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Magnetic Mini-Mover Procedure for pectus excavatum I. Development, design, and simulations for feasibility and safety

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Abstract

Background/Purpose: Correction of pectus excavatum (PE) results in measurable improvement in lung capacity and cardiac performance as well as improved appearance and self-image. The Nuss and modified Ravitch approaches attempt to correct the chest wall deformity by forcing the sternum forward in 1 step and holding it in place using a metal strut. The initial operation requires extensive manipulation under general anesthesia and results in postoperative pain, requiring hospitalization and regional anesthesia. Pain and disability may last for weeks. Both procedures are expensive.

A better principle would be a gradual bit-by-bit repair via small increments of pressure applied over many months. We developed the Magnetic Mini-Mover Procedure and applied this strategy to correct PE.

Methods: The Magnetic Mini-Mover Procedure uses magnetic force to pull the sternum forward. An internal magnet implanted on the sternum and an external magnet in a nonobtrusive custom-fitted anterior chest wall orthosis produce an adjustable outward force on the sternum. Outward force is maintained until the abnormal costal cartilages are remodeled and the pectus deformity is corrected.

Results: We implanted a magnet in human skeletons and measured the force produced by the internal and external magnets, because the distance between them varied. With the 2 magnets 1 cm apart, maximum field strengths at the surface of the heart and at the outer surface of the orthosis were at safe levels.

Conclusions: The Magnetic Mini-Mover Procedure allows correction of PE by applying magnetic force over a period of months. Crucial questions raised during our design, redesign, and simulation testing have been satisfactorily answered, and we have received a Food and Drug Administration Investigation Device Exemption (G050196/A002) to proceed with a phase I to II clinical trial.

Pectus excavatum (PE) can be repaired by several approaches; all involve major surgical reconstruction. The modified Ravitch procedure requires exposure of the cartilages/sternal junctions, removal of abnormal cartilages, and fixation of the sternum in a more normal position with a metal bar for at least a year. The Nuss procedure uses smaller incisions on the chest wall and thoroscopically assisted placement of the metal strut forcing the sternum forward and holding it under tension until the abnormal costal cartilage is remodeled (approximately 2 years). Both procedures require a somewhat brutal procedure under

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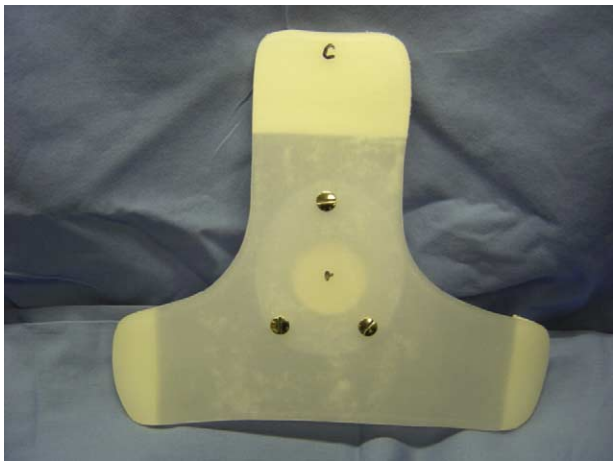

Fig. 1 The external brace (Magnatract). The structural component of the external orthosis is made of polypropylene that it is molded specifically to each patient's anterior chest. The second magnet suspended in this orthosis is the same size as the internal one.

general anesthesia and hospitalization for pain control (usually epidural) [1-6].

The fundamental problem with the available techniques is that they attempt to correct the chest wall deformity at 1 surgical procedure. Deformation of the rigid chest wall under great pressure results in significant morbidity (hospitalization for pain control), a variety of possible complications, and the possibility of incomplete correction or relapse of the deformity. A better principle for correction of chest wall and other structural deformities is gradual (bit-by-bit) correction using minimal force applied over many weeks or months (like that of orthodontics). We have developed a novel method (Magnetic Mini-Mover Procedure or 3MP) to achieve a gradual reformation of the deformed chest wall cartilage without major surgery or hospitalization. A magnetic force field is used to apply controlled outward force on the sternum to promote biologic reformation of structural cartilage (the same biologic principle as distraction osteogenesis).

1. Materials and methods

The 3MP was developed to correct PE by using magnetic force to pull the sternum forward. An internal magnet (Magnimplant) is implanted on the sternum. An external magnet in a nonobtrusive custom-fitted anterior chest wall orthosis (Magnatract) produces an adjustable outward force on the sternum. The outward force is maintained until the abnormal costal cartilages is remodeled and the deformity is corrected.

1.1. Development of the implantable device (Magnimplant)

The first attempts to encase the magnet in epoxy were unsatisfactory. Working with Texcel, LLC (East Longmeadow, Mass), we encased the magnet in a titanium can (Magnimplant) to be implanted on the outer surface of the lower end of the sternum (to minimize the magnetic field at the heart). This device is a cylinder with a 2-in diameter that contains a 1 1/2-in diameter neodymium-iron-boron magnet and a 1/16-in ferromagnetic plate, again, to minimize the magnetic field on the heart. The device is a "button" with a stem placed through a hole drilled in the sternum and an internally threaded nut welded to a plate on the underside of the sternum.

The Magnimplant is designed to be placed through a 3-cm incision made at the sternoxyphoid junction. The xyphoid is separated from the lower sternum with an electrocautery. A space is created under the sternum by blunt finger dissection, and a hole is drilled in the most depressed part of the sternum. The Magnimplant is placed on the outer surface of the sternum and its fixation disk under the sternum, and the halves are screwed together, securely fixing the titanium-encased magnet to the sternum.

We have simulated implantation on human skeletons and cadavers and have measured the outward magnetic force exerted on the sternum by the magnets at varying distances apart. Using a gaussmeter, we also mapped the magnetic field in an anatomical simulation to measure the highest field strength that could reach the heart.

1.2. Development of the external device (Magnatract)

The structural part of the external orthosis (Magnatract) is a polypropylene brace (Fig. 1) that is molded specifically to each patient's anterior chest deformity. The second magnet suspended in this orthosis is the same size as the internal one. The position of the magnet in this brace is adjustable, so the strength of "pull" between the implanted magnet and the external magnet can be regulated. This allows individual adjustment in small increments of the distance (and thus force) and orientation of the outward force applied to the sternum. The low-profile nonobtrusive anterior chest wall orthosis is held in place by the force field between the 2 magnets. Finally, to decrease the magnetic field outward from the orthosis (which might pose a risk to

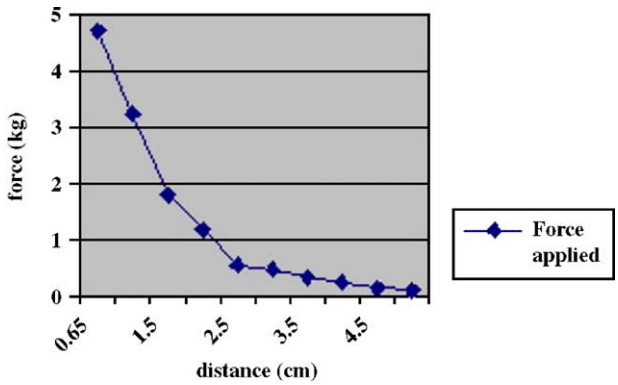

Fig. 2 Measurements of the strength and force generated by various distances of internal and external magnets.

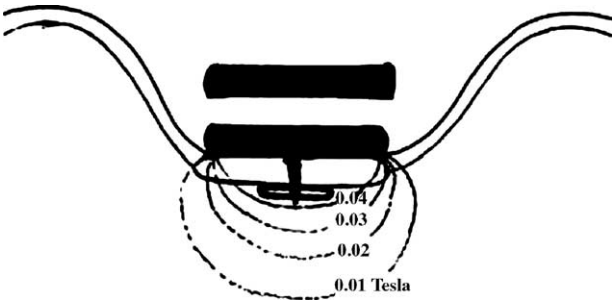

Fig. 3 The magnetic field map measured in the 2-magnet configuration is drawn as isobars. The maximum field strength reaching the surface of the heart is 400 G or 0.04 T, well below the safety limit (4 T).

others), a thin ferromagnetic shield covers the outside part of the orthosis. To test whether the magnetic field could pose a risk to other devices sensitive to magnetic stimulation, we measured the strength of the magnetic field outward from the orthosis with and without the ferromagnetic shield. The composition of the magnets is neodymium-iron-boron.

2. Results

2.1. Simulation of outward force generated by magnets

We have implanted the magnet in human skeletons and tested the variation of the force produced by the internal and external magnets when the distance between them was changed (Fig. 2). The outward force generated when the magnets are 1 cm apart is 4.45 kg.

2.2. Simulation of magnetic field strength at surface of the heart

For the purposes of calculating the maximum field strength at the surface of the heart, we mapped the magnetic field strength isobars with the magnets at varying distances (1-10 cm) apart. When the 2 magnets were 1 cm apart, the maximum magnetic field reaching the undersurface of the sternum was 0.04 T (Fig. 3).

2.3. Simulation of magnetic field strength outside the patient with and without shielding

To decrease the risk that the external magnetic field could interfere with another device sensitive to magnetic fields, we made a thin ferromagnetic metal shield that covers the outside part of the brace to decrease the magnetic field externally to the patient (Fig. 4). The highest field strength at the outer surface of the orthosis was reduced from 150 to 10 G.

3. Discussion

The rationale for correcting PE is well described and documented: Measurable improvement in lung capacity and cardiac performance complement the obvious psychologic advantage of improved appearance and self-image. Techniques to achieve reformation of the rigid chest wall are also well described. The modified Ravitch approach requires resection of parts of the abnormal costal cartilage and positioning of the sternum with a metal strut that remains in place for a year as the cartilage regrows. The Nuss approach achieves repositioning of the sternum under tension without dealing directly with the abnormally shaped costal cartilages and then allowing them to reform over several years. Both techniques require general anesthesia and an operation that most surgeons who do them describe as "brutal." Both standard repairs involve the unavoidable morbidity of a major operation that requires hospitalization for pain control (epidural analgesia), weeks of convalescence, as well as the potential for unsatisfactory outcome or relapse of the

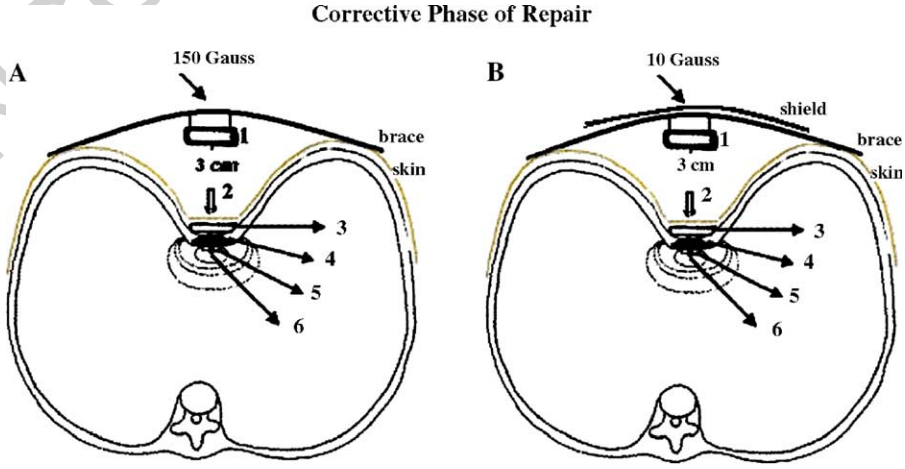

Fig. 4 Representation of the phase that the ribs and sternum were submitted to the force applied by the magnetic device. A, Magnetic field generated by the external magnet without shield. B, Magnetic field decreased to 10 G using the shield. 1 indicates adjustable sternal magnet Magnatract; 2, distance between plates; 3, implanted magnet in titanium can Magnimplant; 4, sternum; 5, titanium plate holding implanted magnet to sternum; 6, screw.

deformity. In addition, both procedures are expensive, with costs estimated at $20,000 to $40,000.

A better approach to the general problem of correction of structural deformities is a gradual bit-by-bit repair in response to small increments of pressure applied over long periods, as in distraction osteogenesis or a more familiar orthodontic treatment. The problem until now has been how to apply outward pressure on the deformed chest wall without the obvious disadvantage of piercing the skin.

A possible solution is to use magnetic force fields to apply constant pressure. Over the last several years, we have developed and tested in various simulations a system in which a magnet is implanted on the sternum in a brief outpatient procedure. The magnet is encased in a hermetically sealed titanium can and attached to the outside part of the sternum through a 3-cm subxyphoid incision. An orthotic device containing a second magnet is crafted to the individual patient's anterior chest wall. The distance between the 2 magnets can be adjusted to regulate the amount of outward force applied on the sternum. The orthosis is held in place by the magnetic attraction. The low-profile non-obtrusive device can be worn essentially around-the-clock.

Several obvious potential problems with this system had to be addressed to achieve approval from the Food and Drug Administration (FDA) to implant a magnet and use the external device. The many engineering problems associated with the implantation and fixation of the device have been overcome using the design demonstrated in this article. Biocompatibility, proof of adequate hermetic sealing of the rare earth magnet within a laser-welded titanium case, and demonstration of feasibility of the fixation have been tested in a variety of simulations and in human cadavers. Q1 The external Magnadjust orthosis has been refined, including methods of suspending the magnet from the orthotic device and of decreasing the external magnetic field that might be a danger to another person using a magnetically sensitive device. In this article, we present the data that have been presented to the FDA to receive approval to begin human trials under an Investigation Device Exemption (G050196/A002).

We first had to demonstrate to the FDA that rare earth magnets of a size compatible with our design could apply enough force to achieve the goal of gradually reforming the abnormal costal cartilages over time. We knew, from the work of Fonkalsrud and Reemtsen [7], that the force necessary to elevate the sternum to a normal position at the time of surgery (under anesthesia) is 2.7 to 23.4 kg, depending on age and pectus severity index. We also knew from the work of Boia et al [5] that the force necessary to move the chest wall 1 cm in an awake child is approximately 2.5 to 5.0 kg and, of course, varies with age and sex, and is limited by pain. In addition, we knew from Schier et al [8] that a pectus deformity can be elevated (and eventually corrected) by a vacuum chest wall lifter. We then simulated the 2-magnet system on skeletons and cadavers and measured the force generated by the 2 magnets. The natural force on the sternum when the magnets are 1 cm apart is 4.5 kg and, of course, can be varied by changing the distance (Fig. 2). We have the additional advantage that we do not have to move the chest wall a great distance at any particular time, but just to move it enough to apply the appropriate mechanical pressure to stimulate reformation of the abnormal cartilages. This biologic stimulus to reformation can then be continuously applied over a period of months.

We conclude that the outward force on the sternum generated by our 2-magnet system is in a range capable of producing a gradual remodeling of the abnormal cartilage in patients with PE. The duration of traction necessary to achieve complete correction is unknown and will certainly vary with the size and age of the patient, that is, the flexibility of the chest wall. One advantage of gradual traction over time is that, even when the chest wall has achieved a good correction, the position of the sternum can be adjusted or held in place while cartilage remodeling completes itself. This is easily achieved by occasional or intermittent traction, for example, wearing the external device at night (much like a child wears a retainer at night after orthodontic braces are removed). The implanted magnet can be electively removed in a brief outpatient procedure once the patient is completely satisfied with the correction.

The most important issue for the FDA was whether a static magnetic field is safe, particularly in terms of the implanted magnet close to the heart. Fortunately, magnetic fields have been extensively studied in relation to human safety, primarily in relation to magnetic resonance imaging. A particular concern is the establishment of a magnetic field in close anatomical proximity to the heart and to its blood flow. These risks have been studied extensively by biophysicists in animal models and humans exposed to magnetic resonance imaging [9,10]. The upshot of these extensive analyses is that there is no detectable effect or changes on cardiac performance or hemodynamic parameters from exposure to magnetic field strength up to 1.5 T. There is an artifactual change in T-wave appearance on electrocardiogram in magnetic fields, but no evidence of functional effect. When we measured magnetic field strength in our 2-magnet system, we found that the magnet strength, although it might increase between the 2 magnets, actually does not vary much on the outside part of the internal or external magnet, and it falls off rapidly as distance from the magnet increases. In our simulations, the maximum magnetic field at the surface of the heart is less than 0.04 T.

Another safety consideration was whether the magnetic field outside the patient could be a danger to another person using a device sensitive to magnetic fields. We have placed a ferromagnetic shield in the outside surface of the brace to decrease to 0.001 T the external magnetic field and added warning labels to all device components.

Another consideration is possible chronic ill effects from long-term exposure to magnetic fields. There are reports of very carefully conducted epidemiologic research examining large populations of workers exposed to high magnetic field strengths, and there was no demonstrable ill effects in the incidence of cardiac disease (myocardial infarction or chronic coronary heart disease) or arrhythmia [11,12]. Another "experiment of nature" that speaks to the effects of long-term exposure to magnetic fields is the common procedure in the cattle industry of using "cow magnets" to prevent a common disease in cattle called *Hardware disease*, which results from ingestion of wires, nails, and other metals. Cow magnets are magnets that are placed in the reticulum (one of the bovine stomachs) for the whole life of the animal without demonstrable ill effect. The magnets, examples of which we have obtained and studied, are similar in strength to our magnet and are at a similar distance from the heart [13].

4. Conclusion

We conclude that the important questions raised during our design, redesign, and simulation testing of the 3MP system have been satisfactorily answered. The FDA has granted an Investigation Device Exemption (G050196/A002) to proceed with a phase I to II trial in patients.

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Discussion

Donald Nuss, MD (Norfolk, VA): First of all, I would like to congratulate Dr Harrison on a very novel idea. When we first started using our technique, we fully expected that people would come up with better ways and more sophisticated ways to do the job, but we thought ours was at least a start. I have a couple questions.

Are you familiar with the work that is being done in Germany with the suction device, because they don't make any incision. They just put a suction device on the chest and try and suck the sternum out in that manner.

Secondly, how long would you need to apply the magnet? We've discovered that if you remove the pectus bar, which is in place 24 hours a day, 7 days a week, 365 days, that you have to leave it in a minimum of 2 years. In fact, we generally leave it in for 3 and sometimes even more years, and that's working 24 hours a day. How would you envision patients wearing this device?

Thirdly, what is the risk of skin erosion because of the magnet, 2 magnets pulling each other together?

Michael Harrison, MD (response): Any comments from Dr Nuss are always appreciated. Thank you so much.

If you can turn the slides back on, I'll show you what Dr Nuss was referring to with the suction device. This is the suction device that was developed by Felix Schier in Germany. I don't think it will work to suck on the skin and soft tissues. I think you have to get a grip on the tough stuff, the sternum, or the cartilage. That is what we do with the magnet.

Erosion of the skin—of course we'll have to watch for it. The nice thing is we can adjust the power that the magnet pulls by simply changing the distance between the external device (the magnet tract) and the implanted magnet. So the kid can go, ooh, this pushes a little too hard, and simply adjust the outer magnet further away.

Your third question is how long it would take and the answer is we don't know. It might be quite a bit of time. Our best estimate from other ways to think about remodeling cartilage is a 6-month to 1-year range.

Donald Nuss, MD (Norfolk, VA): While on the question of time, when we started questioning how long we needed to leave the bar in, I spoke to orthodontic surgeons about their protocols and they leave the braces on for 2 years, but then they put retainers in. I asked them why they put

retainers in and they said because the teeth move apart again. In other words, it takes up to 5 years of correction for the teeth to remain in position.

Michael Harrison, MD (response): Yes, I learned that exact thinking when I was going through it with my daughters' braces and retainers. The neat thing about using an implanted magnet is that there is no downside to walking around without the external device. You can leave your magnet in however many years you want and then apply traction intermittently when you need a little touch-up. You can simply put it back on for a few weeks or a month like a retainer.

James Geiger, MD (Ann Arbor, MI): Wonderful presentation and a great idea. I think the principle of applying constant tension is something that has a role in potentially a lot of pediatric surgical congenital defects. The issue is coming up with devices that are clever enough to do it and this may do that.

I had a question. I was curious about your age group you've chosen. It would seem that a device like this might be something that you might intervene on a severe pectus in a younger age group and wondered why you picked the 8-14 for your FDA application.

Michael Harrison, MD (response): Good question. We did it just because we wanted to start learning from the age group for which there is the most ???. Clearly, it will be easier to do the more pliable younger ones, but there may be an issue with compliance.

Alex Haller, MD (Baltimore, MD): I've learned the hard way not to be too critical of the things that come from Dr Harrison vis-??-vis intrauterine surgery, but I can't believe that that teenager you showed us in the first photograph could possibly have that sternum come out with some very strong effect from your procedure. I therefore want to reiterate what was just asked—would this not be more appropriate in the 2-, 3-, and 4-year olds just as the orthodontists try to get to the children as early as possible. The tissues are not only more mobile and more likely to be easily altered in their relationship, but also, you might have a longer period of time then for growth and development.

Michael Harrison, MD (response): I absolutely agree.

By the way, Alex, another nifty thing you could do to help with tough older and stiffer chests is to work in beautiful little substernal space where you place the magnet and just nick the cartilage underneath or soften it with collagenase.

Alex Haller, MD (Baltimore, MD): Let me just say, Dr Ravitch would have been proud of you to say that (laughter).

Ann Kosloske, MD (Sanibel, FL): Were you concerned about pressure necrosis on the underside of the sternum from the magnet being constantly on? And did you consider using an intermittent field?

Michael Harrison, MD (response): Yes, of course, and we can make it intermittent by just taking the external device off intermittently. The way we designed the button—I didn't get to show it—is with the magnet inside a titanium can on the outer side of the sternum held in place by a big washer on the underside. So the pressure is distributed over a rather large area.

Michael Gauderer, MD (Greenville, SC): Do you think, that we will ever be able to modulate the growth or the strength of the cartilage, because that's really where the problem is? If we were able 1 day to modulate the cartilage, increase the strength, or weaken it temporarily for the-placement of one of these devices, then we will really have attacked the root of the problem rather than its consequences.

Michael Harrison, MD (response): Correct, but what I was hoping, is that we could use mechanical transduction: a little force applied over a long time to achieve a biologic result, which is remodeling of cartilage. Can we help the remodeling by fooling with the cartilage itself? Probably. We've looked at HIFU (high-intensity focused ultrasound) and a bunch of ways to essentially denature cartilage and let it renature when it is in the correct position. My guess is this whole concept of little bit of force, mechanical transduction can be used in lots of ways—back problems, lengthening bowel, lots of things.