Four Decades of Advancement for the Surgical Treatment of Spinal Deformity

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"The responsibility for change…lies with us. We must begin with ourselves not to close our minds prematurely to the novel, the surprising, the seemingly radical. This means fighting off the idea assassins who rush forward to kill any new suggestion on grounds of impracticality."

Alvin Toffler, The Third Wave, 1980.

Introduction:

My passion for the surgical correction of spinal deformity started during my residency in Toronto at the Hospital for Sick Children. I was fortunate to rotate through the service of Dr. John Hall a master surgeon and a visionary. Previously, he had introduced spinal instrumentation to Toronto, Canada after visiting Dr. Paul Harrington in Houston to observe a scoliosis correction with the Harrington distraction and compression rod systems. Dr. Hall was one of the first converts to spinal instrumentation with arthrodesis to correct and stabilize scoliosis. Later, the indications were broadened to include kyphosis as well as other spinal deformities. Typical of Hall, he recognized the advantages of implants that provide internal correction and increased stability to the spine. Meanwhile most others rejected instrumentation as an unnecessary risk and stuck to the standard of care of that time: cast correction arthrodesis through the cast and followed by six months recumbency in cast. Typically, Hall mastered the technique, simplified it and taught this to the many surgeons that visited his operating room. Further, he taught, lectured and published extensively.

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Dr. Hall was also one of the early converts to anterior instrumentation for thoracolumbar curves. The anterior and retroperitoneal approaches to the spine for deformity were techniques that spinal surgeons learned from Alan Hodgson of Hong Kong who popularized this approach for the surgical debridement of spinal tuberculosis. Later, Hodgson and Alan Dwyer from Australia collaborated on a technique for anterior surgical correction of scoliosis. Soon after that, Hall invited Hodgson to Toronto and I was again fortunate to scrub with both of them for the first anterior scoliosis surgery done in Canada using the Dwyer cable system.

Though I didn't recognize it the time, I was witnessing the beginning of a modern era for the surgical treatment of spinal deformity; a paradigm shift from an earlier time when treatment based on anecdotal experience instead of data derived from research. Further, treatment techniques had not changed for many decades. I was a witness to a change that moved spinal surgery towards a new way level of treatment techniques and eventually clinical and laboratory research. This was the beginning of a new subspecialty within orthopaedic surgery devoted to solving the problems of the deformed spine. Initially, this change occurred because of the vision of a few men including Paul Harrington, John Moe and John Hall. With time, more would join this small group to further drive this subspecialty forward. Ultimately, it became apparent to these visionary surgeons that a mechanism was needed to encourage further discussion and the exchange of ideas for the treatment of spinal deformity. Research and the dissemination of information was their goal.

Research and Education

In 1966, the leaders of the spinal deformity movement organized a meeting to exchange

ideas, solve problems, pool their knowledge and attendance at the meeting and they agreed to reconvene annually. These surgeons were founding fathers of the Scoliosis Research Society, the first spine society and arguably the most prestigious. The SRS has grown and become an international society devoted to spinal surgery and research. Research is the SRS' middle name. This became their mission and it has led to an elevation of the standards for research. For example, in time, all the studies would come under scientific scrutiny and standards for improved methodology, such as a minimal followup of two years for clinical research. Biology and biomechanics principles became the foundation for laboratory research, implant design and the guidelines for appropriate care.

The SRS now supports education for spine care world wide including: courses emphasizing the principles for the management of deformity problems, an active educational and interactive web site and an annual traveling fellowship program for young surgeons to visit spine centers outside their home continent. This traveling fellowship program alternates annually develop plans educate others. There were 35 in between North American and International sites. Importantly, the SRS also supports both clinical and laboratory research with grants awarded to both young and experienced investigators.

Led by Randal Betz of Philadelphia and Jurgen Harms of Germany, a second spine meeting (the International Meeting for Advanced Technology or IMAST) evolved in 1994. With industry participation, this meeting emphasized new and developing technologies. This endeavor was so successful that IMAST merged with the SRS and this has provided a second annual meeting for the SRS. It is an important educational tool that fosters investigative ideas that are new and at times, still not fully developed. Ideas can be presented with a less rigid standard, such as two years of followup, than required at the SRS annual meeting. At the same time, IMAST has helped the SRS develop ethical standards for cooperation between the spinal implant industry and surgeons worldwide. Meanwhile, the surgical solutions to correct deformity have exploded with new concepts, techniques and technologies.

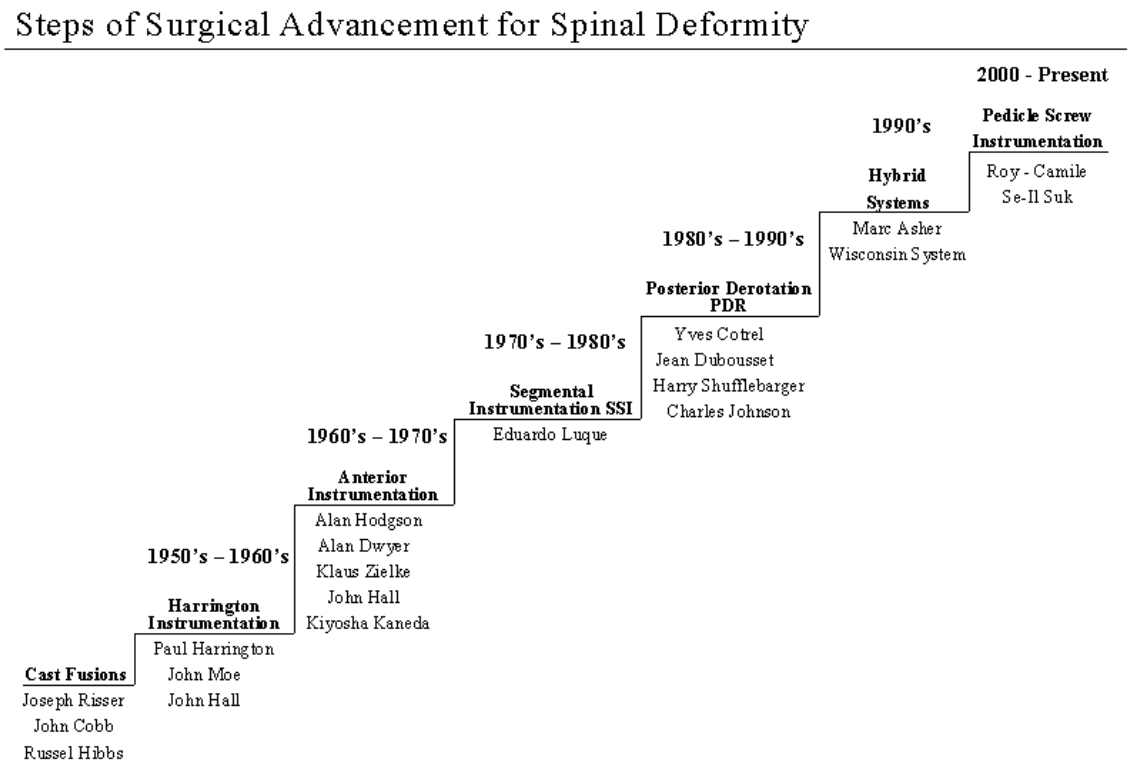

Figure 1. Stairway of Advancement for Surgical Treatment: The techniques shown are those that influenced a major shift in surgical approach.

Developmental Milestones.

"There can be change without progress, but not progress without change…anonymous"

It is impossible to describe all of the developments that contributed to the growth and development of the non-operative and surgical treatment of spinal deformity. I have tried to list those that were a departure from the absolute norm at a particular time. These developments are the ones that led to a paradigm shift away from conventional ideas for surgical treatment at that time and towards newer concepts that provided better correction, improved stability, less morbidity and fewer complications. Some of these developments are depicted in a step like fashion in fig.1.

Step 1: Harrington Instrumentation

Although we owe a debt to earlier spine surgeons such as Hibbs, Risser and Cobb for their contributions, modern surgical treatment really began with Paul Harrington and his development of surgical implant system that corrected frontal plane deformity by distraction (Fig 2). Because many of these early constructs did not provide the biomechanical advantages of load sharing, a post-operative body cast was required to minimize correction loss and pseudoarthrosis. This appeared to be a significant clinical problem early on. Also with distraction, the sagittal curve became flat or hypo-kyphotic., an unphysiologic situation However, Harrington was an observer and student of spine surgery. He recognized the problems and needs of his distraction system early on and he revised his technique to include a careful arthrodesis based on the Hibbs technique. Further, by examining fusion biopsies microscopically, he observed the maturation of the fusion process and based the time needed for external spinal support by cast or brace on this data. Also, he added a compression rod to the convex side of the curve to add construct stability and improve the sagittal contours.

Harrington's work was refined and popularized by John Moe of Minneapolis and John Hall of Toronto and later Boston. Based on their research, Moe with Howard King described a classification system that helped with analyzing curves to determine the best approach to treatment of idiopathic scoliosis with distraction/compression instrumentation. Both Moe and Hall taught and wrote extensively and both were the true advocates so that others respected and followed. But it was Harrington's development of an implant that both corrected the spine and stabilized it from within, that created a paradigm shift for spinal surgery.

Step 2 Anterior Instrumentation

Influenced by Hodgson of Hong Kong and his anterior spinal techniques for managing spinal tuberculosis through an anterior or anterolateral approach, Alan Dwyer of Australia provided an alternative way to correct spine deformity with his anterior correction system that used titanium vertebral screws and a tensioning cable applied to

Figure 2. Harrington Distraction Technique: The construct shows a single distraction rod placed on the concavity of the curve following correction. The rod is attached to the spine by two hooks, one at each end. Note the autogenous graft has been placed in the facet joints and over the spine at the levels of correction.

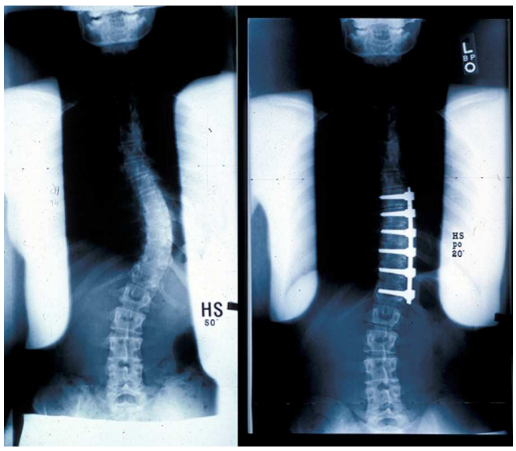

Figure 3. Anterior Instrumentation using a contemporary system: In contrast to the early posterior techniques, the small rod is attached to convexity of the curve rotated and compression applied to the screw heads to achieve correction. Instrumentation was preceded by discectomies and interbody arthrodesis, usually with rib allograft.

the convexity of the curve. Although the system was biomechanically wanting and had a further disadvantage of flattening the sagittal contours, others built on this and solved these problems (fig 3). Klaus Zielke of Germany and John Hall were quick to recognize the value of these concepts and popularized and modified this technique in both Europe and the United States. In Japan, Kaneda developed a two-rod anterior system that is arguably the most refined of the anterior systems. Anterior correction at this time remains an option to the posterior approach, but the priority of where it fits with other options, is still in evolution. It will likely remain most useful for thoracolumbar curves and hyper-kyphotic thoracic curves.

Step 3 Segmental Spinal Instrumentation.

A decade or two later, Eduardo Luque of Mexico developed s a fresh approach to surgical correction of scoliosis. First, he viewed deformity as more than a one-plane problem, second, he recognized the advantages of stress load sharing with multiple points of spinal purchase and finally he introduced the concept of cantilever correction. His technique of sublaminar wiring rods contoured for correction to the deformed spine, gained acceptance for treating idiopathic and neuromuscular deformities. This proved to be a huge conceptual step that stimulated other and newer techniques (fig. 4)

Step 4: Posterior Derotation Instrumentation (PDR)

In the late 1970s, Yves Cotrel of France with his bright young associate Jean Dubousset, introduced the concept of posterior derotation correction. Initially using a rod and hook system,

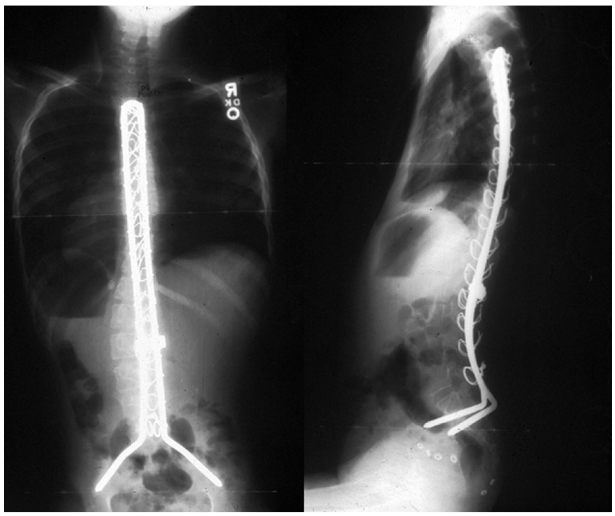

Figure 4. Segmental Spinal Instrumentation: Often called Luque instrumentation after the developer, the technique used load-sharing principles with a sublaminar wire anchor at every level, and applied bilaterally. Further, in respect to the sagittal plane the rods were contoured for physiologic thoracic kyphosis and lumbar lordosis. Despite use for a wide variety of deformities, the technique was particularly ideal for neuromuscular scoliosis.

they set out to correct deformity in all three planes using cantilever, distraction and translation correction forces. The Cotrel-Dubousset (CD) method of correction for posterior derotation correction (PDR) was thus developed. Although this did not prove to be an effective treatment for rotation, it was a potent corrector of coronal and sagittal deformity. They also popularized cross connectors or cross-links. By applying cross-links between the rods at both ends of the construct, the two rods were converted to a more stable unitized quadrilateral frame (fig 5). With time others followed with PDR systems that used the CD concepts. Notably, were the super stable Texas Scottish Rite system (TSRH), Shufflebargers low profile Moss Miami System, Ashers's Isola system that used powerful hybrid constructs, CD Horizon and many others that incorporated pedicle screws as the principal implant-anchor. With time most systems evolved to provide strong biomechanical correction principles, stability and lower profiles with less bulk.

Step 5: Hybrid Systems

Hybridization was built on the notion that it is not necessary to use only one type of implant in the surgical construct. Initially, some surgeons combined the concepts of sublaminar wire purchase to Harrington distraction rods improve correction and provided segmental fixation and stabilization. In Wisconsin, we built on that idea but used two linked rods and fixed to the spine segmentally by button-wires that provide a load sharing property to the construct (fig 6).
Marc Asher of Kansas City popularized the use mixed Hooks, wires and pedicle screws in the same construct with his Isola system (fig 7). He backed his concepts with biomechanical principles and clinical research. The value of hybridization may turn out to have been temporary but the principles acted as a bridge to present technology and practice. The developers of hybrid instrumentation contributed much to innovation, progress and how we look at spinal deformity to solve its many problems.

Step 6: The Age of Pedicle Screw Instrumentation

Pedicle screw fixation was introduced decades ago in France by Roy-Camile. His initial report in the French literature was in 1970. In1987 his work was published in an American text, indicating a delay from Europe to the US of almost twenty years. Likely this was caused by caution and the fear for neurologic complications. The Korean experience of Suk reintroduced the concepts of pedicle screw fixation in North America. The attraction for this concept is the obvious biomechanical advantage of an anchor that has purchase on the three vertebral columns (posterior, middle and anterior columns). This provides the construct with powerful correction features and enhanced stability. Lemke and Bidwell in St. Louis, Peter Newton in San Diego and many more have popularized thoracic pedicle screw techniques in the USA. Pedicular fixation alone or in hybrid form has become the standard of care for most deformity cases figs (7&8).

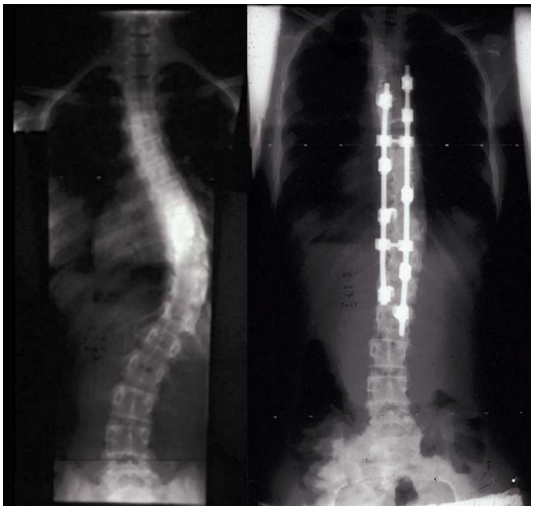

Figure 5. Posterior Derotation (PDR) technique: Sometimes called CD instrumentation after it's two developers, Yves Cotrel and Jean Dubousset, this provided many of the Luque principles with an emphasis on dealing with all plane of the deformity, an emphasis on rod contouring and on load sharing. Although PDR was a misnomer because it did not deliver rotational correction, it did manage frontal and sagittal deformity well. The CD influence can still be observed in most contemporary systems.

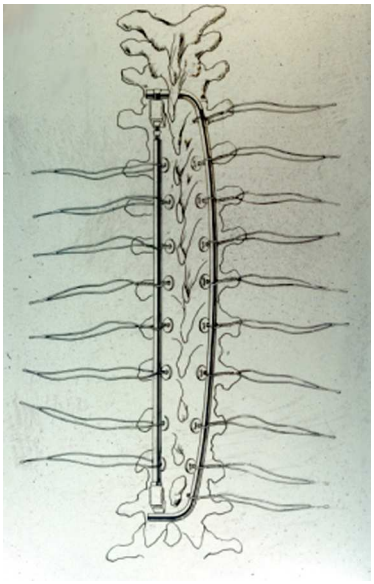

Fig 6. The Wisconsin System: This was one form of hybrid based on distraction and SSI. The system used a button-wire implant attached to the spinous process. With two of these at each level, load sharing was applied.

Visionary Giants and Master Surgeons-Innovators

"Vision is the art of seeing the invisible"
- Jonathan Swift 1667-1745

"A visionary disciplines himself to see the world as if he had only seen it for the first time…"
-Colin Wilson 1957

I have been fortunate to have the opportunity to follow in the footsteps of surgeons that were visionary leaders. They led spinal surgeons through the growth of this relatively new field. They were people of vision that had the will and courage to challenge existing dogmas with conceptual principles and creativity that has resulted in the growth and advancement of the treatment of scoliosis and other spinal deformity. To meet them was to be inspired and to learn from them, for me, generated an excitement for change and scholarly pursuit.

To pick the most important of these leaders is difficult because most conceptual change and advancement are incremental. Like civilization, we did not advance to where we are now on the back of a single person. Generally, there is one surgeon-innovator that develops an idea that challenges the status quo and generates a paradigm shift in the way we think, analyze problems and do things. He or she I define as a ***Visionary Giant***. Following behind them are those, also rare people that have the vision to see the promise of the newly developed concept, embrace it and then refine it. They may not be the visionary giant that created the shift towards advancement, but they are unique in their ability to understand the concept, recognize its potential and refine and improve it and thus carry the idea forward another step. I define them as ***Master Surgeon-Innovators***.

Visionary Giants and Surgeon Innovators

Paul R Harrington (USA): Pioneer for surgical implants for spinal deformity. Inventor of the Harrington distraction and compression systems. Used biomechanical principles and critical evaluation in so doing and taught others the principles.

John Moe (USA): Father of modern surgical treatment for scoliosis. First specialty center and fellowship program dedicated to deformity. With King, he described a classification system for idiopathic scoliosis and with Nash, a classification for rotation deformity. Founding father of the Scoliosis Research Society (SRS), he was the first president of the society and served in that capacity for three years.

John E. Hall (Canada and USA): A master surgeon, a founding father of the Scoliosis Research Society and the society's second president. He is critical thinker that easily grasps the importance of new ideas. He embraces them, refines them and teaches them like no other. He is the one surgeon that spanned from Harrington to the present, critically examining, refining and teaching through these important decades. Hall and John Moe are considered to be the most important leaders of their time to move deformity management forward.

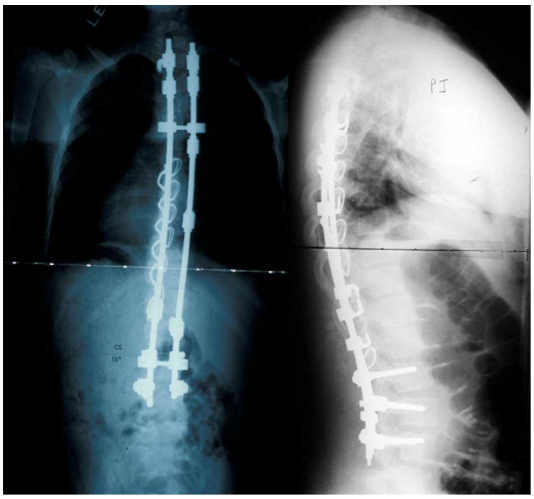

Fig 7. A hybrid construct: Seen here using two rods, hooks, and wires built on a pedicular screw foundation. The principles for this were derived from Marc Asher's Isola system.

Jacqueline Perry (USA): A founding "father" of the SRS, she was first woman member in the SRS and the only one at the first meeting. Perry is best known for her work at the Rancho Los Amigos hospital in Downey California. There, her interests and publications included problems in children with neuromuscular disorders, spinal instability, and spinal cord injury. She is best known for the development of the halo ring, used for stabilization and arthrodesis of the cervical spine.

Eduardo Luque (Mexico): Among other developments, he introduced the Luque

instrumentation system that became used through out the world. Based on bilateral sublaminar wires placed at each segmental level and fixed to contoured rods, the system became the first to stress load sharing at each instrumented level (segmental spinal instrumentation or SSI). Also, it was the first system that respected the importance of the sagittal plane by contouring the rods to provide physiologic kyphosis and lumbar lordosis.

Yves Cotrel (France): The father and mentor of the very productive surgeon-innovators from France. From experience and critical analysis, he introduced many of the principles used by deformity surgeons today. With Jean Dubousset, he developed the Cotrel-Dubousset Implant system that stressed correction of the three-plane deformity. This technique was based on a more rigid approach to the problem with two rods linked together and applied to the spine through multiple anchors or hooks. Based on CD principles, most of presently used systems were developed.

Allen Dwyer: (Australia): Influenced by Hodgson from Hong Kong who showed him the advantages of anterior approaches to the spine, Dwyer applied that technique to deformity correction. He was the first to propose that correction of the scoliosis can be achieved by anterior discectomy and arthrodesis with morselized rib followed by correction of the curve. To achieve this, he developed screw and cable system that when tensioned straightened the frontal (scoliotic) curve. Though there were problems with this system, including inadequate stability of the construct and flattening of the sagittal contours and at worst, lumbar kyphosis. In time, others would solve these problems and Dwyer's concept of anterior spinal instrumentation survived.

Kiyoshi Kaneda (Japan): A surgeon-scientist and innovator that fathered the specialty in Japan, much as Moe and Hall did in the US and Cotrel in France. His contributions are numerous and led to a very productive spinal deformity group in that country. He is best known for solving most of the problems with anterior instrumentation and taking the technique to a new level. He emphasized construct stability with his dual rod system. He also stressed the value of anterior column support to further stabilize the spine and prevent loss of lumbar lordosis. His elegant and thorough technique for anterior surgical release proved valuable for the more rigid curves.

R. Roy-Camile (France): With his1970 report of the technique for pedicular fixation with screws, Roy-Camile is the father of pediclar fixation. Though not strictly developed for deformity work, deformity surgeons have now adopted insertion of pedicle screws in order to enhance stability for spinal constructs. Initially, most were inserted in the lumbar spine to provide a stable base on which to build the implant construct. Recently, the application of the technique has been extended to include most of the spine including all of the thoracic pedicles..

Se-Il Suk (South Korea): A master surgeon and innovator of the techniques for deformity correction with pedicle screw fixation, Dr. Suk is the spinal deformity leader in his native Korea. He is best known for his leadership in spinal instrumentation. In particular he has shown the way and proved the advantages of thoracic pedicle screw insertion at all levels of the thoracic spine. His technique and approach has become popular in the US and the world following the experience of art Steffe of Cleveland for degenerative spine pathologies and both Bridwell, Lemke and many others for deformity. This is undoubtedly a major paradigm change the for scoliosis surgery.

Walter Blount (USA): He is the father of modern orthotic treatment. With the development of the Milwaukee brace and with the long-term followup and the publication of his experience, the principles of contemporary orthotic care born. Others, notably John Hall with his Boston Brace (TLSO), have popularized low profile braces that are better tolerated by the patient and are now used in most pediatric spine centers.

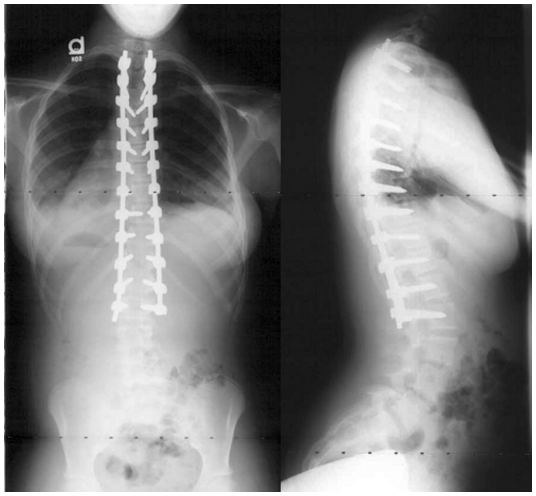

Fig 8. Thoracic pedicle screw construct: This signaled the beginning the twenty-first century approach to spinal deformity. Pedicle screws grasp the three spine columns and thus provide powerful correction forces and increased stability. With thanks to John Dormans MD.

***The Immature Spine*:**
Problems with deformity of the immature spine are related to growth and development. This has implications for progression of the curve, the influence of that on future growth and development and also for treatment. This is well illustrated with congenital thoracic vertebral fusions with or without the associated fusion of adjacent ribs. Besides causing scoliosis and kyphosis, vertebral fusions can significantly retard the growth of the spine and the thoracic cage, the latter can interfere with maturation of the lung buds and possible pulmonary deficit. Most of the leaders for the management of the immature spine today, base treatment concepts on early correction without arthrodesis.

Robert Winter (USA): Past SRS president. Best known for his descriptions of congenital spinal deformity, he made us aware the natural history, the risks and problems associated with the management of both congenital scoliosis and congenital kyphosis. His concept of early arthrodesis prevent ongoing asymmetric growth and curve progression, though challenged as retarder of spinal growth when done for a young child, remains valid for many of the other curve situations. Dr. Winter in the US and Michael McMaster from Edinburgh have given us the framework to approach most congenital spine deformity problems.

Robert Campbell (USA): He recognized the risks for growth retardation related to early conventional treatment of spine deformity associated with congenital fusions of the thoracic vertebrae and ribs. He coined the phrase Thoracic Insufficiency Syndrome that describes the symptom complex associated with the retardation of growth of the thorax and its effect on pulmonary function. He developed an implant system (VEPTR) that applied to the ribs, expands the length and breadth of the chest cage, thus allowing for growth and maturation of the lung. At the same time application of the implants indirectly applies a corrective force to the deformed spine and spinal arthrodesis is withheld. This appears to have promise for young and immature patients early in the first decade, as an option to spinal arthrodesis, thus allowing for thoracic cage growth and lung development.

Other Innovators for Instrumented Correction Without Fusion:

Dr. Campbell is only one of the leaders of a group of surgeons working for the postponement of arthrodesis in the immature and growing spine. Others include: John Emans, Behrooz Akbarnia, George Thompson, Rick McCarthy and Charles Johnston, all from the US and all focused on posterior constructs unaccompanied by an arthrodesis that can be revisited from time to time to reapply correction forces to keep pace with the growth of the child ("growing rod techniques"). They have been responsible for treatment advancements for one of the more difficult problems of pediatric spine deformity.

Spinal Cord Monitoring

Because of better technology and the advancements of anesthesiology, higher risk patients with difficult deformity have become candidates for surgical correction. This situation exposes patients to the risk for spinal cord injury and other neurological problems such as brachial plexus palsy. This has defined a need to accurately monitor spinal cord function during deformity correction surgery.

In the 1970's spinal cord monitoring began with the Stagnara wake up test. With this test, the patient is wakened during surgery and asked to move the legs to command. Though this became the gold standard, there were associated problems. The intra-operative wake up process takes time, usually in the range of 20 minutes

and frequently more. Also, at best, it can only give information at one point of time. With a positive result one cannot know when the insult occurred and valuable time to address the problem could be lost. In the same vane, it does not alert to problems that occur following the wake up. Finally the test is not without complications.

To address these problems, Clyde Nash and Richard Brown of Cleveland introduced the use of real time testing during surgery with Somatosensory Evoked Potential Monitoring (SSEPs). This was a great step forward. Many centers followed including Edgar Dawson from Los Angeles perfected the techniques and published the most complete early report on SSEP monitoring.

Because, SSSEP monitoring primarily tests the afferently mediated posterior sensory tracks and does not directly observe the anterior corticospinal tracks (motor function), several false negative reports have been published using SSEP monitoring alone. These reports point to a need for direct motor track monitoring. Various techniques for motor monitoring have been reported. To this point the best method appears to be the recording efferently directed motor track stimuli, developed with the Transcranial Motor Evoked Potential technique (TceMEPs). To date, tceMEPS has proved to be more sensitive and specific than SSEP monitoring .As well; it appears to be superior to all other reported techniques. Further the response time between the insult to the spinal cord and an electronic alert is faster with TceMEPs than with SSEPs. **Daniel Schwartz Phd**., a long time colleague of mine, has reported the best data on this technique, the most recent report in collaboration with his colleagues from CHOP. He has clearly been the leader in his field and has been at the forefront of multimodality spinal cord monitoring (TceMEPs, SSEPs and EMGs.) Also, he has published the seminal studies in this discipline.

Education Programs

The quality of education for a subspecialty depends on the quality of fellowship programs that focused on the deformed spine. In the USA, Ronald DeWald from Chicago and Keith Bridwell from St. Louis have led the way. Their spine centers and fellowship programs have raised the bar for excellence and other centers have responded. Both have been instrumental in the dissemination of information by publishing authoritative text books based on the education requirements for fellows. Besides these two, John Kostiuk from Toronto and then Baltimore developed a superb center focused on adult deformity. There are several children's fellowship programs that have developed an excellence in spine surgery including Boston Childrens, Texas Scottish Rite Hospital, San Diego Children's Hospital and our own Children's Hospital of Philadelphia. Most of the recent publications and innovative ideas for spine deformity in children have come from these four centers.

It is important to add some of the foreign leaders who have strengthened spine surgery internationally and influenced American surgeons. There are so many French spine surgeons that have provided a bridge for knowledge connecting Europe to North America. Cotrel, the father of French deformity surgery, his disciple Jean Dubousset who is a master of problem analysis and Pierre Stagnara, who taught us to think in three dimensions and was a pioneer for spinal cord monitoring.

From Japan there are also many, but Kaneda appears to have made the greatest contribution to deformity surgery. Finally, SE-Il Suk from Korea has been the principle leader for correction with thoracic pedicle screws and has greatly influenced North Americal surgeons.

Conclusion:

It has been a privilege to observe the birth and growth of this new spine specialty. It has been a gift of timing that is not given to many. It started with an idea and a new technology. How that was used was another issue. It required those with vision to apply principles of scientific observation to determine when, how to apply the idea and how to modify it. This required critical thought and the application of biologic and biomechanical principles. The most exciting thing is that it is an ongoing journey. What we do today hardly resembles what we did before and we will do it differently again in the future. Change is usually incremental as we construct on the building blocks of the past.

My second privilege was to walk the journey with the visionary giants. These great surgeons not only stimulated my generation they were inclusive and eventually passed on the torch to us.