PRODUCTION OF A VIABLE PRODUCT IN MAGNETIC RESONANCE IMAGING USING MgB$_2$

by

DANIELLE CHRISTINE KARA

Submitted in Partial Fulfillment of the Requirements

for the degree of Master of Science

Department of Physics

CASE WESTERN RESERVE UNIVERSITY

January 2014
SCHOOL OF GRADUATE STUDIES

We hereby approve the thesis/dissertation of

Danielle Christine Kara

______________________________________________________

candidate for the Master of Science degree *.

Edward M. Caner (co-advisor)

_______________________________________________

Michael A. Martens, Ph.D. (co-advisor)

________________________________________________

Bruce E. Terry

________________________________________________

Robert W. Brown, Ph.D.

________________________________________________

December 3, 2013

(date) _______________________

*We also certify that written approval has been obtained for any proprietary material contained therein.
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Production of a Viable Product in Magnetic Resonance Imaging Using MgB$_2$

ABSTRACT

by

DANIELLE CHRISTINE KARA

In light of uncertainties regarding future helium supply and pricing, the push to eliminate helium dependence in medical imaging has guided research and development of MgB$_2$ superconducting magnets. In the competitive medical imaging market, ability to build an MgB$_2$ MRI does not imply a successful product. The design of a viable product using MgB$_2$ for use in MRI must maximize the product’s value while minimizing the product’s price. Four MRI design options utilizing MgB$_2$ are considered: 1) 1.5T full-body, 2) 1.5T head/extremity, 3) 0.5T head/extremity, and 4) 0.5T head/extremity with an inhomogeneous main field. Each new option represents a sacrifice in value to the customer in terms of bore diameter (2), main field strength (3), and main field homogeneity (4). Of the options, the 1.5T head/extremity MRI offers the greatest price reduction with the smallest value sacrifice, and therefore has the greatest potential for viability in the medical imaging market.
Production of a Viable Product in Magnetic Resonance Imaging Using MgB$_2$

Introduction

Current Concerns regarding the world’s supply of accessible helium has researchers in multiple industries searching for ways to reduce helium dependence. In magnetic resonance imaging, responsible for 22 percent of global helium consumption,$^1$ the element is used to cool the superconducting magnets at the heart of MRI operation. One method for minimizing helium dependence within the medical imaging industry, therefore, involves the construction of magnets that do not require cooling to traditional operating temperatures. As a mid-temperature superconducting material, MgB$_2$ is a promising raw material for use in constructing superconducting magnets that would require very little helium to cool to operating temperature. Various technical aspects of the wire as well as the highly competitive nature of the imaging industry pose challenges for an MgB$_2$ based MRI unit; however, by optimizing value provided to the customer with a low-cost product, the MgB$_2$ based MRI has the potential to disrupt the current imaging market.

1 Helium

Although helium is the second most abundant element in the universe, estimated to account for more than twenty percent of universal mass,$^2$ experts predict that current, global helium reserves will be depleted within the next thirty years.$^3$ Helium is a non-renewable resource, produced in Earth's mantle and crust by the radioactive decay of terrestrial rock.$^4$ While some gas is able to escape, portions of the gas produced during decay are trapped below the rock formations that also trap natural gas.$^5$ As a result, the natural gas mined around the world contains helium, at concentrations that vary by mine
location. Due to the element's low molecular mass, however, it is capable of escaping the Earth's atmosphere, and must be extracted and stored; otherwise, when natural gas is burned, the helium it contains rises quickly through the atmosphere and "is lost to the Earth forever." While the radioactive decay that produces helium on Earth is a continuous process, the rate at which helium is consumed and released into the atmosphere far exceeds the rate at which it is naturally produced, which will ultimately result in the element's depletion on Earth.

1.1 Crisis?

At present, "the world is not running out of helium by any stretch of the imagination," claims Phil Kornbluth, the Vice President of Matheson Tri-Gas, with support from the U.S. Geological Survey estimate that worldwide helium reserves total 1.2 trillion cubic feet, while worldwide consumption totals 6 billion cubic feet per annum. However, decreased demand for natural gas in the early 2000s slowed natural gas mining, and therefore, helium plants were not running at full capacity. Additionally, maintenance during 2012 to the helium plant in La Barge, Wyoming, which supplies approximately twenty percent of global helium, has further exacerbated recent supply shortages and, thus, price increases.
The U.S. government also contributed to the helium scare with the expectation that sales from the National Helium Reserve, "by far the biggest store of helium in the world,"\textsuperscript{10} would cease in October 2013 with the expiration of terms set by a 1996 law dictating the quantity and price of helium to be sold from the reserve. However, in September 2013, the U.S. Senate passed a bill to continue selling helium from the National reserves. The bill also attempts to rectify the current suppression of helium's market value caused by the low sale price of the reserve's helium, which was set only so high as to recuperate money spent building the $1.3 billion National Helium Reserve, and has forced other helium suppliers to keep their prices low despite the high cost of extracting and storing the gas.\textsuperscript{11} Therefore, although the supply shortage that would have occurred had helium sales from the National Reserve ceased this October, will be forestalled due to the September bill, price increases should still be expected with the end of artificial market devaluation, prompting beneficial research into helium conservation as well as helium alternatives.
1.2 Commodity Market

Whether the Earth's helium reserves will be depleted in thirty years or last for hundreds of years, the recent helium crisis has driven scientists in various industries to search for solutions that eliminate the need for helium. Not only would reduced helium consumption ensure the availability of this element for future generations, but it would also serve to remove instability from the industries that currently depend on helium availability and pricing.

Helium is a commodity - a raw material with nearly uniform quality among suppliers. Because commodity suppliers cannot compete on quality, they must compete on price, with price, in turn, determined by supply and demand. Like helium suppliers, the industries and services that depend on helium, are thus subject to the instabilities of its supply and demand. Additionally, because helium is nearly the same regardless of supplier, companies within industries that depend on helium cannot differentiate their products based on lower cost or better quality helium than their competitors. However, by removing helium dependence from product design, companies not only avoid future supply crises and price instability, but also uncover opportunities for product differentiation, a key aspect of obtaining and maintaining competitive advantage.

In the red ocean of medical industry, specifically medical imaging, product differentiation is critical in creating a viable, competitive product. Particularly in light of the current helium crisis, researchers in medical imaging are driven to reduce the dependence on helium for the operation of superconducting magnetic resonance imaging units as a means of eliminating uncertainties in product pricing and sustainability, as well as producing a unique product with competitive advantage.
1.3 Helium in Imaging

Totaling 350 million cubic feet (10 billion liters) during 2011 in the U.S. alone, the use of Helium in medical imaging, specifically MRI, accounts for more than twenty percent of Helium consumption worldwide. The medical imaging industry exploits the low boiling point of Helium, 4.2 K, to cool the superconducting magnets at the core of modern magnetic resonance imagers.

1.3.1 Superconductors

The first superconducting MRIs were introduced in the 1980s, providing great benefits in terms of weight, power consumption, and image quality over permanent magnet and resistive imagers. While energy dissipation in resistive wires is inevitable, superconducting wires in a superconductive state have zero resistance to current flow, resulting in zero energy dissipation. Steady current flow without energy loss in superconducting wires makes them ideal for the production of time invariant magnetic fields, such as those used in magnetic resonance imaging.
1.3.2 Critical Temperature

To achieve a superconducting state, however, superconducting materials must be cooled to or below a particular temperature, the critical temperature $T_c$. Each superconducting compound has an intrinsic critical temperature, which relates to other critical parameters including current density and the presence of a magnetic field. Superconductors are often classified according to their critical temperatures as low-temperature (LTC), mid-temperature (MTC), or high-temperature (HTC) superconductors.\(^\text{16}\)

1.3.3 Cooling in MRI

Most magnetic resonance imaging systems available today contain Niobium Titanium (NbTi) wire, a LTC with critical temperature 9.5 K in the absence of a magnetic field and 4.1 K in an 11 T magnetic field.\(^\text{17}\) Therefore, to achieve superconductivity, NbTi wire must be cooled below 9.5 K. This is most commonly achieved using a liquid Helium bath, which maintains a constant temperature equal to the boiling point of Helium at atmospheric pressure, 4.2 K. An average 1.5 T MRI requires 2000 L of liquid helium to fill the Helium bath and operate its superconducting coils.\(^\text{18}\)

![Figure 3: The region outlined in bold black indicates the region filled with liquid helium in an MRI.\(^\text{19}\)](image-url)
1.3.3.1 Quench

While developers of cryogenic cooling systems have attempted helium conservation with designs that prevent Helium loss during normal operation, disturbances in operation such as wire micro-motion, flux jump, and epoxy cracking, can cause part of the superconducting magnet to enter a resistive state.\(^{20}\) The sudden presence of resistance in the coil causes Joule heating, which rapidly raises magnet temperature and results in sudden boil-off of the entire Helium bath.\(^{21}\) Not only can quenches be dangerous, but they may also result in permanent magnet damage and always require the costly process of re-cooling the magnet and refilling the cryogenic system with 2000 L of Helium.

1.3.4 Eliminating Helium

With MRI machines averaging three quenches during a nine-year lifetime, helium conservation is not achieved with the design of lossless cryo-coolers.\(^{22}\) Further, even a hypothetical, lossless system that never quenches would require a significant quantity of helium. Therefore, MRI units with lossless cryogenics maintain an element of uncertainty to product sustainability with the uncertain future of helium supply and pricing.

2 Approach

One approach to the reduction of helium dependence from medical imaging is the replacement of the commonly used LTC super conducting wire, NbTi, with a higher temperature superconducting material. While several mid- and high-temperature superconducting materials have been discovered since the commercial development of superconducting NbTi wire in 1962,\(^{23}\) magnesium diboride, MgB\(_2\), stands out among the
competition as the wire with the potential to minimize MRI dependence on Helium. Although the critical temperature of this MTC superconductor is below that of several HTC superconductors, the low cost of its raw materials, magnesium and boron, as well as its superior ductility compared to other warm temperature superconductors, which tend to be expensive and brittle, generates excitement over the compound's potential application in MRI. 24

2.1 Value Proposition
Magnesium diboride wire provides the ability to generate a time invariant magnetic field at temperatures above 4 K for MRI manufacturers who want to diminish the need for helium as a means of cooling superconducting magnet coils, in comparison to other, currently available mid- and high-temperature superconducting materials because only it currently possesses the ductility and low raw material costs required to replace the industry's incumbent superconducting material, niobium titanium.

2.2 Temperature Considerations
An important expectation of employing MgB2 wire is the ability to minimize dependence on helium as a cooling agent in magnetic resonance imaging. This expectation can be realized because magnesium diboride coils are capable of operating at a higher temperature than that required for traditional NbTi coil operation.

2.3 Conduction Cooling
Current methods of cooling niobium titanium to its operating temperature of 4.2 K involve building a cryostat that bathes the coils in liquid helium. While MgB2 can superconduct at any temperature below 39 K, currently available magnesium diboride wire in the form of coils used to generate a magnetic field operates at temperatures of
20 K and lower.

Initial prototypes for magnets using MgB$_2$ operate at 4.2 K, and therefore require the same helium bath cooling as NbTi coils. However, improvements in wire quality and research developments in coil designs have made it possible to operate MgB$_2$ coils at 10-20 K. Cooling to 10-20 K allows for replacement of traditional helium bath cooling with conduction cooling, which requires very little helium, approximately 10 L compared to 2,000 L required to fill a liquid helium bath.

**2.4 Minimum Quench Energy**

Even in a conduction cooled MgB$_2$ system that does not contain helium, a quench is a costly event due to the expensive and time consuming process of cooling the magnets from room temperature down to superconducting temperatures. An additional benefit of using MTC magnesium diboride rather than LTC niobium titanium is the ability to cool the MRI with a greater spread between operating temperature and critical temperature; the larger temperature spread increases the stability of the coil, thus minimizing the likelihood that disturbances in the coil will cause a quench. The stability of a superconducting coil is quantified in terms of the minimum quench energy (MQE), the smallest energy disturbance required to break superconductivity and propagate a quench. For adiabatic coil windings, in which coolant cannot penetrate the winding pack, the minimum quench energy is classified by the proportionality

$$MQE \propto A \frac{h(T_c) - h(T_{op})}{J_{op}} \sqrt{\frac{k(T_c - T_{op})}{\rho}},$$

where enthalpy $h$ is on the order of magnitude of $T^4$, with enthalpy calculations given as a function of the operating temperature $T_{op}$ or the critical temperature $T_c$. $A$, $k$, and $\rho$ are conductor properties, representing cross sectional area, thermal conductivity, and the average normal resistivity of the conductor.
matrix respectively. Finally, $J_{op}$ is the operating current density of the conducting wire.$^{27}$

2.4.1 Stability Comparison

With $T_{op} = 4.2$ K and $T_c = 9.5$ K for NbTi, $h(T_c) - h(T_{op}) \sim 7,800$ J and MQE$_{NbTi}$ is on the order of 10 mJ. Alternatively, MgB$_2$ with $T_c = 39$ K, operating between 4.2 K and 20 K gives $h(T_c) - h(T_{op}) \sim 2,000,000$ J and MQE$_{MgB2}$ ranging from 200 mJ to 600 mJ, representing an order of magnitude improvement over the stability of NbTi.$^{28}$

3 Viable Product

Despite favorable outcome expectations of MgB$_2$ use in MRI coils, several obstacles remain, impeding the installation of MgB$_2$ in commercial products. To make magnesium diboride a viable solution in helium-free magnetic resonance imaging, design challenges due to the critical parameters of this superconducting compound must be addressed.

3.1 Current Considerations

Temperature is not the only critical parameter affecting the superconductivity of a particular material. Operating below its critical temperature, a superconductor enters a resistive state when its current density exceeds a critical value. Critical current depends on temperature as well as particular wire design elements, such as wire diameter and superconductor fraction (% SC), and therefore, its value varies by manufacturer and specific product.$^{29}$
Critical current is extremely important in the use of superconducting wire to create a magnetic field due to the dependence of the magnetic field produced on the current present, as given by the Biot-Savart Law $\vec{B}(\vec{r}) = \frac{\mu_0 I}{4\pi} \int \frac{d\vec{l} \times \vec{r}}{\vec{r}^3}$, for a constant current $I$ through a length of wire $\vec{l}$. The relationship between critical current and superconductivity at a particular temperature, as well as the dependence of magnetic field on operating current, limit the practicality of using a particular superconductor at a specific temperature to produce a target magnetic field. With all other parameters remaining constant, the higher the operating current, the higher the magnetic field produced, but the ability to increase the operating current is always limited by the critical current at a given temperature. Therefore, although MgB$_2$ can superconduct at higher temperatures than NbTi, it is important that MgB$_2$ wire can withstand high enough operating current to generate the desired magnetic field at elevated operating temperatures to be a competitive alternative.

3.2 Coil Considerations

When trying to produce a magnetic field of a particular strength within the limits of low operating current, compensation is possible by adding more current loops. This is clear from the solution to the Biot-Savart law for $n$, circular current loops, which gives the
on-axis magnetic field $\mathbf{B}(z) = \frac{\mu_0 n I}{2} \left( \frac{R^2}{(R^2 + z^2)^{3/2}} \right) \hat{z}$. Additional loops, of course, increase the quantity of superconducting wire required, and thus increase production costs.

However, in MRI coil design using superconducting materials, the number of loops is also limited by the third critical parameter of superconducting materials - the presence of a magnetic field.

### 3.2.1 Magnetic Field Considerations

In addition to resistance free current flow, materials in a superconductive state produce surface currents that exactly cancel the magnetic field within the superconducting material. However, superconductors enter the resistive state when exposed to magnetic fields exceeding a critical value. Like critical current, the magnetic field strength that a superconductor can withstand is related to the operating temperature. Critical magnetic field follows a parabolic relationship to operating temperature, $B_c \approx B_0 \left( 1 - \frac{T_{op}}{T_c} \right)$, therefore superconductivity can be achieved in the presence of higher magnetic fields when cooled to lower ratios of $T_{op}$ to $T_c$, up to a maximum value $B_0$, which would be sustainable at absolute zero.$^{31}$

While the critical magnetic field can be calculated as a function of critical and operating temperature, all three critical parameters: temperature, magnetic field, and current, are related and additionally dependent on operating temperature. In general, critical field decreases as critical current increases for a particular wire design containing a certain type of superconducting material, and operating at a set temperature.$^{32}$
In MRI design, which involves multiple sets of coils to generate a homogeneous, on-axis field of a particular strength within a desired field of view, critical magnetic field is a crucial design parameter to consider. While coils are designed to generate a specific magnetic field within a particular field of view (FOV), the current carrying coils generate an expansive magnetic field in all directions. Therefore, each point on a coil in an MRI experiences a magnetic field due to the vector sum of the magnetic fields produced by the surrounding current carrying coils. Should the total magnetic field at any point on a coil exceed the critical magnetic field, the magnet will quench.

### 3.2.2 Limiting Coils

Critical magnetic field, therefore, further limits magnet design in that achieving a homogeneous, on-axis field of a particular strength within the field of view can bypass critical current limitations with the addition of only so many loops in a given space before the peak magnetic field $B_{\text{peak}}$, the maximum total magnetic field on any particular point in a superconducting coil, exceeds the tolerance of the superconducting material, causing it to enter a resistive state. Additionally, by
\[ \mathbf{F} = \int d^3 r \: \mathbf{j}^* (\mathbf{r}) \times \mathbf{B}(\mathbf{r}) \], a wire carrying a current \( \mathbf{j}^* (\mathbf{r}) \) in a magnetic field, \( \mathbf{B}(\mathbf{r}) \) feels a force related to both the external field and its current, so that increasing the magnetic field experienced at any point on the winding increases stress in the system.\textsuperscript{34}

### 3.3 Conflicting Interests

While the number of coils in a particular space is limited by the critical magnetic field tolerance of the superconducting wire and the amount of stress the system can withstand, pressure for a large field of view with a strong, extremely homogeneous magnetic field distribution - achieved with the addition of extra coils and/or ferromagnetic material- means that MRI magnet designs must be optimized to satisfy conflicting interests.

#### 3.3.1 Homogeneity

Within the current free zone inside the magnet bore, the Ampere’s Law, \( \nabla \times \mathbf{B}(\mathbf{r}) = \mu_0 \mathbf{j}^* (\mathbf{r}) \), is reduced to \( \nabla \times \mathbf{B}(\mathbf{r}) = 0 \) in regions of no current, a magnetic scalar potential can be defined, \( \mathbf{B}(\mathbf{r}) = -\nabla \varphi (\mathbf{r}) \), such that \( \nabla^2 \varphi (\mathbf{r}) = 0 \), since \( \nabla \cdot \mathbf{B}(\mathbf{r}) = 0 \) everywhere. Knowing the solution of the Laplacian in terms of spherical coordinates, it is easy to define \( \varphi (\theta, \phi) \) for a loop of wire carrying a constant current, \( I \), in terms of the spherical harmonics. Using this definition, the axial component of the magnetic field distribution within the bore can be expressed as a series of spherical harmonics

\[
B_z = \sum_{n=0}^{\infty} \sum_{m=0}^{n} r^n P_n^m (\cos \theta) [A_{n,m} \cos (m\phi) + B_{n,m} \sin (m\phi)]^{35}
\]

where \( A_{n,m} \) and \( B_{n,m} \) are constants determined by boundary conditions, and \( P_n^m \) are the associated Legendre polynomials. In this series, the order \( m \) represents the harmonics
causing variations in $B_z$ within the x-y plane, where in an ideal axisymmetric coil set-up, only the m=0 terms are non-zero. The order n represents the set of zonal harmonics causing axial variations in $B_z$, where in an axisymmetric coil set-up, only terms containing even values of n survive. Commonly, modern coil design achieves axial homogeneity, $\nabla B_z$, on the order of 10 ppm by canceling harmonic terms associated with n=2, 4, 6, 8, and 10 "over a FOV with dimensions half those of the magnet bore diameter" using "six field-shaping main coils (three coil pairs in a symmetrical magnet)." 

3.3.1.1 Shimming

While optimization can theoretically lower inhomogeneity to the target value of 10 ppm, various manufacturing tolerances inevitably result in additional inhomogeneities in the actual magnetic field produced. "No matter how homogeneous the magnet design, the as-built magnet will invariably deviate from the theoretical homogeneity, coming short of the level required for imaging." When ignored, inhomogeneities in the magnetic field interfere with the position and phase encoding accomplished using linear gradients, and thus result in inaccurate assessment of the spatial origin of a signal, ultimately leading to degraded image quality. Inhomogeneities introduced during the manufacturing process are often eliminated using active, passive, or hybrid forms of coil shimming.

3.3.1.2 Passive Shimming

Passive shimming is the process of inserting ferromagnetic material either within the magnet bore or within the gradient structure. This ferromagnetic material creates distortions in the magnetic field, and thus can be strategically placed, based
on computer simulations and optimization models, to compensate for unwanted inhomogeneities in the main magnetic field. The appropriate positions for the ferromagnetic materials to achieve the desired level of homogeneity are unique to each magnet; passive shimming, therefore is a custom process for individual magnets, costing additional manufacturing time and resources. Additionally, insertion of ferromagnetic material in active shimming adds significant and undesirable weight to the MRI.38

3.3.1.3 Active Shimming

Alternatively, manufacturing induced inhomogeneities can be reduced using active shimming, in which additional, usually superconducting, coils dedicated to shimming are added to the MRI design. Generally in the form of racetrack coils and arcs, shim coils produce harmonics to cancel those present in the manufactured magnet, with the magnitude of the harmonics produced dependent on the current driven through the shims.

While active shimming avoids "the challenge of excessive mass and force"
introduced by passive shimming, shim coils increase the quantity of superconducting material used in coil design, the volume that must be cooled below the critical temperature, and the overall complexity of the system. Due to the challenges and benefits of both methods, MRI manufacturers often use hybrid shimming, a combination of both active and passive shims, to achieve desired levels of homogeneity.

3.3.2 Imaging Volume

The strategic locations of coil pairs, shim coils, and ferromagnetic materials in MRI design create a highly homogeneous magnetic field within a particular volume. The imaging volume, or field of view, must be at least as large as the sample being imaged. Generally noted in terms of the diameter of the spherical volume (DSV), the size of the field of view can be optimized in terms of various parameters, including bore diameter, bore length, and compensation for harmonic field contributions. One method for increasing the imaging volume involves compensation for higher order harmonics in the main field, which can be achieved with the introduction of additional coils to the extent allowed by critical field parameters of the superconducting wire and by the stress tolerated by the system.

3.3.3 Bore Diameter

Achievable field of view is necessarily related to the bore diameter in that the imaging volume is physically restricted to the space within the magnet bore for a traditional MRI. While concerns for patient comfort pushes magnet designers to increase the inner bore diameter for full body scanners, a wider bore introduces design challenges. Because magnetic field is inversely related to the distance from the
current loop, increasing the inner diameter without changing other design parameters lowers the achieved \( B_0 \). Increasing \( B_0 \) to the desired strength comes with the cost of more current or coils and higher \( B_{\text{peak}} \), which must be limited in terms of the critical parameters.

Particularly when using new, higher temperature superconductors like MgB\(_2\), which tend to be more brittle than the traditional NbTi, challenges of large bore diameters make small bore machines an interesting option for magnet designers looking to enter the MRI market. Although for a full body machine, smaller bore diameters decrease patient comfort, for a specialty machine, imaging only extremities or possibly the head, a small bore diameter does not necessarily sacrifice patient comfort. Bore diameters in extremity machines must only be large enough to accommodate the appropriate body parts.

### 3.4 Persistent Joints

While challenges and tradeoffs regarding the interrelated critical parameters of MgB\(_2\): temperature, current, and field, require optimization techniques to theoretically design a magnesium diboride main magnet of desired bore dimensions and magnetic field strength, with chosen homogeneity within a particular field of view, development of a MgB\(_2\) persistent joint is considered to be "the most critical technical challenge for MR applications."\(^{41}\) In contrast to industry standard NbTi, MgB\(_2\) decomposes when heated to high temperatures, such as those that would be used to form joints via the fusion process, and forms non-superconducting phases including MgB\(_4\) and MgB\(_7\), which introduce unwanted resistance into the system. While several groups, including a research group at MIT, are working to create a persistent joint for MgB\(_2\), "none of them
has yet determined a reliable repeated method to meet the technical requirements for MR magnets."\(^{42}\)

4 Commercialization

Despite a multitude of challenges, the allure of a helium-free MR magnet design drives the current research efforts of universities, small start-up companies, and large original equipment manufacturers (OEMs) alike towards the goal of producing a commercial MgB\(_2\) MRI.

4.1 Open-Sky

In 2010, Paramed became the first company to offer a MgB\(_2\) product with the launch of its 0.5 T, split-open bore, helium-free, Open-Sky scanner. Although the central field is low at only 0.5 T, related to a low operating current of 90 A, the Open Sky offers a patient gap of 58 cm, on target with an average full-body patient gap of 60 to 70 cm, and has the benefit of being a helium free system, using conduction cooling to reach temperatures of 18 K. The original prototype for the Open Sky took its first images in 2006; the original prototype was followed by a second prototype in 2008, and a commercial product in 2010.\(^{43,44}\)

![Paramed’s Open Sky 0.5T, MgB2 MRI](image-url)
4.1.1 Commercialization?

According to a presentation by Columbus Superconductors, the suppliers of the MgB2 wire utilized in the Open Sky's pancake-style main magnets, six magnets had been produced for the Open-Sky by 2010, with the expectation that two to four units would be sold its first year.\textsuperscript{46} According to the Paramed website, however, the third Open Sky unit was sold and installed in early 2013. Three sales in three years seems to fall quite short of the sales required to create a viable product.\textsuperscript{47}

4.2 Sustaining Innovation

Clayton Christensen's ideas on sustaining versus disruptive innovations assist in determining an explanation for the low level of commercial success with regard to the Open Sky scanner. Using Christensen's terminology, the Open Sky's use of MgB\textsubscript{2} is an improvement in component technology\textsuperscript{48} - open MRIs, with design parameters similar to those offered by the Open Sky already exist in the market place. The GE Signa-SP, for example, which was first introduced in 1994, is a horizontal split bore, helium-free, 0.5 T MRI with magnets made of Nb\textsubscript{3}Sn, conduction cooled to 10 K, and a 58 cm patient gap.\textsuperscript{49} The major constructural difference between the GE Signa-SP and the Paramed Open Sky is the Open Sky's use of MgB\textsubscript{2}. Although the cost of the Open Sky relative to the cost of the GE Signa-SP is unknown, the Paramed website makes no mention of cost savings or improved image quality compared to other 0.5 T, open bore machines.

The Open Sky, therefore, is competing in the same market as multiple other models of open bore, 0.5 T or higher MRIs, with the use of MgB\textsubscript{2} offering little benefit to doctors in terms of the main jobs to be done: improve patient comfort during MRI scans, e.g.
free space, position, etc., and take clear images for diagnostic purposes. Competition within an established market further suggests that Paramed's use of MgB$_2$ exemplifies a sustaining innovation. According to Christensen, most successful sustaining innovations are launched by industry leaders, competing to maintain market share in a given industry by showing improvement over previous models, rather than by mid-sized companies looking to gain market share. Particularly with only marginal improvement in product ability to execute the job to be done, Paramed's limited ability to compete against major market shareholders with the sustaining innovation of employing MgB$_2$ in its magnet design has ultimately resulted in low sales of the Open Sky scanner.

4.3 Disruptive Innovation

While it is challenging to compete with large OEMs based on sustaining innovations, Christensen's studies have shown favor on small companies in terms of disruptive innovations. Unlike improvement in component technology within an existing system, architectural innovations change a crucial component of what a product has to offer, thus capturing new audiences and opening sales into new markets. Termed disruptive innovations, changes that capture a new market tend to be low-cost and produced by smaller companies rather than the large incumbents. Use of MgB$_2$ in a new type of MRI produced by a start-up company, offering architectural innovations at a low-cost, therefore, has great potential for capturing new markets as a disruptive innovation. Based on some current challenges in implementing MgB$_2$ into MRI designs, architectural changes that could produce lower cost products include MRIs with reduced bore diameter for use in extremity imaging, elimination of
shimming in favor of inhomogeneous MR imaging, low field MRI, and any combination of the three changes.

Figure 8: Comparison of sustaining and disruptive innovations in MRI

4.4 Blue Ocean

The commercialization of a disruptive innovation that creates and captures a new market, giving a group of people access to a product that they previously could not obtain, is closely related to the ideas of Blue Ocean Strategy. Rather than compete in the crowded red ocean, which exploits existing demand, blue ocean strategy suggests creating new demand for a product that does not trade value for cost. In a blue ocean, "successful companies pursue differentiation and low cost simultaneously." Rejecting the cost versus value tradeoff means enhancing the features that are truly important to customers, while creating savings by eliminating extra features.

Designing a low-cost MgB\textsubscript{2} MRI with the blue ocean strategy means maximizing the features of highest customer value, while finding ways to cut costs by reducing extraneous features.

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i Graph of MRI performance versus time is based on the ideas of Clayton Christensen
5 Cost Analysis

Analyzing the lifetime cost of an MRI to a customer provides important information for determining where to spend and where to save when building a MgB₂ MRI using Blue Ocean Strategy.

5.1 Initial Cost

The current industry standard, 1.5 T MRI costs approximately $1 million. By convention, annual maintenance costs total 10% of the initial investment price. Therefore, $100 thousand in maintenance costs should be expected annually over the lifetime of the MRI.

5.2 Staff

In most hospitals in the United States, an MRI is operated by two technicians per shift, with an average salary of $70 thousand per year. Additionally, a radiologist is required to read the MRI scans. The average radiologist salary in the U.S. is $300 thousand per year. Therefore, given a lifetime per MRI scanner of 9 years, and two shifts of two technicians, the total cost to the hospital of staffing an MRI over its lifetime is $5.2 million.

5.3 Overhead

In addition to staff and the initial cost of the machine, hospitals must pay for the space occupied by the MRI unit as well as the power it consumes. On average, MRI rooms span 1,000 square feet, and due to stringent hospital construction codes, the price of building the room averages $400 per square foot, resulting in $400 thousand in total construction costs. Power costs depend on the utilization of the MRI. In a hospital where the unit is off (drawing 9 kW) for 12 hours per day, ready-to-scan (drawing 14
kW) for 8 hours per day, and scanning (drawing 21 kW) for 4 hours per day, an MRI draws 304 kWh per day.\textsuperscript{58} Given the average price of electricity in the United States as of September 2013 was $0.10 per kWh,\textsuperscript{59} over 9 years it will cost the hospital approximately $100 thousand to power the MRI.

5.4 Helium

Another factor adding to the MRI’s cost to the hospital is the cost of quenching. Not only does quenching result in lost time, but the hospital also incurs the cost of adding new helium to the system. With the current price of helium in the U.S., $10 per liter, it costs $20,000 to fill a 2,000 L Helium bath.\textsuperscript{60} With three quenches during the five-year lifetime of the MRI, the hospital spends an additional $60,000 on helium.

5.5 Total Cost

Summing the various costs, a hospital spends approximately $7.7 million to purchase and operate an MRI over a 9-year lifetime, or $850 thousand per year.

Table 1: Lifetime Cost of a 1.5T Full Body MRI

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Investment</td>
<td>$1,000,000</td>
</tr>
<tr>
<td>Maintenance Costs Over 9 Years</td>
<td>$900,000</td>
</tr>
<tr>
<td>Total Staff Costs Over 9 Years</td>
<td>$5,200,000</td>
</tr>
<tr>
<td>Cost of Building an MRI Room</td>
<td>$400,000</td>
</tr>
<tr>
<td>Electricity Over 9 Years</td>
<td>$100,000</td>
</tr>
<tr>
<td>Helium Over 9 Years</td>
<td>$60,000</td>
</tr>
<tr>
<td>Total Cost of 1.5T MRI over 9 years</td>
<td>$7,660,000</td>
</tr>
<tr>
<td>Cost per year</td>
<td>$851,000</td>
</tr>
</tbody>
</table>

5.6 Cost per Scan

With an average time of 65 minutes per patient, the MRI can run 11 scans if it operates 12 hours per day.\textsuperscript{61} Operating for 12 hours every day, the machine is capable of running
4,015 scans per year, so that the hospital can reach break-even if it receives $210 per scan while operating the MRI at maximum capacity.

5.7 Expense Analysis

From the analysis of the cost of owning and running an MRI in a hospital, it is clear the largest expense of operating the MRI is paying the radiologist and the technicians, which amounts to 68% of the total cost over 9 years. Therefore, one major way for the MRI manufacturer to develop a valuable product capable of cutting hospital costs involves designing an MRI that eliminates the need for one or two operating technicians, although the feasibility of such a product is rather questionable. Additionally, it is important to note from the price per scan analysis that cost of each scan to the hospital is directly dependent on the number of scans that the hospital runs per day. A machine that averages only 4 scans per day, for example, would cost the hospital over $500 per scan, rather than $210 per scan that results from operating at 11 scans per day.

6 Price Analysis

With a better understanding of the customer costs incurred with a traditional 1.5 T MRI, constructed with a NbTi magnet, it is now possible to analyze the effect of replacing NbTi with MgB$_2$. Although the critical parameters, temperature, current, and field, as well as the winding parameters, such as stress and joint complications, of MgB$_2$ do not allow for direct substitution of magnesium diboride for niobium titanium in current designs, it is still useful to compare relative costs as if such substitution were possible. Four possible alternatives using MgB$_2$ to the industry standard 1.5 T, full-body, NbTi MRI will be considered, with various bore diameters, main field strengths, and
homogeneity requirements.

Table 2: Four MgB$_2$ alternatives to the industry standard 1.5 T, full-body NbTi MRI

<table>
<thead>
<tr>
<th></th>
<th>Industry Standard</th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
<th>Option 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire Type</td>
<td>NbTi</td>
<td>MgB$_2$</td>
<td>MgB$_2$</td>
<td>MgB$_2$</td>
<td>MgB$_2$</td>
</tr>
<tr>
<td>Main Magnet Strength</td>
<td>1.5 T</td>
<td>1.5 T</td>
<td>1.5 T</td>
<td>0.5 T</td>
<td>0.5 T</td>
</tr>
<tr>
<td>Bore Diameter</td>
<td>60 cm (Full-Body)</td>
<td>60 cm (Full-Body)</td>
<td>40 cm (Head/Extremity)</td>
<td>40 cm (Head/Extremity)</td>
<td>40 cm (Head/Extremity)</td>
</tr>
<tr>
<td>Required Quantity of Helium</td>
<td>2,000 L</td>
<td>Negligible</td>
<td>Negligible</td>
<td>Negligible</td>
<td>Negligible</td>
</tr>
<tr>
<td>Main Field Homogeneity</td>
<td>&lt;10 ppm (homogeneous)</td>
<td>&lt;10 ppm (homogeneous)</td>
<td>&lt;10 ppm (homogeneous)</td>
<td>&lt;10 ppm (homogeneous)</td>
<td>&gt;10 ppm (inhomogeneous)</td>
</tr>
</tbody>
</table>

6.1 Full-Body, 1.5T MgB$_2$, 10-20 K

6.1.1 Wire

The average cost of niobium titanium is $1.50/kAm, which correlates to $1.20/m for wire with a critical current of 800 A.\textsuperscript{62} By comparison, MgB$_2$, as quoted by HyperTech, currently costs $4.50/m, which correlates to $6.60/kAm given a critical current density of 7.5 kA/sq mm in a wire that is 0.8 mm in diameter and has a superconductor composition of 18%, or a critical current of 675 A.\textsuperscript{63}

An average 1.5 T machine requires 65 km of NbTi, costing $78 thousand. By comparison, the model 1.5 T MRI designed by CWRU requires 75 km of MgB$_2$, which would cost $338 thousand, $260 thousand more than the cost of the raw material for the NbTi magnet.\textsuperscript{64} With all other factors remaining the same, direct substitution of MgB$_2$ into the current NbTi model would thus result in a 26% price increase, from $1 million to $1.26 million.
6.1.2 Conduction Cooling

The MgB$_2$ system, however, may offer savings over the NbTi system in the form of cooling. CWRU has created a model which indicates that it is possible to design a 1.5T full-body MRI using MgB$_2$ that operates at 10 K. Operation at 10 K means that conduction cooling, rather than a helium bath, can be employed to cool the magnet. While the price of the conduction cooling system is yet to be determined, if it is on the order of magnitude of the cost of the currently employed cooling system sans helium, then savings on helium would total $20 thousand initially, and $80 thousand over the lifetime of the machine. With this assumption, subtracting $20 thousand from the initial cost of the machine, the MgB$_2$ substituted MRI cooled to 10K would be expected to cost $1.24 million, a 24% price increase over the NbTi equivalent cooled to 4.2 K.

Table 3: The costs and savings of substituting MgB$_2$ for NbTi in a 1.5 T full-body MRI

<table>
<thead>
<tr>
<th>Description</th>
<th>NbTi</th>
<th>MgB$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire Cost ($/m)</td>
<td>$1.20</td>
<td>$4.50</td>
</tr>
<tr>
<td>Length of Wire Required (km)</td>
<td>65</td>
<td>75</td>
</tr>
<tr>
<td>Total Wire Cost per Machine</td>
<td>$78,000</td>
<td>$337,500</td>
</tr>
<tr>
<td>Cost of Helium ($/L)</td>
<td>$10</td>
<td>$10</td>
</tr>
<tr>
<td>Liters of Helium</td>
<td>2,000</td>
<td>~ 0</td>
</tr>
<tr>
<td>Total Initial Helium Cost</td>
<td>$20,000</td>
<td>~ 0</td>
</tr>
<tr>
<td>Total Machine Price</td>
<td>$1,000,000</td>
<td>$1,240,000</td>
</tr>
</tbody>
</table>

6.2 Head/Extremity, 1.5T MgB$_2$, 10-20 K

Because the increased cost of the 1.5 T machine where MgB$_2$ is substituted for NbTi is due to the current high cost of MgB$_2$ per meter, an effective way to reduce costs is to reduce the required quantity of wire, which can be achieved by reducing the bore diameter. While a machine with reduced bore diameter could not accommodate a full body, it could be a machine dedicated to extremity or head imaging. The average male
head is 23 cm long with a 60 cm circumference, foot is 27 cm long by 10 cm, and hand is 19 cm long by 9 cm wide. Given that the average male shoulder width, typically a person’s widest dimension, is 46 cm and the average inner bore diameter is 60 cm, the bore diameter is 130% of the average shoulder width. Using a similar approximation, a head scanner should be 130% the widest part of the head, which given a circumference of 60 cm and a non-spherical head, should be 20 to 30 cm, resulting in a required bore diameter of 26 to 39 cm. An extremity scanner, for hands, elbow, feet, and knees, should be large enough to accommodate the largest dimension, the length of the male foot, which would result in a bore diameter of 35 cm.

**Table 4: A comparison of dimensions of the average male body**

<table>
<thead>
<tr>
<th>Description</th>
<th>Measurement (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>23</td>
</tr>
<tr>
<td>Circumference</td>
<td>60</td>
</tr>
<tr>
<td>Width (approximate)</td>
<td>30</td>
</tr>
<tr>
<td>Foot</td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>27</td>
</tr>
<tr>
<td>Width</td>
<td>10</td>
</tr>
<tr>
<td>Hand</td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>19</td>
</tr>
<tr>
<td>Width</td>
<td>9</td>
</tr>
<tr>
<td>Shoulders</td>
<td></td>
</tr>
<tr>
<td>Width</td>
<td>46</td>
</tr>
</tbody>
</table>

Based on a 2010 MRI IMV Market Summary Report, 22% of all procedures image the head and 24% of all procedures image an extremity. If the machine is large enough to image the head, it should be large enough to image an extremity as well. A head/extremity imager, thus, would be able to handle 46% of all MRI cases, given the ability to move the bore so as to be able to position patients comfortably.
Because circumference is proportional to diameter and assuming that the bore length scales with diameter, a head/extremity machine with a bore diameter of 40 cm, two-thirds the inner bore diameter of the full body scanner, should require only two-thirds the amount of MgB$_2$, 50 km. 50 km of MgB$_2$ at $4.50/m would cost $225 thousand rather than $338 thousand. In the NbTi, 1.5 T MRI, non-main magnet raw material costs and mark-up total $900 thousand. Scaling these costs to 30% by estimating that volume, which scales with the bore diameter cubed, and cost scale linearly, results in non-main magnet raw material costs of $270 thousand. The total cost of a 1.5 T MgB$_2$ head/extremity MRI, therefore, would be $495 thousand.

6.3 Head/Extremity, 0.5T MgB$_2$, 10-20 K

Raw material costs in the form of wire price can be further reduced by creating a 0.5 T head/extremity MRI because the central magnetic field is proportional to the number of loops in each coil. Reducing the magnetic field by one-third, while keeping the operating current, diameter, and total number of coils constant, can be achieved using one-third the number of loops in each coil, and therefore, one-third the amount of wire. With this rationale, the main magnet of a 1.5 T MgB$_2$ head/extremity scanner with an inner
diameter of 40 cm, can be produced using approximately 20 km of wire. At a price of $4.50/m, the raw material cost of the main magnet would be $90,000. Due to the increased simplicity of a 0.5 T, small scale MRI over the 1.5 T whole body, it is reasonable to assume that further reductions in cost other than main magnet costs, will be possible, so that the 0.5 T machine would cost less than $360 thousand.

6.4 Inhomogeneous Head/Extremity, 0.5T MgB$_2$, 10-20 K

Thinking in terms of the end customers, the doctors who will be using the MRI to generate images for diagnostic purposes, it becomes apparent that the costly process of shimming to generate a highly homogeneous magnetic field, may be an expense that could be spared given the computing power of modern technology, as the quality of the image produced is important, but the method of producing the high quality image is not a particularly pointed customer concern. Should it be possible to generate a competitive quality image using an inhomogeneous background field, thus eliminating the need for shimming, the price of a small bore system would likely be reduced by up to an additional $30 thousand due to weight reduction, lower raw material costs, less concern regarding space inside the bore, and no shimming installation costs. For the 0.5 T head/extremity machine, this could mean a selling price under $350 thousand.

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i See Appendix for a detailed discussion of inhomogeneous imaging
7 Execution Risk

While the price of each MgB$_2$ MRI of varying size, strength, and homogeneity can be estimated using substitution and scaling of the traditional full-body 1.5T NbTi MRI, the actual design and construction of the various MRI products is a less straightforward task. Thus, execution risk, the possibility that despite models, designs, and prototypes, the product as desired will not be successfully developed into an operational product in reproducible manner, cannot be overlooked when examining product viability.

7.1 Persistent Joints

Without solving the problem of persistent joints, each coil in the MR unit must be powered by an extremely stable and expensive DC power supply. Such an expense would add to the price of the machine, undermining efforts to reduce sale price while maximizing value offered to the customer.
7.2 Conduction Cooling

Similarly, conduction-cooling units, which operate successfully at 10 K, have been developed. However, in the calculating the sale price of the ideal MRI unit, it was assumed that the cooling unit would not cost significantly more than the cryogenic system currently employed. It is also assumed that the conduction cooling unit will not require more power to operate than the current cryogenic system. Any additional cost would have to be factored into the predicted sale price and electrical costs, and will affect the hospital's lifetime cost of owning the MgB$_2$ unit.

7.3 Inhomogeneous Execution

Product design involving inhomogeneous main field MR imaging faces additional execution risk related to the development of successful imaging sequences. While publications, such as studies by Epstein and Magland (see Appendix Section A.2), have introduced theoretically viable sequence designs and inhomogeneous MRIs, such as the Magnevu MV1000, have been used to generate images, a company producing an inhomogeneous MRI system would need to develop a plan for programming each unit to compensate for inhomogeneities, accounting for additional inhomogeneities that may be introduced during shipping.

8 The Magnevu – An Antilog

The commercialization of an inhomogeneous, low-field extremity scanner has previously been attempted in the United States. The Magnevu MV1000, small, lightweight and low-cost MRI with a 0.18 T U-shaped permanent main magnet, was introduced in 2001 and had its first reported sales in 2002.\textsuperscript{73} Intended as a scanner dedicated to the detection of rheumatoid arthritis, the MV1000 is small, relatively lightweight, and does not require
shielding and, thus, is ideal as a point of care scanner, installed in doctor's offices rather than large hospitals.

![Person standing next to the MV1000 in a doctor’s office](image)

**Figure 11:** A person standing next to the MV1000 in a doctor’s office

### 8.1 The Technology

The scanner operates within the category of inhomogeneous imaging in which the inhomogeneities in the main field are large compared to applied gradients. To image with this method, a slice of large thickness is excited, and the image is taken slowly, analogous to the process of long exposure when taking a picture in low light.

### 8.2 Challenges

While originally estimated to sell for $100 thousand, pressure from shareholders resulted in the ultimate selling price, $220 thousand per unit. Phil Grice, who joined Magnevu in 2004 and now maintains what remains of the Magnevu products, estimates that the decision to double the selling price severely limited the market for the low-cost machine, resulting in sales of 150 units by the time the company filed for bankruptcy in 2007, rather than 2-3 thousand units that could have been possible with a lower selling price.

Additionally, Grice speculates that GE had a hand in the decline of the Magnevu. In 2003, it was announced that Magnevu has signed an exclusive distribution agreement
with GE, with the industry giant predicting a large market for the machine. By 2007, however, GE had only sold 80 units and announced that the market for the machine was extremely limited, despite initial projections. When GE dropped Magnevù in 2007, the company's financials were in shambles as were the relationships between the owners and the investors, ultimately resulting in the decision to file for bankruptcy in 2007. While it would be easy to blame low sales on the pallid effort exhibited by GE, and accept the notion that GE purposely signed the distribution agreement with the intent of killing the company so as to prevent the availability of a low cost machine, which would threaten GE's more expensive models, it is more useful to examine the underlying factors in the ultimate demise of the Magnevù. Knowing why the Magnevù failed provides a canvass of problems to be avoided if attempting to market an MgB2 analog of the MV1000.

8.2.1 Scan Volume

Without having seen the Magnevù in operation, the first step in determining the cause of the company's demise is analyzing whether the technology actually worked. Per a conversation between Ed Caner of CWRU and a doctor located in Warren, OH - the owner of a Magnevù machine - the MV1000 performed well, providing the doctor with high quality images for use in the diagnosis of Rheumatoid Arthritis. The problem with the machine was its inability to pay for itself due to low patient volume and lack of reimbursement from insurance companies. As was evident in the analysis of the lifetime cost of an MRI, the cost per scan is greatly increased with low patient volume (see Section 5.7), suggesting that an extremity machine in the United States, installed in a doctor's office may not be capable of scanning enough patients per day
for the machine to be a cost effective alternative to the full-body MRI readily available in hospitals around the country, many boasting same day appointment capabilities.

8.2.2 Insurance Reimbursement

The second consideration in terms of expense per scan relates to the low field strength of the Magnevu. At present, accreditation commissions in the United States do not accredit machines of main field strength less than 0.3 T. Because the 0.18 T machine, therefore, is not accredited, insurance companies will not reimburse patients or doctors’ offices for scans using the low-field machine. This means that patients must pay for scans using the Magnevu out-of-pocket, which is an unreasonable expectation when patients have health insurance that would pay for a scan using an accredited machine, as available with same day appointments in a nearby hospital.

The apparent combination of insurance reimbursement policies and rapid availability of full-body MRI scanners, in need of patients to increase utilization an decrease cost per scan in the US ultimately crippled the market for the low-field point of care scanner offered by Magnevu, with or without a hand from GE in crushing the low-cost product.

9 Spend and Save

Using the model of the Magnevu as an antilog – a business model that ultimately failed, but offers insights into how to create a successful business model by avoiding the mistakes of the antilog company – in combination with the information garnered from the cost analysis of various types of MR units, the cost-value dichotomy can be optimized to identify a product offered at a reduced cost with maximum value to the customer.
The ideal customer will be the customer for which the least adoption chain risk exists. The market associated with the ideal customer does not necessarily need to be very large, however a viable product in a small market must be sold with a high profit margin so as to compensate for the effect of limited sales.

9.1 Adoption Chain Risk

Adoption chain risk describes the possibility that the predicted end customer or any customer within the minimum viable footprint\textsuperscript{78} of a product market will not adopt the new product. For example, a magnet company hoping to sell its product to an OEM, which in turn sells complete MRIs to hospitals that finally sells scans as a service to patients, faces adoption chain risk from three groups: the OEMs, the hospitals, and ultimately, the patients. If any one of the three groups rejects the product, the market will collapse and the product will not be viable.

9.1.1 United States

In the U.S., adoption chain risk is high for new imaging technologies. Because hospitals in the United States compete on quality, following the Red Ocean Strategy in which value and price form a necessary tradeoff, the idea of a low-cost, low-field machine, immediately implies reduced image quality, and thus, is not likely to gain acceptance among doctors and hospitals. As learned from the Magnevu, additional challenges regarding insurance reimbursement for higher-field machines but not low-field machines, combined with the accessibility of accredited machines that require high patient volumes to keep operational costs low, also contribute significantly to adoption chain risk for a product containing a low main field or a small bore diameter in the United States.
9.2 Low Accessibility

A crucial aspect of Blue Ocean Strategy is creating a new market; given the high adoption chain risk for new, low-cost imaging technologies in the United States, it may be useful to look into customers in other countries where it may be easier to create a new market, particularly for a low-cost machine.

A major factor preventing adoption of a low-cost, head/extremity system in the U.S. is the current accessibility to full body scanners, which need high patient throughput to keep the cost per scan low. Introducing extremity scanners into countries with low accessibility to full body, 1.5 T scanners, therefore, would lessen adoption chain risk.

9.2.1 Canada

Over the past several years, Canada has suffered from low-accessibility to MRIs, resulting in the longest wait times for diagnostic imaging in the developed world. In a study by the Fraser Institute, the patients in Canada, on average, waited 8.4 weeks to receive an MRI in 2012, with wait times up to 12 or 16 weeks in some provinces. With approximately 8.2 MRI machines per million people in Canada, compared to 36.1 MRI units per million people in the US, running 11 scans per day, a wait time of 8.4 weeks corresponds to 170 thousand people waiting for scans (assuming one scan per patient), or 0.5% of the population.

If enough head/extremity machines were sold in Canada, the wait time could theoretically be reduced by 46%, as head and extremity procedures account of 46% of total scans. This would reduce the number of patients waiting to 98 thousand people, and the wait time to 4.8 weeks. While this is an improvement over current wait times, accessibility still would not compare to that of the United States.
9.2.2 India

To target customers for whom a low-cost MRI would generate an order of magnitude impact on healthcare accessibility, the need must be greater than demonstrated in Canada. In India, for example, accessibility is limited more than in Canada, with India having only one MRI unit per million people, an order of magnitude less than Canada.\textsuperscript{82} Such restricted access results in average wait times to receive a scan of six months to two years, during which any problems inevitably grow worse and could conceivably result in a preventable death.\textsuperscript{83} Running 11 scans per day given one scanner per million people, there are 2.8 to 11.2 million people waiting to receive an MRI at any given time in India.

![International comparison of MRI units per million people](image)

Figure 12: Graph comparing the number of MRI units per million people in the United States, Canada, India, and Japan

9.3 Target Customer

Due to large and dense population with limited access to diagnostic imaging technologies, India is an alluring target customer for a low-cost, high-value MgB\textsubscript{2} MRI. With helium prices higher in India than in the United States or Canada, approximately $15/L compared to $10/L, a cryogen-free system has greater appeal than in the U.S. and
Canada as a means of reducing operating costs. Additionally, a cryogen-free system is likely to simplify shipping, thus lowering shipping costs, which can be substantial for machines sent from the United States to India. A cost analysis over the lifetime of a 0.5 T and 1.5T, head/extremity MRI operating at 10 K again helps identify ways to reduce customer costs while maximizing customer value.

9.3.1 Staff

One of the largest contributing factors to the cost of operating an MRI in the United States is the total payment of staff salaries over the lifetime of the MRI. By comparison, the pay scale in India is approximately an order of magnitude lower than in the United States, with radiologists averaging $35 thousand per year and imaging technicians averaging $4 thousand per year. Therefore, the cost of staffing an MRI in India with one radiologist and two imaging technicians for 9 years is $387 thousand, only slightly more than the annual salary of a radiologist in the United States.

9.3.2 MRI Room

While some low-field MRI units, such as the Magnev, do not require shielding, an MRI unit still requires its own room. It is possible that the 0.5 T small bore MRI could be placed in an existing room without or with minimal shielding. Still, the floor space used should be taken into consideration. Given the order of magnitude reduction in pay scale, an order of magnitude reduction in the cost per square foot seems appropriate. Thus, a one thousand square foot room would cost $40 thousand at a cost of $40 per square foot.
9.3.3 Cooling

In determining power consumption of the extremity machine, it is important to note that the majority of the power the machine draws is used to run the cryogenic cooling system. Without a sample conducting cooling system, it is challenging to determine the power required to run the helium-free system. Should the system require a similar amount of power as the cryogenic system used to cool a 1.5 T MRI, the power usage over the lifetime of the MRI will remain close to 300 kWh per day. At an average price of $0.08/kWh in India, powering the magnet over 9 years costs $79 thousand.86

9.3.4 Total Cost

For the 1.5 T head/extremity system, with a projected purchase cost of $495 thousand and 10% annual maintenance costs, the total cost of purchasing and operating an MRI with a 9 year lifetime is $1.4 million, resulting in an annual cost of $160 thousand. Alternatively, a 0.5 T machine with an initial cost of $350 thousand and 10% annual maintenance costs results in a total lifetime cost of $1.2 thousand over 9 years, or $130 thousand per year.

Table 5: Estimated lifetime cost of operating an MRI in India

<table>
<thead>
<tr>
<th>Expense Description</th>
<th>0.5 T Head/Extremity</th>
<th>1.5 T Head/Extremity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine</td>
<td>350,000 $</td>
<td>495,000 $</td>
</tr>
<tr>
<td>Maintenance, 1 year</td>
<td>35,000 $</td>
<td>49,500 $</td>
</tr>
<tr>
<td>Maintenance, 9 years</td>
<td>315,000 $</td>
<td>445,500 $</td>
</tr>
<tr>
<td>Radiologist Salary</td>
<td>35,000 $ per year</td>
<td>35,000 $ per year</td>
</tr>
<tr>
<td>Technician Salary</td>
<td>4,000 $ per year</td>
<td>4,000 $ per year</td>
</tr>
<tr>
<td>Total Staff, 1 year</td>
<td>43,000 $ per year</td>
<td>43,000 $ per year</td>
</tr>
<tr>
<td>Total Staff, 9 years</td>
<td>387,000 $ per 9 years</td>
<td>387,000 $ per 9 years</td>
</tr>
<tr>
<td>Room Cost</td>
<td>40,000 $</td>
<td>40,000 $</td>
</tr>
<tr>
<td>Power Consumed</td>
<td>300 kWh per day</td>
<td>300 kWh per day</td>
</tr>
<tr>
<td>Power Consumed, 9 years</td>
<td>985,500 kWh in 9 years</td>
<td>985,500 kWh in 9 years</td>
</tr>
<tr>
<td>Price of electricity</td>
<td>0.08 $/kWh</td>
<td>0.08 $/kWh</td>
</tr>
<tr>
<td>Price of electricity, 9 years</td>
<td>78840 $</td>
<td>78840 $</td>
</tr>
<tr>
<td>Total Lifetime Cost</td>
<td>1,170,840 $/9 years</td>
<td>1,446,340 $/9 years</td>
</tr>
<tr>
<td>Annual Cost</td>
<td>130,093 $/year</td>
<td>160,704 $/year</td>
</tr>
</tbody>
</table>
9.3.5 Cost per Scan

Continuing to use 11 scans per day as the maximum scan utilization for a scanner operating 12 hours per day, the hospital operating at maximum scan capacity would have to charge $40 per scan to break-even on the 1.5 T model, and $32 per scan to break-even on the 0.5 T model. Recalling that the pay scale in India is reduced by a factor of 10, and noting that an MRI scan in the United States averages $1,100, a price of $32 - 40 per scan to break even at maximum scanning capacity is likely to be an unmanageable burden for patients in need of a scan, reducing utilization, and thus increasing the hospital's required scan price to break-even, starting another cycle of customer isolation and price increase.

9.3.6 Price Point – Low Estimate

To determine a target price per scan, and thus a target selling price for the MRI unit, it is useful to consider as an analog the price structure in a country where MRI is very successful, Japan. Whereas the United States has 36.1 scanners per million and India has 1 scanner per million, Japan has 46 MRI units per million people, and the average cost of an MRI in Japan is $160.\textsuperscript{87} To estimate the scan price in India that would have a similar impact to the scan price in Japan, the scan price can be considered as a percentage of annual income. With an average annual income (GNI per capita)\textsuperscript{88} of $45 thousand, a scan in Japan costs 0.35% of a person's annual income. Considering the per capita GNI in India is $1,530, a scan that is 0.35% of a person's net income would have to cost less than $5. For comparison, a scan in the US is currently 2.4% of the per capita GNI at $1,100, and would have to cost less than $180 to be on scale with Japan, an order of magnitude reduction in cost.
9.3.6.1 Entry

Due to extremely low insurance coverage, with just over one-third of the country covered, most patients in India would have to pay for a scan out of pocket. This means it is extremely important that scans are affordable. The ideal cost of $5 per scan, on target with pricing in Japan represents the extreme best-case scenario. However, many Americans struggle to pay for an MRI scan without the assistance of health insurance. Therefore, an ideal price per scan as a percentage of income would be lower than it is in the United States, but higher than it is in Japan. Taking the average of the two values, 0.35% and 2.4%, an ideal entry price per scan as a percentage of income would be 1.4%, or $20 per scan.

9.3.6.2 Reaching the Target

Reductions in the cost of MgB$_2$ alone are not sufficient to reach the price point of $20 per scan. However, if the maximum number of scans per day can be increased to 18, then given an initial price of $350 thousand for the MgB$_2$ head/extremity scanner, charging $20 per scan would allow the hospital to break-even. Achieving a 0.5 T head/extremity scanner that can be sold for $350 thousand appears to be possible at the current price for MgB$_2$, $4.50/m, as it was earlier predicted that such a machine would cost less than $360,000. To achieve a 1.5 T head/extremity machine that can be sold for $350,000, keeping all other expenses fixed, the cost of MgB$_2$ would have to be $1.60/m. It is possible that with an inhomogeneous 1.5 T head/extremity machine, reductions in shimming costs, approximately $30,000 for the small DSV of the extremity machine, would allow for the target sale price with wire costing $2.20/m.
9.3.7 Price Point – High Estimate

In refusing to sacrifice value for cost, an alternative to providing a 0.5 T head/extremity MgB$_2$ MRI for the general population in India, is providing a 1.5 T head/extremity MgB$_2$ MRI at the conceivable current cost of $495,000 for the wealthiest citizens of India.

9.3.7.1 Flaw of Averages

In utilizing the GNI per capita to determine a manageable price to charge for an MRI in India, the low estimate price point is subject to the flaw of averages – GNI does not take into consideration the distribution of income among Indian citizens, and thus does not provide accurate information regarding a sustainable market in India.

9.3.7.2 Top Ten Percent

Knowing the great disparity between the richest and poorest members of Indian society suggests that wealthy citizens could feasibly spend more than $20 for an MRI scan. According to The World Bank, the top ten percent of the population in India earned 28.8% of the country’s income in 2010, meaning that the average income per capita for people in the top ten percent during 2010 was $9,900 (see Table 6).$^{89}$

Recalling that a hospital in India could breakeven by charging $40 per scan, running 11 scans per day over the 9 year lifetime of a 1.5 T head/extremity MgB$_2$ MRI (see section 9.3.5), the breakeven price per scan is less than half a percent of the income earned per capita by the top ten percent, and thus represents a conceivably affordable rate for the 124 million people who comprise the top ten
percent of the population.

Table 6: Important quantities in the calculation of the high price point estimate for affordable imaging in India among the top ten percent of national earners

<table>
<thead>
<tr>
<th>Description</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>1,240,000,000</td>
</tr>
<tr>
<td>10% of Population</td>
<td>124,000,000</td>
</tr>
<tr>
<td>GNI per Capita (2010)</td>
<td>$3,430</td>
</tr>
<tr>
<td>Total GNI (2010)</td>
<td>$4,240,000,000,000</td>
</tr>
<tr>
<td>% of Income Earned by Top 10%</td>
<td>28.8%</td>
</tr>
<tr>
<td>Income Earned by Top 10%</td>
<td>$1,220,000,000,000</td>
</tr>
<tr>
<td>Per Capita Income of Top 10%</td>
<td>$9,880</td>
</tr>
</tbody>
</table>

By charging $50 per scan, equivalent to 0.5% of the income earned by the top ten percent, hospitals in India would profit $10 per scan when running the proposed 1.5 T head/extremity machine at 11 scans per day over its 9 year lifetime. In one year, therefore, the hospitals would make $40,000 in gross profit by running the machine, and it would profit $360,000 over the lifetime of the machine.

9.3.8 True Blue Ocean

With the price comparison detailed in Figure 10, it is clear that the 1.5T head/extremity MgB$_2$ MRI offers the greatest reduction in price with the least sacrifice in quality. From full body to head/extremity at 1.5T, the price of the machine is reduced 60%, whereas sacrificing magnet strength in the head/extremity scanner only results in a 30% reduction in cost, and using an inhomogeneous rather than a homogeneous main field only results in savings of 8%.
The 1.5 T head/extremity machine, which has the image quality of the 1.5T machine, with the ability to scan up to 46% of all patients requiring an MRI, while costing the hospital only 40% of the initial price of a full body machine, exemplifies a blue ocean product offering maximum value at a low price. With hospitals in India able to charge $50 per scan, an affordable price for the wealthiest ten percent of the Indian population, installation of the 1.5 T head/extremity machines would give access to diagnostic imaging to more than one hundred million people in India, where access is currently extremely limited.

10 Business Plan

With a product intent on capturing a new market rather than competing in the existing imaging space dominated by giant incumbents, a start-up company manufacturing 1.5 T head/extremity MRI using MgB$_2$ magnets cooled to 10 K has the potential to disrupt the
In India, there is only one MRI for every million people, and people wait 6 months to 2 years to receive an MRI scan, meaning that at any given time, there could be as many as 11 million people waiting to receive an MRI. With a population of 1.2 billion people, 11 million people does not even represent 1% of the total population in India. Yet, with 1 scanner per million people, imaging 11 people per day, 14 thousand people in total are served per day in India, and 5 million are served per year. Not only does this indicate that there are more people waiting to be imaged at any given time than are served in one year, but it also indicates that only 0.4% of the population receives an MRI per year.

By similar calculation, as many as 39 million people in the United States, 12% of the population, receive scans annually. Thus, while long wait periods indicate the existence of a certain level of demand in India, the extremely low percentage of people served annually and the relatively low percentage of the population waiting to be scanned indicates that there is ample room for generating new demand and a new market with the introduction of a low cost, extremity scanner.

Figure 14: Currently in India, only 0.4% of the population receives an MRI annually. At half the U.S. standard, 6% of the population would be able to receive an MRI annually.
10.1 Market Size

Increasing the number of MRIs so that the top ten percent of the population has the access to MRI that is standard in the United States, meaning 12% of that group could receive scans annually, would require 3,700 scanners each performing 11 scans daily. With 1,400 scanners already in place, Indian hospitals would need to acquire 2,300 scanners to provide the desired market with access to MRIs every year. Given that 46% of all scans are either brain scans or extremity scans, it would be possible to substitute 1,150 of the required number of scanning units with the 1.5T head/extremity scanners. At a price of $495,000, the maximum market size is $568 million.

Table 7: Market for the 1.5 T Head/Extremity MRI among the top earning 10% in India

<table>
<thead>
<tr>
<th>Market Analysis for the 1.5 T Head/Extremity MgB₂, Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired Market: 12% of Top Ten Percent</td>
</tr>
<tr>
<td>Machines Needed to Serve Desired Market*</td>
</tr>
<tr>
<td>Machines Currently in Place</td>
</tr>
<tr>
<td>Additional Machines Needed</td>
</tr>
<tr>
<td>Machines that can be Replaced by Head/Extremity</td>
</tr>
<tr>
<td>Market for Machine at $495,000</td>
</tr>
</tbody>
</table>

*(11 scans per day per machine, 365 days per year)

10.2 Cost Analysis per Machine

To analyze the viability of producing and selling the 1.5 T MRI for $495,000, the cost of building the machine must be analyzed in terms of raw material, labor, overhead, administrative, and additional expenses. For the 1.5 T head/extremity machine, with MgB₂ costs of $4.50/m, total wire costs sum to $225,000. Based on estimates provided by Mike Tomsic of Hyper Tech, additional costs of raw and outsourced materials, such as the cooling technology, shimming, and coil supports, total $95,000, so throughput per unit is $175,000. Tomsic additionally estimates overhead and labor costs per unit of $32,500, for $142,500, or 29%, gross profit per unit.
10.3 Company Reverse Financials

For the company to earn $6 million before taxes with a 15% return on sales, it would have to sell 81 scanners at $495,000, resulting in revenue of $40 million and capture of 7% of the predicted $568 million market. For $6 million in earnings before taxes given $40 million in revenues, total expenses must total $34 million. Given the per unit expenses calculated, total material costs for 81 scanners sum to $20 million, and total labor and overhead costs come to $2.6 million, resulting in a gross profit of $16.2 million, leaving $10.2 million for sales and administrative expenses as well as interest.

![Reverse Financials at 15% Return on Sales](image)

Figure 17: Reverse financials for a 15% return on sales resulting in $6 million in earning before taxes

10.4 Resource Based View

Achieving capture of 7% of the predicted $568 million market for a 1.5 T head/extremity scanner made with MgB$_2$ wire and priced at $495,000 requires that the company is organized to “exploit and external opportunity and neutralize external threat[s],” with resources and capabilities that are valuable, rare, and difficult to
Magnesium diboride wire is a valuable resource in that it allows the manufacturing company to exploit the push for high temperature superconductors resulting from the current helium shortage and subsequent rise in helium prices. While there are a limited number of other companies that also produce MgB$_2$ wire, such as Columbus Superconductors in Italy, company patents detailing the method for manufacturing MgB$_2$ intermetallic superconductor wires and a method for creating low loss joints for superconducting wire, protect its product from imitation. In addition, the company has formed valuable relationships with universities, CWRU and Ohio State, as well as with companies in the MRI industry, having earned as a team several government grants to aid in product development during the early stages of production.

11 Competition

Despite attempting to enter a blue ocean, where competition is made irrelevant by giving access to MR imaging technology to doctors, and thus patients, in regions where it is currently inaccessible due to high initial and operating costs, the allure of the large and currently non-captured market is sure to draw attention from a multitude of companies.

11.1 GE Optima MR430s

In October 2011, GE installed its first Optima MR430s, extremity MRI scanner at Balgrist University Hospital in Switzerland.
11.1.1 Similar Qualities

GE describes and promotes the specialty MRI with three mantras, each highlighting the same value to the customer without sacrifice of quality offered by the 1.5T head/extremity MgB$_2$ design.\textsuperscript{94}

“Extremely compact, surprisingly powerful.”

“Extremely comfortable, surprisingly clear.”

“Extremely valuable, surprisingly affordable.”

Additionally, the GE Optima MR430s uses only 49 L of liquid Helium,\textsuperscript{95} as opposed to the 2,000 L required by a traditional, full-body NbTi Machine, resulting in both initial and lifetime savings in machine operation comparable to those offered by the proposed MgB$_2$ design.

11.1.2 Design Differences

While the GE Optima MR430s has many attributes of the proposed head/extremity machine, with a diameter of 40 cm, the Optima’s smaller bore diameter, 28.6 cm,
would prohibit the machine from performing MR imaging on the brain, and thus the
Optima could only image half the cases that the proposed head/extremity scanner
would be able to handle.

11.1.2 Room for Disruption
Two years after the installation of the first GE Optima 430s, there are 18 units
installed in the United States and 1 installed in Japan, as well as a few additional
specialty scanners installed around the globe. Surprisingly, however, GE has yet to
install one of its GE Optima scanners in India or Canada. Multiple installation sites in
the United States and no installation sites in India or Canada suggest that the GE
Optima 430s is not as affordable as it needs to be to enter underserved markets, which
would mean that there is still room for a low cost, head/extremity machine to disrupt
the MR Imaging market.

11.2 Samsung GEO line
Although Samsung is a well-known name in electronics, it is a recent entrant into the
medical device industry with the launch of its GEO line of medical devices in March
2013.

11.2.1 Global Health
Outside the realm of MRI, but still within the field of medical imaging, Samsung is
among the competitors looking to capture the business of people who currently do not
have access to expensive medical technologies. According to the company website,
“GEO is Greek for earth, and is included in model names to demonstrate the
company’s commitment to global health through innovative medical devices”

96
11.2.2 CereTom

Samsung’s new medical imaging line includes digital radiology and ultrasound devices, as well as CT scanners as a part of the company’s acquisition of NeuroLogica in January, 2013.\textsuperscript{97} NeuroLogica’s CereTom, a portable and battery powered CT, is specifically designed with a small imaging volume that is 32 cm in diameter for head imaging and could feasibly be used for extremity imaging as well. Weighing less than 800 pounds, the portability of the machine as well as the typically low cost of CT scanners compared to MRI scanners, suggests that the CereTom could be extremely valuable in currently underserved regions. Portability would allow for convenient sharing of the machine between departments in a hospital, increasing its utility and allowing for cost sharing.

![CereTom CT scanner](image)

Figure 17: Samsung recently acquired NeuroLogica, the company that produces the portable CereTom CT\textsuperscript{98}

11.2.2.1 CT versus MRI

While CT scans are traditionally used to image dense bone tissue and MRI is most useful in obtaining detailed images of soft tissues, CT and MR Imaging are generally viewed as competing medical imaging techniques. In addition to
traditionally low initial investment costs, CT scanners have the benefit of avoiding the instability associated with uncertainties in the helium market as they do not require helium to operate. However, unlike MRI, CT scanners expose patients to high quantities of harmful ionizing radiation, with the CereTom delivering 85-125 mGy to the patient during a scan.\textsuperscript{99}

11.2.2.2 Head/Extremity

Like MRI, brain scans account for more than twenty percent of all CT images taken, according to a 2006 IMV report; unlike MRI, however, extremity scans only account for 6\% of all CT scans performed.\textsuperscript{100} Therefore, although the CereTom would be competing with the proposed head/extremity MRI design for use in diagnostic imaging of the brain, superior performance in the imaging of soft tissue, such as ligaments and tendons, makes the proposed MRI unit more useful in extremity imaging than CT, thus allowing for a broader potential market.

11.2.2.3 Price

Although MRI machines tend to cost significantly more than CT machines, the portable, small bore CereTom currently sells for $410,000, and has estimated yearly maintenance costs of $41,000,\textsuperscript{101} which is similar in cost to the projected 1.5T Head/Extremity MgB\textsubscript{2} MRI. With other CT scanners on the market that are less expensive and capable of performing more scans due to a larger bore, the CereTom, unlike the proposed 1.5T Head/Extremity design, does not represent a disruptive innovation capable of capturing a new, low-cost market, such as those existing within underserved populations.
11.3 Cryogenic

In addition to imaging technologies that have the potential to compete with the helium free, MgB$_2$ scanner, new cooling technologies provide substantial threat to MgB$_2$ scanners, not just in the determined head/extremity market, but rather in all potential markets for MgB$_2$ scanners. Cryogenic, for example, has developed a method of cooling superconducting magnets to 4.2 K using just 0.5 L of helium. The company’s mechanical refrigerators “rely on the compression and expansion of a fixed volume of helium gas supplied under pressure in a closed, self-contained circuit.”$^{102}$ While the company’s United States branch currently offers only very small bore magnets, with bore diameters ranging from 4 to 7.5 cm,$^{103}$ far too small to be used in MRI, the United Kingdom branch offers a 1.5 T, 28 cm bore diameter, highly homogeneous magnet system, designed for use in MRI.$^{104}$ Developments in the technology thus have the potential to eliminate the need for expensive mid- and high-temperature superconducting coils while removing the instability associated with dependence on helium from the MRI industry given continued development efforts.

![Figure 18](image)

Figure 18: a) CryogenicUSA’s desktop magnet with a bore diameter of 7.5 cm$^{105}$ b) The Cryogenic, Ltd. (UK) 1.5 T magnet with a bore diameter of 28 cm$^{106}$
Should the low-helium system achieve the capability to cool magnets with a bore diameter of 40 cm, it would have to cost less than the additional cost of using MgB$_2$ instead of NbTi to compete with the MgB$_2$ head/extremity scanner. As previously determined, a magnet with a 40 cm bore diameter requires 50 km of MgB$_2$, which at $4.50/m, costs $225,000. Should a magnet with the same bore diameter require approximately the same length of NbTi at $1.20/m would cost $60,000. Therefore, to be competitive, the cost of the low-helium cooling system could only cost as much as $165,000 more than the conduction cooling system used to cool the MgB$_2$ coils.

**Conclusion**

The search for a blue ocean in the MRI market exposed that the greatest cost reduction associated with the least sacrifice of value to the customer occurs when a 1.5 T MRI is constructed with a compact design, specialized for the imaging of the head and extremities rather than generalized for the capability to image the whole body. Costing 40% of the price of a full-body MRI and able to relieve large scanners of up to 46% of their workload by imaging the brain and extremities, a 1.5 T head/extremity MRI has the magnet strength of a full body scanner, and thus does not sacrifice image quality despite reduced price.

The capability to relieve the industry standard, 1.5 T full-body machines makes the 1.5 T head/extremity machine particularly valuable in countries where access to MRI is currently limited, resulting in long wait times for diagnostic imaging procedures. Therefore, in countries like Canada and India, the 1.5 T head/extremity machine would be able to scan large volumes of patients – up to 46% of those waiting for a scan – providing value to hospitals at an affordable cost. Particularly in India, which currently
possesses one MRI unit per million people compared to 36 units per million people in the US, there is a multimillion-dollar market for the 1.5 T head/extremity machines, with which hospitals could charge millions of people affordable rates for lifesaving diagnostic imaging procedures.

Despite competition from large companies in the medical imaging industry, offering products with similar values to the proposed specialty machine, the potential exists for disruption of the imaging market with the introduction of the 1.5 T head/extremity machine priced at less than $500,000 because only it combines the quality of imaging of the industry standard machine with the capability to serve up to 46% of those in need of an MRI at the low price usually associated with a disruptive technology.
Appendix: Understanding Inhomogeneity

A.1 Basic Principles of MRI

The underlying principle allowing for magnetic resonance imaging is that nuclei (protons) precess in the presence of a magnetic field at a resonant, or Larmor, frequency proportional to the field strength $\omega = \gamma B$; therefore, if the magnetic field is specified at each point in space, it is possible to know where a proton is located based on its precession frequency. The first step in MRI involves exposing a sample to a time-invariant field, $B_0$, as created by the main MRI magnets, which causes protons to precess about an axis parallel or anti-parallel to the direction of the background field at a frequency given by $\omega_0 = \gamma B_0$. By applying linearly varying gradient fields in the x, y, and z directions, the resonant frequency of a precessing proton is given in terms of the superposition of magnetic fields at its location in space: $\omega = \gamma \left( B_0 + (F \cdot G) \right) z$, using the convention that $B_0$ points along the z axis. The slice select gradient is applied along the axis of the main magnet, which excites a "slice" of protons. The slice select is then reversed to refocus the spins of the excited protons. Following slice select and rephasing, gradients are applied in the x and y directions, where the read gradient is generally chosen as $G_x$ and the phase encoding gradient chosen as $G_y$. The read gradient superimposes a linear gradient in the x-direction, which alters proton precession frequencies according to spatial location along the x-axis. The phase encoding gradient superimposes a linear gradient in the y-direction, which alters the phase of the received signal according to location. The received signal as a function of frequency and phase, $S(k_x, k_y)$, is then translated into the spin density of the sample as a function of position, $\rho(x,y)$ using a Fourier transform, and the spin density as a function of position is used
A.2 Alterations for Inhomogeneity

Ignored inhomogeneities in the background field mean that the field a proton experiences is not what it is expected to be, and thus its frequency is altered from its expected value. Because frequency encoding translates to position in image reconstruction, the presence of inhomogeneities generally leads to phantoms or blurring. In inhomogeneous imaging methods, the variations in the background magnetic field are taken into account, thus reducing the occurrence of image distortion.

Currently, there are two cases of static inhomogeneous imaging that have been studied:

1) the inhomogeneity in the field is on the order of magnitude of or smaller than the applied gradient fields
2) the inhomogeneity in the field is significantly larger than the applied gradient fields

The system of interest, where the inhomogeneity in the system is a result of the elimination of the shimming process, so that inhomogenities due to manufacturing tolerances remain, but the main magnet coils are designed to theoretically eliminate inhomogeneities caused by harmonics through n=10 would fall under the first category. With typical inhomogeneities on the order of 100 ppm in pre-shimmed main magnets, corresponding to fluctuations up to 0.15 mT within the 1.5 T main magnet field in the FOV. By comparison, most gradients produce variations of 20 mT/m, which over a DSV of 0.25 m, for example, would result in a $\Delta B$ across the FOV of 5 mT.
A.2.1 Linear Approximation

Imaging in the first case, where inhomogeneity is similar in size to applied gradients, and not large compared to the strength of the main magnet, introduces minimal complications in pulse sequence design as well as additional calculation requirements. As demonstrated in a paper by Epstein and Magland, a convenient simplification for initial understanding involves assuming that inhomogeneities in the field can be represented by a permanent linear gradient in the z-direction. Given the simplification of the permanent linear z gradient, the major adjustment from homogeneous main field imaging is the inability to flip the polarization of the slice select gradient to rephase magnetization in the selected slice. Instead, a refocusing pulse can be applied immediately following the selective RF-pulse.

![Figure 19: Pulse Sequence for the linear model of inhomogeneity (slanted slice, multiple spin-echo)](image)

With the solution to accumulated phase in the direction of the permanent gradient, the pulse sequence for an MRI with a linear, permanent gradient is very similar to a slanted slice 2D multiple spin-echo sequence, in which the excited slices are at an angle to the gradient in the static field. During the slice select pulse, the read gradient is turned on so that the magnitude of the read gradient during slice select is given by

\[(g_r)_{ss} = u_{ss}g_{pm},\]  

where \(g_{pm}\) is the permanent gradient caused by the linearly varying main field and \(u_{ss}\) is the non-negative ratio of \((g_r)_{ss}/g_{pm}\). With its polarity flipped, the
read gradient is also turned on during signal acquisition, so that magnitude of the read gradient during signal acquisition is given by \((g_r) = -u_r g_{pm}\), where \(u_r\) is the non-negative ratio of \((g_r)/g_{pm}\). If \(u_{ss}u_r = 1\), the read gradient must be orthogonal to the slice select gradient, so that the pulse sequence is nearly identical to that used in slanted slice imaging. Alternatively, \(u_{ss}u_r < 1\), indicates that the read gradient and the slice select gradient are not orthogonal. In both cases, the phase encode gradient would be orthogonal to the xz-plane.\(^{110, 111}\)

![Diagram](image)

Figure 20: Orientation of the selected slice to the applied gradient fields for a) \(u_{ss}u_r = 1\) and b) \(u_{ss}u_r < 1\)

Generalization to the non-linear case involves the definition of level sets labeled by the Larmor frequency. Designing an RF-pulse to excite spins with Larmor frequencies within a narrow frequency range, the signal from a given level set can be obtained. As in the linear case, two basic gradients are used to spatially encode the signal following slice selection. The gradient fields defined in the region of the level set are linear combinations of the two basic gradient fields, so that signal measurements are "samples of the Fourier transform, up to a single change of coordinates...determined by the background field \(B_o\) and the basic gradient fields. As such it need only be computed once [per machine] and stored,"\(^{113}\) so that images can
be created using inhomogeneous static fields. One possible method for calculating the change of coordinates required for post processing of the measured signal for image reconstruction involves the possible use of a phantom image to collect information on the background field inhomogeneities.\textsuperscript{114}

**A.2.2 Consequences of Inhomogeneous Imaging**

Because unaccounted for inhomogeneities generally result in low image quality, the idea of inhomogeneous imaging is immediately met with concerns regarding the expected signal to noise ratio. Additionally, the increased number and complexity of calculations suggests a need for increased computing power and increased time spent reconstructing an image. However, Epstein and Magland claim that the slanted slice and post-processing method "produces high quality images, with acquisition times comparable to what would be used in a standard imaging device."\textsuperscript{115}
CITATIONS


4 Ibid.


8 Ibid.


15 Yuri Lvovsky, et. al., 2013, p. 2.


17 Ibid.

18 Yuri Lvovsky, et. al., 2013, p. 1.

19 Ibid., p. 7.
20 Ibid., p. 22.


24 Guillaume Donnier-Valentin, 2011.

25 Yuri Lvovsky, et. al., 2013.


27 Yuri Lvovsky, et. al., 2013, p. 21-23.

28 Ibid., p. 22.


30 Ibid.


32 Guillaume Donnier-Valentin, 2011.

33 Ibid.

34 Yuri Lvovsky, et. al., 2013.

35 Ibid., p. 4.

36 Ibid., p. 4-6.

37 Ibid., p. 5.

38 Ibid.


40 Ibid.

41 Ibid., p. 21.

42 Ibid., p. 22.

43 Ibid., p. 24.


49 Yuri Lvovsky, et. al., 2013, p. 10.


51 Ibid.


53 Ibid., p. 82.

54 By the standard that MRI cost in millions is approximately equal to the magnet strength.


60 Yuri Lvovsky, et. al., 2013, p. 2.


62 Yuri Lvovsky, et. al., 2013, p. 25.

63 David Doll, et. al., 2013.

64 “Fastlane Generate Proposal as Submitted,” 2012.

65 Based on proportions and a 6 ft tall man.

66 Based on average male shoe size of 10.5 (US).

Based on proportions and a 6 ft tall man.

Yuri Lvovsky, et. al., 2013, p. 8.


Ibid.

Based on shimming costs up to $100,000 in a 1.5T system, given a reduction in the imaging volume of the extremity unit to 8/27 the imaging volume of the full body unit, assuming price scales linearly with volume.

www.magnevu.com via the Way Back Machine


Information from a phone call with Phil Grice, September 2013.

Ibid.

Ibid.


“In India we have approximately one MRI per million people,” Express Healthcare, 14 August 2013, http://healthcare.financialexpress.com/specials/in-imaging/1895-in-india-we-have-approximately-one-mri-per-million-people.


Yuri Lvovsky, et. al., 2013, p. 2.


Ibid.

