Thoracoabdominal Aortic Aneurysm Repair: From an Era of Revolution to an Era of Evolution

Alice Le Huu, MD,[*,†,‡] *Susan Y. Green, MPH,*[*,†,‡] *and Joseph S. Coselli, MD*[*,†,‡]

Thoracoabdominal aortic aneurysm (TAAA) repair has a rich and storied tradition that began in Houston, Texas with great pioneer surgeons such as Drs Michael E. DeBakey, Denton A. Cooley, and E. Stanley Crawford. Their early attempts to repair TAAA were complicated by the persistent threats of renal and spinal cord ischemia and difficulty in reattaching the branching vessels of the thoracoabdominal aorta. Today, under the tutelage of Dr Joseph S. Coselli, the Texas Medical Center remains at the forefront of TAAA repair. In this place where great surgeons once walked the halls, their legacy continues.

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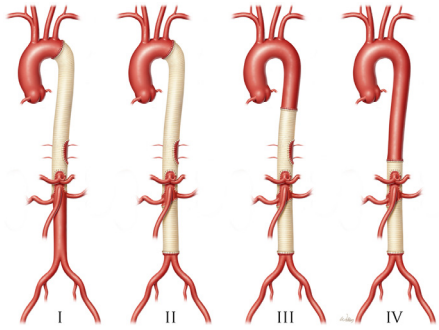

Crawford extents I–IV for thoracoabdominal aortic aneurysm (TAAA) repair.

Central Message

Pioneer surgeons began the storied tradition of TAAA repair at the Texas Medical Center in Houston, Texas—a legacy that continues there today through the practice of Dr Joseph S. Coselli.

AN ERA OF REVOLUTION

On December 31, 1952, a 46-year-old man was admitted to Houston Methodist Hospital after reporting a vague lower abdominal and inguinal pain during the previous 3 months. On this admission, the patient's pain had changed both in quality and quantity, which he described as sharp and constant. With only upper gastrointestinal barium studies and a radiograph of the thoracolumbar spine, a large aneurysm measuring 20 × 20 cm was identified. The admission of the patient to the hospital corresponded with the unfortunate death of a 21-year-old trauma patient, which led Drs Michael E. DeBakey and Denton A. Cooley to plan a risky procedure for the repair of the life-threatening aneurysm. They carefully harvested a 15-cm length of the descending thoracic aorta from the deceased patient, and the graft was stored in sodium chloride and impregnated with streptomycin and penicillin for 6 days while they meticulously planned every detail of the operation. Finally, on January 5, 1953, Drs DeBakey and Cooley successfully repaired what would eventually become known as a Crawford extent I TAAA by replacing the diseased aorta with a homograft through a thoracoabdominal incision. The operation was a monumental feat, completed in an astonishingly short timeframe of 4 hours and 40 minutes. The patient was discharged on postoperative day 13, and he resumed his duties as a sheriff shortly thereafter.[1] Although this operation was initially described in 1953 as a thoracic aneurysm repair, it was for many years considered to be the first acquired descending thoracic aortic aneurysm repair because of the type of incision used, as well as the encroachment of the aneurysm on the visceral arteries. Dr Cooley later made the argument that this operation could be reasonably considered the first TAAA repair.[2]

In 1955, Professor Charles Rob[3] of London's St. Mary's Hospital reported on his experience in a series of 33 patients with abdominal aortic aneurysms and an additional 26 patients with occlusive disease of the abdominal aorta and iliac arteries; he divided his report into patients with abdominal aneurysms above the renal arteries and patients with abdominal aneurysms below the renal arteries. For the 6 patients with aneurysms above the renal arteries, he described a left thoracoabdominal incision

*Division of Cardiothoracic Surgery, Michael E. DeBakey Department of Surgery, Baylor College of Medicine, Houston, Texas
†Section of Adult Cardiac Surgery, Texas Heart Institute, Houston, Texas
‡CHI St. Luke's Health–Baylor St. Luke's Medical Center, Houston, Texas

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Address reprint requests to Joseph S. Coselli, MD, Department of Surgery, Baylor College of Medicine, One Baylor Plaza, BCM 390, Houston, TX 77030. E-mail: jcoselli@bcm.edu

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following the line of the ninth rib, as well as the exposure, isolation, and reimplantation of the visceral arteries during aortic replacement. Despite his description of these repairs as treatment for abdominal aortic aneurysms, they are reasonably interpreted as treatment for TAAAs, especially considering the use of a thoracoabdominal incision and a clear description of the exposure and isolation of the visceral arteries, although the precise extent of repair is unclear.[3] A few months after Professor Rob's report, Dr Samuel Etheredge and colleagues[4] from the Veteran's Hospital in Oakland, California reported the successful repair of an upper abdominal aortic aneurysm in a 37-year-old patient by using a homograft replacement, along with a temporary shunt. Again, although this repair was originally termed an abdominal aortic aneurysm repair, the illustration and text present a Crawford extent IV TAAA repair. Despite this aortic replacement approach being in its infancy, the authors stated the following: "The practice of resection and replacement by graft would now seem so well established as the treatment of choice that the previous types of therapy, such as ligation, wiring, wrapping, or endoaneurysmorrhaphy, will either be rapidly discarded or reserved for the particular cases where such a major procedure cannot be carried out for one reason or another."[4] Professor Rob and Dr Etheredge are often credited with performing the first TAAA repair operation.

In 1956, Dr DeBakey, along with Drs Oscar Creech, Jr. and George Morris, Jr.,[5] reported the repair of aneurysms in the thoracoabdominal aorta in 4 patients, clearly distinguishing this type of aneurysm from the more common abdominal aortic aneurysms that arise below the renal arteries. In this paper, they described the use of aneurysmal excision and aortic replacement by using a homograft and reimplanting 3 visceral arteries (in 2 cases) or all 4 visceral arteries (in the remaining 2 cases). These repairs would now be classified as a Crawford extent III ($n = 3$) or IV ($n = 1$) TAAA repairs. The paper was notable for the use of the term "thoracoabdominal" to describe the aneurysm location, as well as for the use of mild hypothermia achieved through a cooling blanket during 1 repair. In addition, temporary shunts were used to provide distal perfusion during 3 repairs that followed native anatomy with a separate anastomosis of the visceral arteries. In this report, early death was formidable; 2 of 4 patients died, resulting in a 50% mortality rate.[5]

During this time, Dr DeBakey and others in Houston who were inspired by Dr Voorhees' use of Vinyon to create a synthetic aortic replacement graft[6] experimented with the use of various synthetic aortic replacement grafts (eg, nylon-Dacron, crimped nylon, Ivalon sponge, vinyl plastic, and others). Dr DeBakey turned his attention to developing a better aortic conduit. The choice of Dacron was a product of luck and scarcity. Dr DeBakey originally planned to use nylon, but the local department store did not have any in stock, so the salesperson suggested Dacron. Dr DeBakey took the material home and used his wife's sewing machine to carefully construct a Dacron artery (Fig. 1). After several different types of synthetic aortic substitutes were tested, Dacron was deemed superior.[7]

With Dacron established as a preferred aortic substitute, Dr DeBakey and colleagues explored extra-anatomic approaches

Figure 1. Photo of Dr Michael E. DeBakey sewing a synthetic aortic replacement graft with Dacron. Dr DeBakey had been taught to sew by his mother (early 1950s). Used with permission of Baylor College of Medicine.

to thoracoabdominal aortic replacement. Building on their earlier experience with temporary shunts to maintain distal perfusion during the TAAA procedure, they used grafts in a permanent bypass position. They performed the proximal anastomosis in an end-to-side fashion and curved the graft around the aneurysm, then completing the distal anastomosis in an end-to-side fashion (Fig. 2). Next, the renal arteries were

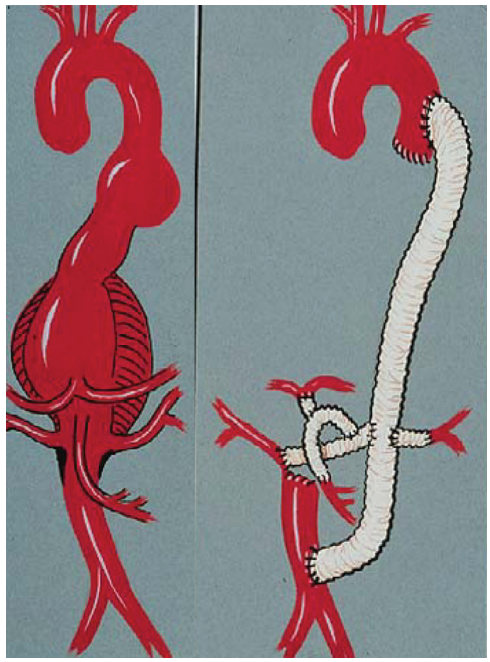

Figure 2. Illustration showing an extra-anatomic approach to thoracoabdominal aortic replacement. The development of synthetic grafts permitted the use of the graft as a shunt around the aneurysm during the reattachment of the visceral arteries as separate branches. The aneurysm is then fully extirpated. Used with permission of Baylor College of Medicine.

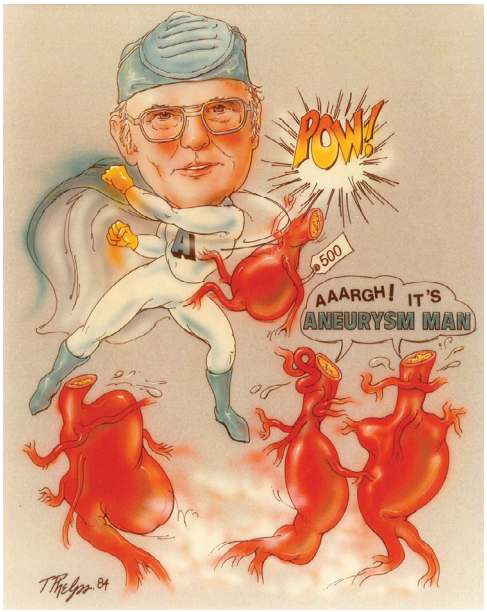

Figure 3. Illustration of Dr E. Stanley Crawford as "Aneurysm Man," a super hero who repairs aortic aneurysms. Dr Crawford achieved worldwide recognition for his approach to thoracoabdominal aortic aneurysm repair. Used with permission of Baylor College of Medicine.

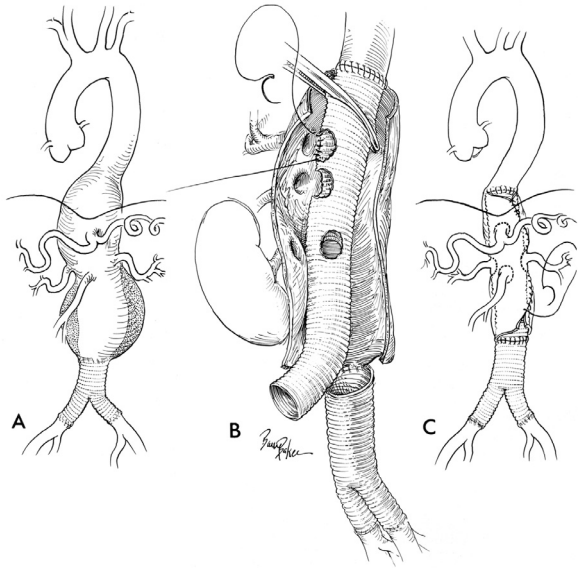

Figure 4. Illustration of Dr E. Stanley Crawford's shift to an anatomically based aortic inclusion approach to aortic replacement (late 1970s) for repair of a thoracoabdominal aortic aneurysm (A). The visceral arteries are incorporated into the repair (B) by patching small islands of aortic wall tissue containing the vessel ostia to the replacement graft. The partly resected section of the thoracoabdominal aorta (C) is then wrapped around the graft. Used with permission of Baylor College of Medicine.

individually reattached to the main body of the graft with sections of small-diameter grafts to bridge the gap. Then, the superior mesenteric artery and celiac axis were similarly reattached individually. Notably, an extra-anatomic approach that fully extirpated the aneurysmal section of the aorta necessitated the sacrifice of the intercostal arteries. Findings in a series of 42 such repairs were reported[8]; although the patient mortality rate was improved, it remained substantial at 26%.

Dr Stanley E. Crawford's work from the 1970s to the 1990s laid the foundation for modern thoracoabdominal aortic surgery (Fig. 3). His paper titled "Thoraco-abdominal and abdominal aortic aneurysms involving renal, superior mesenteric, celiac arteries"[9] revolutionized surgical technique. In this report, Dr Crawford described his results with 23 patients and an additional 5 patients in the addendum, with only 2 deaths (7%). Transitioning from an extra-anatomical approach, he reintroduced the concept of an in situ anatomically based TAAA repair. He advocated using a longitudinal incision of the aneurysmal sac, followed by an intra-aortic anastomosis with a Dacron graft, which facilitated the reimplantation of patches of the aortic wall containing the origins of the intercostal arteries and visceral arteries. These arteries were subsequently attached as islands to oval openings made in the graft (Fig. 4). As repair progressed along the aorta, Dr Crawford used sequential aortic cross clamping to minimize distal ischemia. Furthermore, rather than performing a time-consuming aneurysmectomy, upon completion of graft replacement, he wrapped the remnant aortic wall around the graft and secured it. Crawford's report introduced surgical approaches that are widely used in the present day more than 4 decades after his initial publication.

For the next 2 decades, in addition to training the next generation of aortic surgeons, Dr Crawford continued to refine his approach by initiating clinical studies and adopting the promising techniques of others. He explored the use of left heart bypass (LHB), the selective perfusion of renal arteries, Miyamoto's cerebrospinal fluid (CSF) drainage, and Borst's elephant trunk approach—all to improve patient outcomes.[10–13] Additionally, Crawford conceived his namesake classification system (ie, the Crawford extents I–IV of repair), which has played a pivotal role in determining the surgical management of patients with TAAA.[14,15] Dr Crawford's lifetime of experience with TAAA repair was summarized by Dr Lars Svensson in a report of 1509 TAAA repairs, which was published shortly after Crawford's death.[16] Dr Svensson's analysis revealed consistently low rates of mortality that are enviable by today's standards, with an early mortality rate as low as 8%, although the incidence of spinal cord deficit remained concerning at 15% and 31% for Crawford extent I and II repairs, respectively. Dr Crawford's book titled *Diseases of the Aorta: Including an Atlas of Angiographic Pathology and Surgical Technique*, which he coauthored with his son, is considered the definitive textbook on aortic pathology and repair.[17]

AN ERA OF EVOLUTION

The field of TAAA repair continues to evolve at a rapid pace. Open techniques presently in use are based on the innovations of early pioneers with some contemporary additions, including the widespread use of systemic heparinization, mild permissive

hypothermia, reimplantation of the intercostal arteries, cold renal perfusion, CSF drainage, selective visceral perfusion, and LHB for extensive TAAA repairs (namely Crawford extent I and II TAAA repairs). Other additions include the as-needed use of endarterectomy, small-diameter stents, or bypass grafts to manage visceral artery disease.[18] At the Baylor College of Medicine in Houston's Texas Medical Center, Dr Joseph S. Coselli and others have continued to make several noteworthy contributions to open TAAA repair, as demonstrated by the results of key clinical trials and studies.[19–27]

Spinal cord protection continues to be an area of intense interest in TAAA repairs, especially the use of CSF drains and the surgical reimplantation of intercostal arteries. Three randomized clinical trials—all of which were performed at Baylor College of Medicine in Houston—have focused on the use of CSF drainage to reduce postoperative spinal cord deficit. The first randomized clinical trial, led by Dr Crawford in 1991, failed to establish the effectiveness of CSF drainage because the restrictions placed on the amount of CSF drained hampered its clinical effectiveness.[28] The second randomized clinical trial, led by Dr Svensson in 1998, combined the use of CSF drainage with intrathecal papaverine. The rationale was that papaverine is an arterial dilator, which can lead to increased spinal cord perfusion. In this trial, 33 patients were randomized to undergo a Crawford extent I or II repair with or without a CSF drain and intrathecal papaverine. The results showed that the use of a CSF drain and intrathecal papaverine led to significantly reduced neurologic injury.[29] In the third trial, led by Dr Coselli's team in 2002, 145 patients were randomized to undergo Crawford extent I or II TAAA repair with or without CSF drainage. In the patients who received a CSF drain, an 80% relative risk reduction in paraplegia was observed.[22] The work of the 2 latter trials was reflected in the 2010 American Heart Association/American College of Cardiology Foundation Guidelines that indicated class I, level B evidence for the use of CSF drainage for spinal cord protection during open and endovascular thoracic aorta repair in patients at high risk for spinal cord injury.[30]

Likewise, in recent years, evidence for the use cold renal perfusion has become more definitive. Dr Coselli's group has performed 2 randomized clinical trials to assess cold renal perfusion. In the first trial, 30 patients were randomized to receive normothermic blood or cold (4°C) crystalloid to provide renal perfusion during TAAA repair; the results showed that significantly fewer patients had postoperative renal dysfunction in the cold crystalloid group than in the normothermic blood group (3 vs 10, $P = 0.03$).[23] In the second trial, Dr Coselli's group investigated whether cold (4°C) blood or cold (4°C) crystalloid provided superior renal protection in 172 patients; both cold perfusion strategies provided effective protection against renal injury, although, for ease of use, cold crystalloid is generally preferred by this group.[27]

In recent years, the role of LHB has also become an area of considerable interest. There is a dearth of randomized controlled studies that support the use of LHB in TAAA repairs. However, Dr Coselli and colleagues[19] showed in a retrospective study that the incidence of paraplegia was significantly reduced from 13.1% to 4.8% when LHB was used. Therefore, their current practice is to use LHB in Crawford extent I and II repairs, and their cannulation approach is to use the left inferior pulmonary vein for outflow and the distal thoracic aorta for inflow. This technique represents a shift from traditional femoral access, which may decrease the amount of atheroma dislodged.

Modern outcomes of TAAA repair reflect the culmination of more than a half century of surgical advances. The contemporary results of Dr Coselli and colleagues, which represent a lifetime of performing TAAA repairs, have shown a low rate of 30-day mortality (4.8%), in conjunction with an exceptionally low incidence of permanent paraplegia (2.9%). Furthermore, these results have demonstrated the durability of open repair, showing an estimated rate of freedom from repair failure of 94.1% ± 0.8% at 15 years.[31] Although endovascular methods have become increasingly prolific in recent years, the surgical repair of TAAA will remain relevant in complex cases for which other techniques are unsuitable. The history of open TAAA repair, from its early origins in the hands of brilliant pioneers to its contemporary practice, is a fascinating tour of surgical innovation.

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