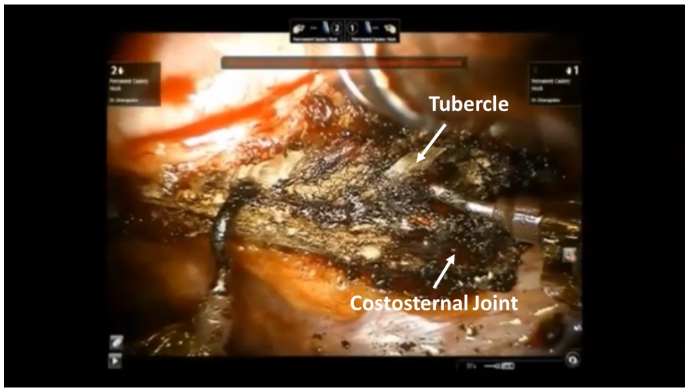

Figure 7. Intraoperative photograph shows the right first rib with a 30-degree down viewing scope. Two robotic hook cautery instruments are used. The hook cautery in the left-hand places downward traction as the hook cautery in the right hand is used to dissect the rib away from the subclavian innominate junction and disarticulate the costosternal joint. The abnormal tubercle at the costosternal joint is seen clearly.

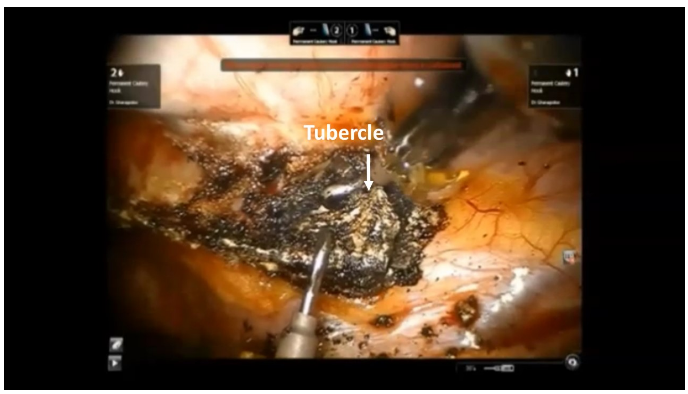

Figure 8. Intraoperative photograph shows the right first rib with a 30-degree down viewing scope. Two robotic hook cautery instruments are used. The hook cautery in the left-hand places downward traction as the hook cautery in the right hand is used to dissect the rib away from the subclavian innominate junction and disarticulate the costosternal joint. The abnormal tubercle at the costosternal joint is seen clearly. Dissection progresses until the joint is disarticulated completely.

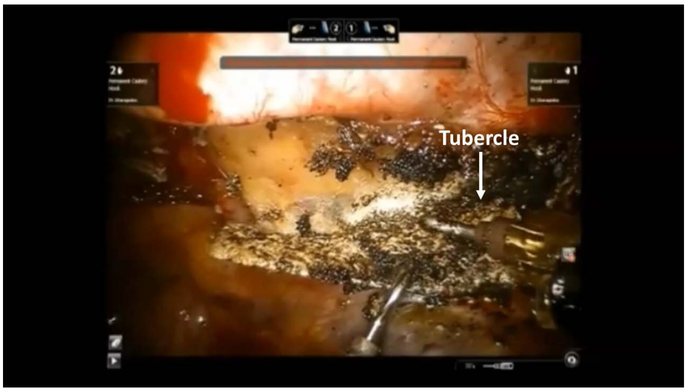

Figure 9. Intraoperative photograph shows the right first rib with a 30-degree down viewing scope. Two robotic hook cautery instruments are used. The hook cautery in the left-hand places downward traction as the hook cautery in the right hand is used to dissect the rib away from the subclavian innominate junction and disarticulate the costosternal joint. The abnormal tubercle at the costosternal joint is seen clearly. The subclavian vein lies under the fatty tissue.

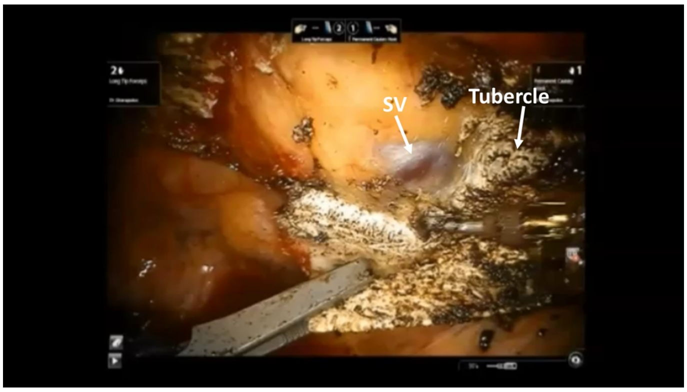

Figure 10. Intraoperative photograph shows the right first rib with a 30-degree down viewing scope. The first rib and tubercle that compresses the subclavian innominate junction are peeled away from the subclavian vein (SV) with immediate decompression of the subclavian innominate junction.

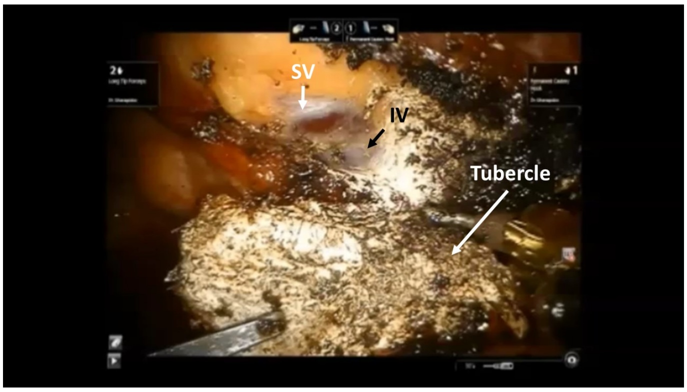

Figure 11. Intraoperative photograph shows the right first rib with a 30-degree down viewing scope. The first rib and tubercle that compresses the subclavian innominate junction are peeled away from the subclavian vein (SV) with immediate decompression of the subclavian innominate junction. Innominate vein (IV).

robotic camera is introduced through Incision #1. A hook cautery is placed in the right robotic arm in Incision #2, and a second hook cautery is placed in the left robotic arm in Incision #3. The hook in the left arm is used to put downward traction on the rib as the hook cautery (30 cut/30 coagulation setting) is used to dissect the first rib away from the SV, disconnect the scalene muscles from the rib, and disarticulate the rib from the sternal and times clavicular joint (**Figures 7-11**).

7.5. Phase V—Analgesia and Chest Closure

Following the completion of the robotic procedure and undocking of the robot, the camera trocar is removed. An endoscopic camera (Olympus Endoeye 0 Degree) is introduced through the anterior port and used to visualize the paravertebral pleura. In this technique, a specially designed tunneling device is introduced through the camera port and used to begin the formation of a subpleural tunnel. After the formation of the tunnel, the metal tunneling device is withdrawn, and a peelable sheath is positioned over the tunneler and replaced in the pleural tunnel. The metal tunneler is withdrawn, and the sheath is left inside the pleural tunnel. Two 5-inch On-Q soaker catheters are introduced through separate puncture sites placed anteriorly in the same IC space as the inferior incision. The On-Q soaker catheters are passed into the long subpleural sheath. The sheath is withdrawn and peeled away, leaving the soaker catheters in the subpleural tunnel. The catheters are positioned in an overlapping staggered manner in order to provide an infusion of the local anesthetic for the entirety of the pleural tunnel extending from the second to the 8th IC spaces. We use two catheters, an infusion of approximately 4 mL/hour (2 mL per catheter) with a 400 mL reservoir with 0.125 bupivacaine. This system is used after the patient is discharged from the hospital and gives the patient 10 days of local pain control [35].

8. Conclusion

The excellent results which are associated with robotic resection of the "offending portion" of the first rib in patients with neurogenic and venous TOS are due to the advantages of the robotic platform, as well as the greater understanding of the pathogenesis and appropriate diagnosis of TOS. Neurogenic and Venous TOS appear to represent a different clinical manifestation of a congenital abnormality of the first rib at the SC joint. This congenital abnormality, which by definition is bilateral with variable expression in the two upper extremities, results in extrinsic compression of the SV at its junction with the innominate vein by a bony tubercle at the SC joint. The compression of the subclavian-innominate junction in the thoracic outlet results in a spectrum of symptoms that range from neurologic symptoms resulting from venous ischemia of the upper extremity nerves (Peet's neurogenic TOS) to thrombosis of the SV-caused by prolonged compression (Paget Schroetter or Peet's venous TOS). Therefore, neurogenic and venous TOS represent different clinical manifestations of the same disease and represent the spectrum from pain to venous thrombosis. It is suggested that these conditions are best classified as "subclavian vein compression syndrome". MRA with maneuvers definitively identifies the extrinsic compression of the SV at its junction with the innominate vein and is diagnostic for this form of TOS. In turn, robotic transthoracic removal of the "offending portion" (the abnormal SC junction) of the first rib with preservation of the posterior aspect of the rib results in relief of the extrinsic compression and return of normal venous flow while obviating the neurologic complications that are associated with complete first rib resection and tranaxillary and supraclavicular techniques.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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