The Importance of Sternal Approximation and Mechanical Stability in Bone Healing

Introduction

Approximation and rigid fixation are key factors in supporting good bony union. These principles apply to the fixation of the sternum following a sternotomy. In 1957, Julian immediately recognized “The solidity of the closure is important because it completely immobilizes the chest from abnormal movements and renders the postoperative period more comfortable. The security of wire sutures is essential.” Wire is effective at approximating sternal halves, but does not provide rigid fixation. The use of plates is one method that provides the rigid fixation needed to support healing following approximation. Because it is rare to have an environment where the gap is completely reduced, another type of primary repair is gap repair. In this environment, a slight gap may be visible, but not enough for cartilage or woven bone formation; therefore repair is initiated by marrow cells of the bone and lamellar bone is laid down. However, the new bone is laid down perpendicular to the old bone, and therefore must be remodeled to match the old bone.

Bone Healing Requires Approximation and Rigid Fixation

When bones fracture, depending on the amount of environmental stability surrounding the fracture, different mechanisms of bone repair are utilized.

- **Primary bone formation (Intramembranous ossification):** Little to no separation due to a very stable environment; bone heals by direct contact without callous formation.
- **Secondary bone formation (Endochondral ossification):** Greater separation and mobility between the bony fragments due to unstable environment; bone heals by deposition of intermediate cartilage layer.

While the two mechanisms of bone healing may be different, both require approximation and stability for bone remodeling to occur. In both primary and secondary healing, approximation and stability allows for the formation of blood vessels which bring nutrients and initiates the repair process to the injured site.

During primary healing, because the gap is reduced by the use of internal rigid fixation, good vascularization is possible, therefore allowing repair via direct contact without the formation of cartilage. Bone repair is then initiated by the Haversian system of the lamellar bone. When bone fractures, blood vessels in the bone are also broken, depriving the area of any nutrients; therefore causing bone tissue to become necrotic. Before new bone can be laid down, the necrotic tissue must be removed. Bone cells (osteoclasts) with cutting cones at the front resorb the necrotic bone and new lamellar bone is then synthesized and laid down parallel to the old, therefore eliminating the need for additional remodeling. Because it is rare to have an environment where the gap is completely reduced, another type of primary repair is gap repair. In this environment, a slight gap may be visible, but not enough for cartilage or woven bone formation; therefore repair is initiated by marrow cells of the bone and lamellar bone is laid down. However, the new bone is laid down perpendicular to the old bone, and therefore must be remodeled to match the old bone.

During secondary healing, the inflammation surrounding the fracture stimulates the periosteum (membranous tissue surrounding bone) to develop cells which replicate and eventually transform into cartilage and woven bone. The periosteal cells closest to the fracture gap develop into cartilage
while those distal to the gap form into woven bone. The new tissue grows until they bridge together and form what is known as a fracture callous.\textsuperscript{2, 12} Once the area is stabilized with the callous, blood vessels are then able to infiltrate and assist with the mineralization into hardened lamellar bone. If movement and separation continues in secondary healing, the soft callous may either fail to mineralize (therefore fail to harden) or lengthen the time in which complete bone healing occurs.\textsuperscript{2, 12}

Animal studies have demonstrated the amount of interfragmentary movement between the fractured ends and size of osseous gaps, specifically those larger than 2mm may affect the quality of bone healing.\textsuperscript{13} Distraction studies using canines have shown that the ideal distraction length is 1 mm per day and 2 mm a day has proven to be detrimental in bone lengthening.\textsuperscript{14} Thus, a gap that is of sufficient size may prevent bridging by callous formation, and potential non-union or malunion may be observed.\textsuperscript{13} Mobility of the fracture site could also have adverse results such as dehiscence, osteomyelitis and mediastinitis.\textsuperscript{7}

In a primate study comparing rigid fixation to wires in sternal healing, Sargent showed that at four weeks, stability and union was seen across the fractured site after removing the plates and manipulating the sternum. In comparison, wires showed unstable sternums and mobility upon manipulation at the fractured site. “Rigid fixation of the sternum resulted in earlier union with primary osseous healing, suggesting greater inherent stability.”\textsuperscript{5} By eight weeks, both groups were healed and no difference was seen between the two treatment methods. This study illustrated primary healing with plates and secondary healing with wires.

**Sternal Wires Support Approximation but Do Not Prevent Sternal Separation**

Studies have shown that using re-enforced or various wiring techniques do not limit sternal separation.\textsuperscript{3, 9, 10} In a human cadaveric study comparing median sternotomy closures with common wire techniques, Losanoff demonstrated that using the Robicsek weave or pericostal figure of eight did not increase the mechanical stability of sternal fixation, or reduce the amount of sternal separation, relative to simple peri-sternal wires. Instead, mechanical stability was shown to be considerably weaker in the Robicsek weave and sternal separation was highest in pericostal figure of eight.\textsuperscript{7} A second study in cadavers also revealed that the amount of sternal separation and displacement seen in double wires was comparable to single wires.\textsuperscript{3} The forces used in both studies (0-800N) were based on forces considered average to maximum (400-1200N) for coughing.\textsuperscript{3} These forces resulted in 4.8mm to 16.0mm of sternal separation after just 1 cycle of loading. Minimum permanent separation of the sternal halves after only 10 cycles was 1.3mm.\textsuperscript{3, 9} This study recognizes that the number of wires and configurations affects the closure’s integrity, stating, “Improved stability during the early healing stages is associated with more rigid sternal fixation, confirming that a stable sternotomy is essential to complete and durable healing.”\textsuperscript{15}
Significant differences \((p<0.05)\) were seen between plates and wires in resisting forces. Sternal separation with wires was 8-10 times more than with plates. When tests were completed to show how much force could be withstood before failure, in both cadaveric and polyurethane models, the plated models demonstrated the ability to withstand twice the force (400N) in contrast to the wired models (200N). In addition, the failures seen by the plates were due to rib fractures and tearing of intercostal muscles near the clamps gripping the cadaveric sternum. Whereas for the wired sternums, failure occurred due to wire pulling through at the midline.\(^6,7\)

**Sternal Plating Results in Rigid Fixation and Reduced Sternal Separation**

Mechanical studies with sternal plating have shown reduced sternal separation and increased mechanical strength with sternal plates compared with wire cerclage. In a cadaveric biomechanical study by Wong, sternal closure with rigid plate fixation and wires were tested by simulating natural forces applied on the sternum in vivo. The study demonstrated 400\% and 1600\% increase in stiffness (lateral distraction and longitudinal shear; \(p<0.05\)) and a 40\% and 45\% increase in strength (lateral distraction and longitudinal shear; \(p<0.05, p>0.05\)) in plated sterna in contrast to wired sterna.\(^6\) Sternal plate fixation showed significant improvements in resisting forces not only of lateral distraction, but also longitudinal shear when compared to wire cerclage. In another study that utilized polyurethane foam models to remove the variability of cadaveric sterna specimens, wires and plates were tested using forces similar to coughing (120N and 180N).\(^7\)

**Mechanical Properties Impact Sternal Union**

Overall, studies with wires have shown poor bone healing\(^4\) (with similar outcomes and complication rates for simple and modified wiring technique).\(^3,11\) In a CT scan study on sternal healing using wires completed by Bitkover, wire cerclage showed 0\% healing at
3 months and only 50% healing at 6 months. Callous was not visible on the radiographs three months after median sternotomy was performed even for patients without suspected infection. A randomized prospective study completed by Schimmer comparing simple wire cerclage to Robicsek weave after a midline sternotomy did not result in lower wound complication rates. Rather, no significant difference in sternal dehiscence rates was seen between the Robicsek weave and simple wires. “The key factor in preventing sternal dehiscence and sternal wound infection is a stable sternal approximation.” Rigid fixation with sternal plates may provide additional mechanical stability needed to support bone healing. After failing to stabilize the sternum using standard wire to close the sternum on a small population, Voss conducted a study using plates to rigidly fixate the sternum and was able to demonstrate effective stabilization of the sternum. Another study utilizing rigid fixation was conducted by Neaman. He showed that patients who had undergone a history of chest radiation (a known cause for inhibiting tissue wound healing) had none of the problems often associated with poor sternal healing including non-union, sternal infection or mediastinitis after undergoing a median sternotomy for cardiothoracic procedure using plates.

CT scans and operative images support the principle that good bony healing necessitates approximation and rigid fixation (Fig. 6-7). Wires were used to approximate the sternum in plated and wired patients. Operative photographs illustrate how well the sternal halves were approximated during the surgery in both groups and CT scans document bone healing. Combined with the operative photographs, this data supports that approximation alone does not lead to bone healing, but approximation plus rigid fixation supports bone healing.

Conclusion

Sternal reduction along with rigid fixation may support improved clinical outcomes by providing the opportunity for improved bone healing and union.

References