The success rates of surgical and non-surgical approaches in the management and treatment of spinal stenosis
THE SUCCESS RATES OF SURGICAL AND NON-SURGICAL APPROACHES IN THE MANAGEMENT AND TREATMENT OF SPINAL STENOSIS

by

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DEDICATION

I would like to dedicate this work to my Mother and Father, my two brothers: Bill and Andrew, and the anesthesiology team at CHOP. Thank you for all your support and encouragement throughout the completion of my master’s thesis.
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To my dear friends, especially Chris, Michael, John, Andrew, and Sam, I have enjoyed the journey and look forward to the future.

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ABSTRACT

This thesis presents a literature review of the diagnosis and treatment of lumbar spinal stenosis (LSS), including a brief description of the patient history and non-surgical options while focusing mainly on the current array of surgical techniques.

LSS is defined as a narrowing of any part of the lumbar spinal canal. This narrowing places excessive pressure on both the spinal cord and peripheral nerves resulting in pain, numbness and weakness in the lower extremities. LSS has a large spectrum of potential treatment options since the disease itself has a wide range of severities. An extensive physical exam, using the appropriate clinical surveys, physical manipulations, and imaging studies, is of paramount importance in the successful diagnosis.

Currently, conservative treatment, while an important first step in managing LSS, seems to be limited to a first line of defense, lasting only a short period of time. Physical therapy results appear to be beneficial for only six months to a year, and despite their increased usage in recent years, management through the use of non-steroidal anti-inflammatory drugs, opiates, and corticosteroid injections seem to provide very little benefit.
Surgical treatment for LSS ultimately appears to be the most effective method in reducing pain and disability for the patient who fits the clinical and radiological findings indicative of LSS. Although current surgical options available are numerous, including different types of fusion, bone grafts, and innovative joint replacements, the most promising procedures appear to be minimally invasive lumbar disk replacement surgery and dynamic stabilization. These procedures offer the benefits of a minimally invasive surgical approach, while reducing stenosis though hardware that not only reduces pain but also allows patients to maintain spinal flexibility and natural functional motion.
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LIST OF ABBREVIATIONS

ALIF ........................................ Anterior Lumbar Interbody Fusion
BMP ................................................ bone morphogenic protein
CT .................................................. Computed Tomography
DS ................................................ Dynamic Stabilization
EMG ........................................... Electromyography
ESIs ............................................. Epidural Steroid Injections
FDA ............................................. Federal Drug Administration
LS ................................................ Lumbar Stenosis
LSS ............................................. Lumbar Spinal Stenosis
MIS ........................................ Minimally Invasive Surgical
MRI ........................................ Magnetic Resonance Imaging
NC .............................................. Neurogenic Claudication
NS ............................................... neurogenic intermittent claudication
NSAIDs .................................. Non-Steroidal Anti-Inflammatory Drugs
ODI ........................................ Oswestry Disability Index
PLIF ........................................... Posterior Lumbar Interbody Fusion
R-M ............................................. Roland-Morris Disability Questionnaire
TDR ............................................ Total Disk Replacement
TLIF ........................................... Transforaminal Lumbar Interbody Fusion
ULBDs ..................................... Unilateral Laminectomy for Bilateral Decompressions
XLIF ........................................ Extreme Lateral Interbody Fusion
CHAPTER 1: INTRODUCTION

The first medical report of lumbar spinal stenosis (LSS; also referred to as lumbar stenosis or LS) occurred in the early 1800’s. In 1803, Portal of France postulated that back and leg pain could be caused by bone impingement on the central or peripheral nerves of the spinal cord (Wiltse et al., 1991). Today lumbar stenosis is defined as a narrowing of any part of the lumbar spinal canal (Joaquim et al., 2009). Stenosis occurs when the space around the spinal cord narrows. This narrowing places excessive pressure on both the spinal cord and peripheral nerves resulting in pain, numbness, and/or weakness in the lower extremities. Absolute stenosis has been defined as an anteroposterior lumbar spine diameter of less than 10 mm (Joaquim et al., 2009).

It is important to note that while patients may exhibit a radiographic abnormality indicating the possibility of LS, it does not necessarily mean that they are symptomatic (Joaquim et al., 2009). However, when LS patients exhibit symptoms they usually present as weakness, reflex alterations, gait disturbances, bowel or bladder dysfunction, motor and sensory changes, radicular pain or atypical leg pain, and neurogenic claudication (Botwin et al., 2003). Neurogenic claudication (NC) is a term used to define intermittent pain or paresthesia in the lower extremities brought about by walking or standing and relieved by sitting or lying down (Hall et al., 1985). In order for a patient to be diagnosed as having LS, a correlation of clinical symptoms along with radiographic imaging is necessary (Botwin et al., 2003).
Lumbar stenosis can be either congenital or acquired. In 1976, Arnoldi and Brodsky classified LSS into the following categories as shown in Table 1.

**Table 1: Classification of Lumbar Spinal Stenosis.** Shown is a classification of the categories of lumbar spinal stenosis as originally described by Arnoldi and Brodsky. Table taken from (Arnoldi et al., 1976).

**Classification of Lumbar Spinal Stenosis**

<table>
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<th>Category</th>
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<td>Congenital-developmental stenosis</td>
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<tr>
<td>Idiopathic</td>
</tr>
<tr>
<td>Achondroplastic</td>
</tr>
<tr>
<td>Acquired stenosis</td>
</tr>
<tr>
<td>Degenerative (most common type)</td>
</tr>
<tr>
<td>Combined congenital and degenerative stenosis</td>
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<tr>
<td>Spondylitic/spondylolisthetic</td>
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<tr>
<td>Iatrogenic (i.e. postlaminectomy, postfusion)</td>
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<tr>
<td>Posttraumatic</td>
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<tr>
<td>Metabolic (i.e. Paget’s disease, fluorosis)</td>
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Congenital-developmental LS is characterized by a narrow canal resulting from congenitally short pedicles. Patients with congenital LS usually become symptomatic in their third through fifth decade of life (Katz et al., 2008). While these subtle degenerative changes are usually tolerated in the general population, patients with congenital LS experience symptoms early due to their smaller central canal.

Acquired degenerative lumbar stenosis is the most frequently observed type of stenosis, and that of which will be the primary focus of this thesis. Acquired stenosis usually has its onset in patients 50 to 60 years old and commonly arises alongside age-associated degeneration of the lumbar and facet joints (Botwin et al., 2003). This degenerative process leads to a loss of disk height due to bulging of the spinal disc and in-folding of the ligamentum flavum (Katz et al., 2008). Degenerative facet-joint
hypertrophy as well as facet osteoarthritis can also lead to osteophyte formation and the thickening of the joint capsule (Figure 1).

**Figure 1: Pathology of Degenerative Lumbar Spinal Stenosis.**
Top left shows an axial view of a cross section of a normal lower lumbar spine. Bottom left shows the same axial view with pathologies consistent with LSS; these include a thickened ligamentum flavum, hypertrophy of the facet joints and bulging of the intervertebral disk. The right figure shows a sagittal view of degenerative disk changes and protrusion into the foramen. Figure taken from (Katz et al., 2008).
In addition, the acquired lumbar stenosis patient will usually present with symptoms of neurogenic claudication. Both back pain and stiffness are commonly experienced, with pain exacerbated by lumbar extension and improved with lumbar flexion; both related to the pathology of the normal degenerative process (Katz et al., 1995).

**Treatment Options**

Currently there are nonsurgical and surgical treatments available for patients suffering from spinal stenosis. Surgical intervention is usually considered depending on the patient’s quality of life and progression of stenosis (Kalff et al., 2013). Nonsurgical conservative treatments are mainly aimed at alleviating the major clinical manifestations of degenerative instability, although they appear to only provide transient relief (Kalff et al., 2013). Common conservative treatments include non-steroidal anti-inflammatory drugs (NSAIDs), a short course of oral corticosteroids, on site epidural cortical steroid injections (ESIs), opioids if required for pain management, and muscle relaxants (Thome et al., 2008).

Surgical treatments for LS patients are another alternative if the patient’s pain persists despite the previously mentioned conservative treatments. The main goal of surgery is simple, to relieve patients pain by widening the central canal and neural foramina (Joaquim et al., 2009). However, the range of surgical options is vast, currently including laminectomies, spinal fusions, bone graphs, adjuncts to fusions, and new
innovative alternatives to fusion including lumbar disk replacements and interspinous spacers.

Currently the two most common surgical techniques are laminectomies with or without spinal fusions (Acton et al., 2013). A laminectomy (also called a decompression) is a procedure involving the removal of the bone, bone spurs, and ligaments that are compressing the nerves (Figure 2) (Bauwens et al., 2013). Spinal fusion surgery involves restoration of the collapsed disk height with subsequent insertion of pedicle screws and a fusion cage (Figure 3) (Bohinski et al., 2013).

**Figure 2: Lumbar Laminectomy Surgery**
Shown is a spinal laminectomy (decompression) a procedure involving the removal of the bone (lamina), bone spurs, and ligaments (ligamenta flava) that are compressing the spinal cord and peripheral nerves. Figure taken from (Bauwens et al., 2013).
Figure 3: Spinal Fusion surgery
Spinal fusion surgery involves restoration of the collapsed disk height (here using an interbody fusion cage) with subsequent insertion of pedicle screws and a fusion cage. Figure taken from (Bohinski et al., 2013).

Specific Aims
This review will explore the current patient population undergoing LSS treatments; discussing their radiological findings, nerve conduction study results, physical exams, and possible differential diagnosis. The variety of treatment options available to patients with LSS will then be explored, focusing mostly on the variety of surgical techniques currently available as well as the benefits and drawbacks of non-surgical alternatives.
Currently there is a wide range of treatment options available to patients who have LSS. As with many major medical decisions, it can be complicated to decipher which option is best to deal with the management and hopefully treatment of this condition. The goal of this thesis is to provide guidance by offering a review of both the non-surgical and surgical options available to the patient. A cost-benefit analysis will then be discussed regarding both options when considering different factors such as age, sex, and quality of life.

Furthermore, since spinal surgery is a relatively new and innovative field, the treatment options available surgically can seem rather overwhelming to patients. Thus to further understand the procedure’s risks and benefits, surgical treatment of LSS will be compared with a hip arthroplasty, a well-accepted procedure whose risks and benefits are well known.
CHAPTER 2: PATIENT HISTORY AND DIAGNOSIS OF LSS

Radiological Findings

The spinal canal is bordered anteriorly by the vertebral body, intervertebral disc, and longitudinal ligament; posteriorly by the laminae, pars interarticularis, ligamenta flava, and facet joints; and laterally by the pedicles. Hypertrophy of any of these structures can result in the narrowing of the central canal leading to stenosis (Jane et al., 1997) (Figure 4).

Figure 4: Spinal Canal and Associated Ligaments
Shown anteriorly are the vertebral bodies, intervertebral disk, and posterior longitudinal ligament. Shown posteriorly are the laminae (see Figure 2), ligamenta flavum, and facet joints. Pedicles are seen laterally. Figure taken from (Bridwell et al., 2010).
As seen in the literature, morphologic and immunohistochemical studies have shown that the ligamentum flavum undergoes fibrotic and chondrometaplastic changes during aging, with the proliferation of fibrocartilage, ossification, and calcium crystal deposition along the ligament. This hypertrophy of the ligament results in a 3 to 4 mm difference in the thickness of the ligament in patients with stenosis versus the normal population (Botwin et al., 2003).

All of these changes described above result in what is called central stenosis. Found at the intervertebral level, central stenosis is mainly caused by the ligamentum flavum buckling inwards, hypertrophy of the ligamentum flavum (described above), disc protrusion, and degenerative spondylolisthesis. These changes are usually distinctive with multiple vertebrae levels involved (Botwin et al., 2003).

Both computed tomography (CT) and magnetic resonance imaging (MRI) may confirm the presence of stenosis. Bone anatomy is most clearly seen on CT, whereas soft tissue lesions are more detectable on MRI scans (Joaquim et al., 2009). On CT scans, a midsagittal lumbar diameter of less than 10mm is indicative of absolute stenosis of the central canal, while diameters of less than 13 mm are indicative of relative stenosis (Botwin et al., 2003).

In addition to central spinal canal narrowing resulting in stenosis, lateral spinal stenosis is the most common cause of radicular neuropathies. Here, the lateral lumbar spinal canal containing the lumbar nerve roots are narrowed resulting in either lateral or foraminal stenosis (Figure 5) (Botwin et al., 2003).
Figure 5: Lateral Spinal Stenosis
The lateral lumbar spinal canal containing the lumbar nerve roots (shown in green) is narrowed due to the thickened lateral recess and intervertebral foramen. This is shown alongside a thickened ligamentum flavum, indicative of central stenosis. Figure taken from (Joy et al., 2015).

These two areas (the lateral recess and intervertebral foramen) forming the lateral spinal canal have been divided into three anatomical zones by Dr. C.K. Lee to further the understanding of the anatomy of peripheral stenosis (Lee et al., 1980). These zones are denoted the entrance zone, the midzone, and the endzone (Figure 6). It was determined that a lateral recess height of 5 mm is normal, while a height of 2mm or less is considered pathogenic (Lee et al., 1980). The most common cause of entry zone stenosis is hypertrophic osteoarthritis of the zygapophyseal joint. Midzone stenosis is most
commonly caused by a defect in the pars interarticularis, resulting from osteophyte formation under the pars interarticularis where the ligamentum flavum is attached; and exit zone stenosis is caused by progressive hypertrophic osteoarthritic changes in the zygapophyseal joints with subluxation (Botwin et al., 2003).

![Figure 6: Zones of Lateral Stenosis](image)

**Figure 6: Zones of Lateral Stenosis**
Shown are the three zones of lateral stenosis: (1) The entrance zone or lateral recess, (2) the mid zone, and (3) the exit zone or intervertebral foramen. Figure taken from (Rothman et al., 1992).

As displayed above, the radiographic studies are therefore especially useful in determining whether surgery is required, and if so, what type of stenosis the patient is experiencing. However, it should be noted that while the sensitivities of CT and MRI for
spinal stenosis pathologies do exceed 70%, radiological findings consistent with LS are found in 20% of asymptomatic patients older than 60 years. These statistics demonstrate that while LS pathologies can be picked up visually on imaging studies, visual indication of narrowing does not necessarily mean that one is clinically showing symptoms of LS. Thus, while imaging studies have a high sensitivity to LS, their specificity is difficult to determine (Katz et al., 2008; Joaquim et al., 2009).

In addition to CT and MRI imaging, standing plain film radiographs (anterior-posterior, lateral-neutral, flexion, and extension) are also helpful if the surgeon suspects the patient may have sagittal imbalance (Figure 7) (Joaquim et al., 2009). This is especially important, since positive sagittal balance was identified as the radiographic parameter most highly associated with an increased rate of complications, demonstrated in a 2005 multicenter study of 298 adult LS patients (Glassman et al., 2005).
Figure 7: Sagittal Balance
Illustrated above are examples of spinal positive and negative sagittal balance. To measure, a technique is used where a line is drawn from the C7 vertebrae down to L5. Figure taken from (Glassman et al., 2005).
Neurophysiological Testing

While MRI provides the structural details of the nerve roots and surrounding tissues, needle electromyography (EMG) provides an electro-diagnostic evaluation that measures the physiological integrity of the peripheral nerves (Nardin et al., 1999). Although not usually essential, EMG and nerve conduction studies may assist in ruling out lumbosacral plexopathies and peripheral neuropathies from possible diagnosis; it may also be useful in patients with diabetes or other types of preexisting neuropathies (Dumitru et al., 2002; Katz et al., 2008).

However, while often essential, both EMG and MRI procedures have their inherent limitations. For example, the spectrum of possible electrophysiological findings in patients with LSS is broad - early stages of the disease may provide normal results while more advanced disease states may demonstrate a significantly reduced nerve conduction (Haig et al., 2005). Furthermore, the usefulness of EMG studies may be limited by the fact that LSS and peripheral neuropathy may coexist. Moreover, MRI may reveal structurally irrelevant spinal abnormalities and may not be an option for patients with claustrophobia or metallic implants (Nardin et al., 1999).

The Physical Exam

While radiological findings are especially important in diagnosing LS, the general diagnosis is essentially clinical, using CT and MRI images to confirm. When examining a patient, the physical exam is extremely important in deciding what treatment options should be considered in order to alleviate symptoms. LS usually presents as pain or
discomfort in the lower back, buttocks, and legs; these radicular symptoms are most commonly associated with lateral recess stenosis although neurogenic claudication (NC) may also result in these findings as a result of central canal stenosis (Joaquim et al., 2009).

In a recent study of 35 patients with LSS, 75% of patients with neurogenic claudication reported that their pain was significantly worse on one side, becoming more noticeable with prolonged walking and lumbar extension and improving during flexion. Although symptoms typically occur in both legs, this asymmetry was important in differentiating central canal and lateral recess stenosis; moreover, the asymmetry provided information on which side was most appropriate to decompress (Jane et al., 1997).

Objective neurological findings are not commonly present on physical examination. The Laségue test (straight leg raise test) is usually negative, differentiating an acute disc herniation from lumbar stenosis (Figure 8) (Deburge et al., 1990). In addition, the Romberg test may be conducted, in which the patient stands with eyes closed and is observed for neurological function. This may reveal a wide-based gait or unsteadiness in the patient (Katz et al., 2008). This observation is important since the specificity of wide-based gait in LS patients exceeds 90%, while sensory and motor defects only occur in about half of patients (Katz et al., 2008). Motor impairments are typically mild, and while muscular weakness is not common, if present it may be due to underlying pain (Sheehan et al., 2001). Although rare, compression of the cauda equina may also be present, resulting in sphincter
dysfunction and necessitating urgent surgery. The severity of all symptoms present at the time of visit should be measured using the Oswestry Disability Index (Table 2) (Joaquim et al., 2009).

Figure 8: The Lasègue Test
While patient is lying flat on their back, the physician lifts one leg while the knee is kept straight. If the patient’s experiences sciatic pain between 30 and 70 degrees the test is positive, thus a herniated disc is most likely the source of the patient’s pain. Figure taken from (Fairbank et al., 2010).

The Oswestry disability Index (ODI) and the Roland-Morris disability questionnaire (R-M) are the two most commonly recommended tests given to patients with spinal disorders (Fairbank et al., 2000). The ODI measures symptoms in ten sections as shown in Table 2, including factors such as pain intensity, personal care, lifting, walking, and sleeping. This test, offered currently in ten different languages, has
been proven to be a versatile questionnaire in assessing the symptoms of LS patients at the time of visit to their provider. The choice of which condition-specific questionnaire to administer is up to the clinician, although the ODI has been found to favor patients with more severe symptoms, while the R-M is favored more frequently in a primary care setting and in the elderly (Fairbank et al., 2000).

Table 2: The Oswestry Disability Index Version 1. Shown is the first version of the ODI given to patients to record different factors at their time of visit. Figure amended from (Fairbank et al., 2000).

**ODI Version 1.0**

**Section 1 – Pain Intensity**
- I can tolerate the pain I have without having to use painkillers.
- The pain is bad but I manage without taking painkillers.
- Painkillers give complete relief from pain.
- Painkillers give moderate relief from pain.
- Painkillers give very little relief from pain.
- Painkillers have no effect on the pain and I do not use them.

**Section 2 – Personal Care (washing, dressing, etc.)**
- I can look after myself normally without causing extra pain.
- I can look after myself normally but it causes extra pain.
- It is painful to look after myself and I am slow and careful.
- I need some help but manage most of my personal care.
- I need help every day in most aspects of self-care.
- I do not get dressed, wash with difficulty and stay in bed.

**Section 3 – Lifting**
- I can lift heavy weights without extra pain.
- I can lift heavy weights but it gives extra pain.
- Pain prevents me from lifting heavy weights off the floor, but I can manage if they are conveniently positioned.
- Pain prevents me from lifting heavy weights but I can manage to light to medium weights if they are conveniently positioned.
- I can lift only very lightweight.
- I cannot lift or carry anything at all.

**Section 4 – Walking**
- Pain does not prevent my walking any distance.
- Pain prevents me walking more than 1 mile.
- Pain prevents me walking more than ½ mile.
- Pain prevents me walking more than ¼ mile.
- I can only walk using a stick or crutches.
- I am in bed most of the time and have to crawl to the toilet.
Table 2 continued: The Oswestry Disability Index Version 1. Shown is the first version of the ODI given to patients to record different factors at their time of visit. Figure amended from (Fairbank et al., 2000).

**Section 5 – Sitting**
- I can sit in any chair as long as I like.
- I can sit in my favorite chair as long as I like.
- Pain prevents me sitting more than 1 hour.
- Pain prevents me from sitting more than ½ an hour.
- Pain prevents me from sitting more than 10 minutes.
- Pain prevents me from sitting at all.

**Section 6 – Standing**
- I can stand as long as I want without extra pain.
- I can stand as long as I want but it gives me extra pain.
- Pain prevents me from standing more than 1 hour.
- Pain prevents me from standing more than 30 minutes.
- Pain prevents me from standing more than 10 minutes.
- Pain prevents me from standing at all.

**Section 7 – Sleeping**
- Pain does not prevent me from sleeping well.
- I can sleep well only by using tablets.
- Even when I take tablets I have less than 6 hours of sleep.
- Even when I take tablets I have less than 4 hours of sleep.
- Even when I take tablets I have less than 2 hours of sleep.
- Pain prevents me from sleeping at all.

**Section 8 – Sex life**
- My sex life is normal and causes no extra pain.
- My sex life is normal but causes some extra pain.
- My sex life is nearly normal but is very painful.
- My sex life is severely restricted by pain.
- My sex life is nearly absent because of pain.
- Pain prevents any sex life at all.

**Section 9 – Social life**
- My social life is normal and gives me no extra pain.
- My social life is normal but increases the degree of pain.
- Pain has no significant effect on my social life apart from limiting my more energetic interests, e.g. dancing, etc.
- Pain has restricted my social life and I do not go out as often.
- Pain has restricted social life to my home.
- I have no social life because of pain.

**Section 10 – Traveling**
- I can travel anywhere without extra pain.
- I can travel anywhere but it gives me extra pain.
- Pain is bad but I manage journeys over two hours.
- Pain restricts me to journeys of less than one hour.
- Pain restricts me to short necessary journeys under 30 minutes.
- Pain prevents travel except to the doctor or hospital.
Differential Diagnosis

One of the largest challenges in diagnosing LSS is the lack of a generally accepted “gold standard” among health care professionals. Anatomically speaking, LSS is defined as a progressive narrowing of the spinal canal – however, since many patients exhibit this anatomical manifestation yet remain asymptomatic, there are limits to defining LSS anatomically. Consequently, a balancing act of correlating patient symptoms, physical examinations, and imaging studies is necessary to establish a definitive diagnosis (Genevay et al., 2010).

Highly sensitive and specific diagnostic procedures are especially important in LSS patients, as false-positive test results may lead to unnecessary surgery and/or expensive additional diagnostic interventions (Schepper et al., 2013). Overall, highly sensitive clinical findings for LSS include radiating leg pain that is exacerbated while standing up, thigh pain, bilateral buttock pain, absence of pain while seated, improvement of symptoms when bending forward, and a wide-based gait (Schepper et al., 2013). While a good history and physical examination can help narrow down the general differential diagnosis, individual physical examination tests are not as clinically useful as symptoms.

Some common conditions that may cause similar symptoms as LSS are hip osteoarthritis, trochanteric bursitis, peripheral neuropathy, and vascular claudication. Hip osteoarthritis may be present when pain is exacerbated by internal rotation of the hip (Via the Faber test – flexion, abduction, external rotation), trochanteric bursitis presents as pain over the greater trochanter, and vascular claudication is not influenced by either lumbar extension or flexion, differentiating each from LSS (Kenna et al., 1989).
It is important that the clinician takes all possible differential diagnosis into account when examining the patient. This may prove difficult since like LSS, osteoarthritis, and peripheral vascular disease are common in the elderly; moreover, trochanteric bursitis is frequently observed among patients with symptomatic LSS. One way a physician may distinguish between the two conditions is to administer a selective injection of corticosteroid into the trochanteric bursa or hip joint to determine to what degree each condition may be contributing to the patient’s pain (Katz et al., 2008).
CHAPTER 3: TREATMENT OF LSS

Overview

Before any type of treatment is proposed, it is important to discuss the natural history of LSS. Most patients with LS have a slowly progressive clinical course, most often without acute deterioration and rarely with neurological issues present. As mentioned previously, there are both non-surgical and surgical treatments available for LS; however current evidence is rather conflicting on which course of action is best.

In a recent prospective cohort study enrolling 148 patients with LS, 4 year outcomes were measured in both surgical and non-surgical populations. After 4 years, 70% of the surgically treated population and 52% of the non-surgical population reported that their predominant symptom, either leg or back pain, improved (Atlas et al., 2000). The researchers therefore concluded that for patients with severe LS, surgical treatment is associated with greater improvement over a four-year period than non-surgical treatment, even when adjusting for baseline differences in each group. Moreover, while they noted that the relative benefit of surgery declined overtime, surgery still remained superior to nonsurgical treatment (Atlas et al., 2000).

Consequently it would seem that surgical treatment is the preferred method of treatment. However in another prospective cohort study, where 32 patients with moderate LS were followed for 4 years without surgical intervention; the results showed that only 16% experienced worsening pain, thus questioning the risks of surgical intervention where management seems like a suitable alternative (Johnsson et al., 1992).
Below, both non-surgical and surgical treatment options will be discussed in greater detail.

**Non-Surgical Treatment**

Non-operative management of LS is a common first step in treatment. However, there have been few high-quality trials accessing its effectiveness at different stages of stenosis. As a result, treatment is usually guided by a mixture of clinical judgment, observational literature, and analogy to other spinal conditions. The three most commonly used non-operative treatments include physical therapy, non-steroidal anti-inflammatory drugs (NSAIDs), and epidural corticosteroid injections (ESIs). Non-operative treatment usually progresses through these three options until pain is either stabilized, relieved, or surgery is required (Katz et al., 2008).

Once a patient begins to experience symptoms of LS, the first step of spinal rehabilitation is usually in the form of some type of physical therapy. Exercises that improve abdominal strength, as to avoid excess loading of the lumbar spine, have been shown to be beneficial (Whitman et al., 2006). Moreover, passive modalities such as heating and cooling pads, lumbar corsets (rarely used), transcutaneous electrical stimulation (TENS), and ultrasound may also provide transient relief (Katz et al., 2008). The literature also indicates that exercises performed using lumbar flexion, such as bicycling and rowing, are better tolerated than those performed using lumbar extension such as walking (Whitman et al., 2006).
Accessing what form of physical therapy is best suited for a particular patient is typically up to the discretion of the physical therapist performing the therapy and the surgeon managing the patient’s care. In reviewing the literature, however, it would appear that all physical therapy techniques do not provide the same outcome. In a recent randomized clinical trial of 58 patients with LS, two physical therapy treatment programs were compared – one a more manual PT approach (walking and exercise) and one a stretching based PT group (practicing flexion and extension of the spine). The results yielded a greater proportion of patients achieving improvement by employing a more manual based approach. The study concluded that these results were clinically significant between 6 weeks and 1 year of starting therapy (Whitman et al., 2006).

If physical therapy proves ineffective in alleviating symptoms, acetaminophen may be prescribed prior to beginning a regimented dosage of NSAIDs. However, if pain is not responsive to NSAIDs or if the patient cannot tolerate the medication, muscle relaxants, and opioids may be used as an alternative. Anticonvulsants and tricyclic antidepressants may also be prescribed as well – albeit much less commonly than traditional medications. It is important to note, although commonly prescribed, none of these medications have been tested in randomized, class one control trials to prove their effectiveness in alleviating symptoms specific to LS (Joaquim et al., 2009).

Epidural corticosteroid injections provide the last line of defense in treating LS non-surgically. Although the approach is controversial, some patients have shown temporary (weeks to months) control over their symptoms after having these injections. However, the average magnitude of effect is small, and the generalizability of these
observations has been based on only a few selective studies (Armon et al., 2007). Additionally, between 1994 and 2001 there has been a 271% increase in injections administered with a cost-per-injection nearly doubling in a short 7-year period ($115 to $227 per-injection) (Friendly et al., 2007). Despite this increase, injections are being offered at an increasing rate based on the assumption that these injections will provide some relief from LS symptoms that may have resulted from inflammation at the interface between the nerve root and the compressing tissues.

**Surgical Treatment**

*Overview*

After all non-operative care options are exhausted; surgical treatment is the next step that should be considered by patients with LS. The ultimate goal of surgery, regardless of the chosen surgical technique, is to decompress the central spinal canal and neural foramina thus eliminating the pressure on the spinal cord and peripheral nerve roots.

There is currently an array of surgical techniques available, however there is no global consensus amongst spinal surgeons on which technique is most effective. As a result, many surgical techniques are used – some more commonly than others. The traditional approach to relieving pressure on the spinal cord is a lumbar laminectomy and partial facetectomy as described in Figure 2 of the Introduction (Weinstein et al., 2008). This approach removes the spinous processes, lamina, ligamenta flava, and medial portions of the facet joints and thus removes pressure on the cord and peripheral nerves.
Partial facetectomies and unilateral laminectomies for bilateral decompressions (ULBDs) are modified complete laminectomies that preserve the midline structure of the spinal cord and dorsal tension band (Oertel et al., 2006). Some spinal surgeons advocate their usage as they help prevent iatrogenic instability without the use of instrumentation; furthermore, this surgery can be done using minimally invasive techniques (Oertel et al., 2006).

Lumbar laminectomies and partial facetectomies are currently the only surgical techniques supported by class-one evidence (Joaquim et al., 2009). In a randomized clinical control trial, with a two year follow up, patients who exhibited LS symptoms for more than 12 weeks were found to have improved functional capability and pain control post-surgery compared with patients using non-operative treatments. The benefits of initial surgical treatment were shown to diminish over time, but outcomes remained favorable for at least two years (Malmivaara et al., 2007).

Fusion and instrumentation procedures represent a growing proportion of all LS surgeries being done. Despite this growth, currently there is no class one evidence to prove that instrumentation (pedicle screws, plates, and cages) or biological agents (bone morphogenetic protein) should be used to enhance osseous fusion in patients without criteria of instability (Malmivaara et al., 2007). However, there are many studies that present class 2 evidence levels that demonstrate that fusion is both a safe and satisfactory technique in achieving optimal outcomes in elderly patients and patients with degenerative disk disease (Yone et al., 1996, Pavlov et al., 2004). While this evidence is promising, it should be noted that fusion procedures, especially those involving
instrumentation, are associated with increased surgical costs and complications (Katz et al., 1995).

There are currently many instrumentation techniques available to the surgeon to achieve fusion. The use of autologous bone fusion along with pedicle screws and rods has become an increasingly common way to instrument and fuse the lumbar spine. This technique is often supplemented with anterior or column support to distract the disc space and improve fusion rates (Joaquim et al., 2009). Below, these supplemental techniques will be explored and analyzed in their association to segmental instability, LSS revision procedures, severe degenerative disc disease, and sagittal plane deformities. The techniques discussed include four types of fusion procedures, bone grafts and adjuncts to fusion and four new alternatives to fusion procedures.

**Fusion**

*Posterior Lumbar Interbody Fusion (PLIF)*

One of the earliest forms of interbody fusions available, PLIF is performed through a posterior approach with the patient lying face down on the operating table. First a midline incision is made, for example from L3 to L4 (although this depends on the area requiring decompression). The lamina is then removed from the L3 and L4 vertebrae, and bilateral foraminotomies are performed to decompress the peripheral nerves (Figure 5). The disc material between L3 and L4 is then removed and an interbody spacer is inserted (Figure 3). Finally pedicle screws are inserted and the interbody fusion cage is placed, secured, and tested for a tight fit (Figure 9). The retractors are then
removed and the procedure is concluded, typically requiring a post-operative hospital stay of between 2 to 4 days (Periasamy et al., 2008).

This technique is a common approach used amongst spinal surgeons to alleviate LS symptoms. Although common, when compared to other surgical techniques, PLIF requires the greatest manipulation of the thecal sac required for placement of the interbody spacer. As a result, this places patients at a higher risk of surgical related nerve root injuries (Periasamy et al., 2008).

Figure 9: Posterior Lumbar Interbody Fusion
Pictured is the final result of a PLIF procedure. The goal of this fusion is to stimulate the two adjacent vertebrae (as explained L3 and L4) to grow together into one solid, immovable column of bone. This procedure is done though an incision in the back of the patient (the posterior) and is used to treat disc degeneration, disc herniation and spinal instability – all contributing factors to the overall condition of LSS. Figure taken from (Orthogate.org, 2006).
**Anterior Lumbar Interbody Fusion (ALIF)**

ALIF surgery is performed using a retroperitoneal approach with patient lying on his or her back on the operating table. To begin, the surgeon makes a 5-6 inch incision just below the navel to expose the L4-5 interspace. The peritoneal sac is then retracted to expose the L4/L5 vertebrae. Next the damaged intervertebral disc is removed, and cancellous bone grafts are harvested from the iliac crest to be used as an interbody spacer (optional depending on the material used as an interbody spacer). The lumbar endplates of the L4 and L5 vertebrae are then drilled and smoothed, preparing the interspace for fusion. Finally, a fusion cage filled with bone graft is placed in the L4-5 interspace thus concluding the procedure. This procedure may be done with or without bone graft fusion cages and also may be done in conjunction with PLIF, depending on the severity of stenosis and number of fusions required (Figures 10 & 11) (Hsieh et al., 2007).

Anterior lumbar interbody fusion surgery has been proven to restore lumbar lordosis and foraminal height, as well as improve sagittal balance and local disc angles. Additionally it also provides the surgeon with greater exposure to the interspace between vertebrae; as a result, greater arthrodesis can be achieved with ALIF than PLIF alone (Hsieh et al., 2007).

However, the surgery does have its risks. While PLIF requires a large amount of manipulation of the thecal sac, ALIF requires the movement of the abdominal aorta, the largest artery of the body, in order to provide access to the spine (Figure 12). If these vessels are injured during retraction, this may cause internal bleeding. Also patients who
have a BMI of 30 or greater are not eligible for the ALIF approach (Hackenberg et al., 2005).

**Figure 10: Anterior Lumbar Interbody Fusion without Cages**
Pictured is the final result of an ALIF procedure, without cages, using bone harvested from the iliac crest. The goal of the fusion is to stimulate the two adjacent vertebrae (as explained L4 and L5) to grow together into one solid, immovable column of bone. This procedure is done through an incision in the front of the patient (the anterior) and is used to treat disc degeneration, spinal instability, and improve sagittal balance. Figure taken from (Orthogate.org, 2006).

**Figure 11: ALIF Using Fusion Cages and PLIF**
Pictured is the final result of an ALIF/PLIF dual procedure, with cages, using bone harvested from the iliac crest. The metal plates and screws applied using the posterior approach provide additional support and stability for the fused vertebrae and prevent them from moving. The posterior fusion cage also protects the anteriorly placed graft so that it can heal better and faster. These two surgeries can be done together or completed at different times. Figure taken from (Orthogate.org, 2006).
Figure 12: Retraction of the Abdominal Aorta and Inferior Vena Cava using the ALIF Approach.
Pictured is the retraction of the abdominal aorta and inferior vena cava during ALIF. This approach avoids the need to move the thecal sac in order to access the spine. Another advantage of ALIF is that the normal anatomy of the spine is preserved since the anterior approach takes advantage of normal tissue planes, thus not requiring a laminectomy. Figure taken from (Rifenbery et al., 2014).

**Transforaminal Lumbar Interbody Fusion (TLIF)**

Transforaminal lumbar interbody fusion, also known as TLIF, is a new and innovative procedure used to remove the damaged disc and improve lumbar lordosis, foraminal height, and sagittal balance – all symptoms of LSS. This is accomplished through a minimally invasive spinal procedure (Salehi et al., 2004).

To begin, the patient is lying face down on the operating table; a 2-3 inch incision is then made on the more symptomatic side of the spine. A series of dilators of increasing size are then passed through the muscles and soft tissue using the guidance of
a portable x-ray machine. A retractor is then placed into the portal and the dilators are removed. Once this is achieved, the surgeon performs a complete unilateral facetectomy, for easier access to the spinal disc. The damaged disc is then removed, and an implant filled with bone graft is inserted into the interspace. The remaining area of the interspace is then filled with bone graft materials and pedicle screws and rods are inserted to provide increased support and improve the chance of a successful fusion (Figure 13) (Salehi et al., 2004).

The benefit of TLIF is that it provides comparable results to other interbody fusions but with less morbidity than PLIF and ALIF (Joaquim et al., 2009). Other advantages to TLIF include the avoidance of the anterior approach, thus avoiding contact with the abdominal aorta and reducing posterior trauma to the thecal sac associated with PLIF. Furthermore, the minimally-invasive TLIF technique has the benefits of smaller incisions, less blood loss, shorter hospital stays, and quicker recovery times as compared to the traditional PLIF procedure – sometimes required when the patient is undergoing multiple-level fusions requiring bilateral facetectomies (Figure 14) (Hackenberg et al., 2005).
Figure 13: Minimally Invasive TLIF Requiring Unilateral Facetectomy
Pictured is a minimally invasive TLIF surgery requiring a unilateral facetectomy. Here the surgeon uses a special tool to remove the degenerated disc and insert the TLIF fusion cage. This is done unilaterally, thus no manipulation of the abdominal aorta (associated with ALIF) or the thecal sac (associated with PLIF) is required. Pedicle screws with rods and bone graft material may be used to increase the probability of a successful fusion. Figure taken from (Montgomery et al., 2003).
Figure 14: Open versus Minimally Invasive TLIF.
TLIF surgery can be done through a traditional open approach, where a larger incision is made in the middle of the back (similar to PLIF) or through a minimally invasive surgical (MIS) approach. The MIS approach is usually preferred for cases requiring single-level fusions, and unilateral facetectomies (Hackenberg et al., 2005). Figure taken from (Jeffords et al., 2014).

Extreme Lateral Interbody Fusion (XLIF)

Extreme lateral interbody fusion, also known as XLIF, is a novel, minimally invasive spinal procedure commonly used to treat a variety of spinal conditions resulting in LSS, most commonly degenerative disk disease with accompanying radiculopathy.

To begin the XLIF procedure, the patient is lying on his or her side on a special operating table designed specifically for the procedure (Figure 15). The surgeon then creates two 3-4 cm incisions on the patient’s side – one probe incision, one guide incision. The probe incision helps guide the surgeon to detect and avoid nerves along the side of the spine; fluoroscopic X-ray images are also used to guide the probe to the proper position on the side. Next, as with TLIF, a series of dilation tubes are passed through the
incision site with increasing size, concluding with the placement of the retractor device used to move aside muscle tissue and gain access to the spine (Figure 16). The surgeon will operate through the channel created by this retractor. The damaged disc is removed and a surgical implant cage is inserted with bone graft material, similar to the TLIF procedure, into the interspace between vertebrae (Figure 17). As with the other fusion procedures mentioned, pedicle screws may be inserted to supplement the interbody fusion cage and provide additional support (Ozgur et al., 2006).

Since its inception, surgeons and patients alike have been drawn to the minimally invasive approaches TLIF and XLIF offer. These surgeries typically include fewer soft tissue traumas during the surgical approach, less post-operative pain, shorter hospital stays, and a faster return to daily living activities (Ozgur et al., 2006). XLIF also excels over the more traditional fusion procedures when used. Its approach from the side requires only the lateral muscles to be separated, as opposed to cutting the backs muscle fibers, and thecal sac manipulation as required in PLIF procedures.

XLIF’s lateral approach also has other advantages as no major blood vessels need to be moved like in ALIF procedures, This which removes the additional need for a vascular surgeon to assist in the operation as well as reduces the risk of surgery-associated internal bleeding (Figure 18). Lastly, as opposed to TLIF, XLIF has the benefit of anterior spine access, therefore removing the need to perform a unilateral/bilateral facetectomy to fully access the degenerative disk (Ozgur et al., 2006).

However, although promising, XLIF is not without its risks. One particular risk is damage to the lumbar plexus, which is especially true in trying to approach the lower
lumbar segments such as L4-L5 (Ozgur et al., 2006). Other risks include, but are not limited to, persistent pain after surgery, failure to fuse (non-union), and surgery-associated neurological injury. Furthermore, a greater acceptance of minimally invasive procedures has been hampered by known complications associated with microsurgery. These include anesthetic complications, visceral damage, large vessel bleeding, and sexual dysfunction. Moreover, spinal surgeons attempting to use MIS techniques are challenged by the required technical skills, steep learning curve, and smaller available access during surgery (Ozgur et al., 2006). XLIF surgery is also not capable of being performed on patients requiring fusions between the L5-S1 disc space and for patients with high-grade spondylolisthesis, or bilateral retroperitoneal scarring from prior surgery (Joaquim et al., 2009).

Figure 15: Surgical Position for XLIF Surgery.
XLIF surgery is done with the patient lying on his or her side as to create an appropriate position for the surgeon to access the spine. Figure taken from (MDnews.com, 2011).
Figure 16: Placement of Probes, Dilation Tubes, and Retractor during XLIF.
Pictured here is the initial placement of the surgical probe, accompanied by an increasing diameter series of dilation tubes and finally a surgical retractor to move aside muscle tissue as to provide clear surgical access to the lateral spine. Figure taken from (MDnews.com, 2011).

Figure 17: Unilateral Removal of the Degenerative Disk via XLIF.
Pictured here is the surgical removal of the degenerative disk, using a microsurgical instrument. After removal, a surgical implant cage is inserted with bone graft material, similar to the TLIF procedure, into the interspace between vertebrae. Figure taken from (Pimenta et al., 2014)
Figure 18: XLIF Lateral Surgical Approach versus PLIF and ALIF. XLIF approaches the spine laterally through two 3-4 cm incisions. This approach removes the risks of manipulating the thecal sac as in PLIF and abdominal aorta in ALIF surgeries. It also reduces scarring, decreases hospital stay and reduces blood loss. Figure taken from (Kasif et al., 2014).

**Bone Grafts and Adjuncts to Fusion**

The ultimate goal of using instrumentation in the procedures mentioned above is to alleviate pressure on the spinal disk, cord, and peripheral nerves via a successful fusion. As mentioned, along with surgical hardware, bone graft material has become an increasingly common method to achieve complete fusion. Researching this possible avenue to fusion is important as nearly 50% of all autogenous bone grafting procedures
performed annually are for spinal fusion (Hsu et al., 2008). During these procedures cancelous bone is taken from the iliac crest to achieve fusion. Iliac crest bone grafts have become the “gold standard” in reconstructive surgery due to their reservoir of osteogenic cells that are both osteoinductive and osteoconductive, and contain non-immunogenic properties. The iliac crest is also easily accessible via surgery, and contains a large availability of both cortical and cancelous bone – all accessible with a relatively low surgery-associated morbidity (Ahlmann et al., 2002).

However, despite this low morbidity, harvesting bone from the iliac crest is associated with some potentially serious complications, a fact that is well documented in the literature. In a 1995 study, J.C. Banwart found that harvesting bone grafts from the iliac crest for use in spinal surgery was associated with rates of major complications ranging from 2.8% to 10% and rates of minor complications ranging from 5.6% to 39% (Banwart et al., 1995). Moreover, morbidity seems to be independent of the chosen iliac crest donation site. In a recent study of 88 LS patients, it was found that rates of major and minor complications were 5.3% and 25% at anterior iliac crest donor sites and 11.3% and 18.4% from donations at posterior iliac (Ahlmann et al., 2002).

As a result of the associated surgical morbidity when obtaining bone from the iliac crest, many substitutes are currently being studied, one being cadaveric allograft bone. Cadaveric bone is a promising option, as it is contains both osteoconductive and osteoinductive properties as well as displays an extremely low risk of disease transmission (Zipfel et al., 2003). New generations of allograft bone are also being studied. Currently, demineralized bone matrix has been shown to offer osteoinductive
properties when used in animal studies – although current evidence in human spinal fusion trials has yet to be established (Schizas et al., 2008).

Other options for artificial bone grafting are also being explored. Recombinant growth factors such as bone morphogenetic proteins (BMPs) have been used to enhance spinal arthrodesis rates in recent years. These BMPs have significant osteoinductive potential when administered within a carrier (typically a collagen sponge) and work to avoid complications typically associated with iliac bone harvest (Hsu et al., 2008). Recent studies have offered significant promise for BMPs, specifically rhBMP, by demonstrating their ability to introduce de novo bone formation at a non-bony site, with the possibility of decreasing future need for instrumentation (Shields et al., 2006). Further evidence suggests that BMPs will lead to higher success rates in minimally invasive procedures such as TLIF and XLIF, including less operating time, blood loss during surgery, and hospital stays as well as more successful fusion rates (Shields et al., 2006).

Despite the initial successes of BMP to enhance fusion rates, there are significant risks and costs associated with its usage. Recent studies suggest that BMP, when used at supraphysiological doses during spinal surgery, may lead to postoperative complications such as hematomas, dysphagia, and excessive edema (Shields et al., 2006). Moreover, it has been noted that while BMP has been proven effective for ALIF surgery, PLIF involves a more difficult healing environment and thus an increased risk of complications when using BMP (Glassman et al., 2007). Practical application of BMP is also limited by significant surgical costs, up to $7,000 per fusion level (Boden et al., 1990). Currently,
BMP is approved for use in ALIF procedures using fusion cages and PLIF procedures when using bone expanders (Joaquim et al., 2009).

**Novel Surgical Alternatives to Fusion**

**Lumbar Disk Replacement**

Although widely used in Europe for almost 30 years, lumbar disk replacement has only recently become available to U.S. patients. Since its approval by the Federal Drug Administration (FDA) in 2004, lumbar total disk replacement (TDR) has been regarded as a fascinating potential alternative to spinal fusions in the treatment of LSS (Shim et al., 2007). For many years, spinal arthrodesis has been a proven way to increase foraminal height and stabilize the spine, thus effectively decreasing back and radicular pain. However, while the spine is now stabilized post-arthrodesis, joint motion at the level(s) of fusion is lost, and the increased stress on adjacent levels (transition syndrome) may cause further problems later on in life (Guyer et al., 2004). Lumbar TDR solves this problem.

Lumbar TDR surgery is a very similar procedure to ALIF surgery described previously. During the operation, the patient lies on his/her back and a small incision is made directly below the navel. Working anteriorly, a vascular surgeon moves aside the appropriate soft tissue and abdominal aorta – granting access to the front of the spine. The disc is then removed and two metal endplates serving as surgical prosthesis are inserted between the two vertebrae (Figure 19) (Shim et al., 2007).
Currently, the two most common lumbar TDR devices available are the CHARITE system and ProDisc (Figure 20). In a recent prospective randomized study comparing lumbar TDR with ALIF fusions, the clinical outcomes were similar, except TDR complication rates were lower and satisfaction rates higher – showing a better efficacy of TDR over fusion (Blumenthal et al., 2005). However, unexpectedly high rates of degradation of the facet joint at the level of replacement were observed, raising questions about the long-term efficacy of lumbar TDR prosthesis (Shim et al., 2007).

Figure 19: Lumbar Disk Replacement Surgery
After the diseased disk is removed, the adjacent vertebrae are spread apart to make more room for instrumentation. Using a microscope, any residual disc material is removed, and the prosthesis is inserted. The spine is then manipulated in various positions to test the prosthesis; X-ray imaging may be used to double check the location and fit. Figure taken from (Marco et al., 2007).
Prosthetic disks used in TDR are made of metal, ceramic, and plastic. A plastic polyethylene core fits between two cobalt chromium alloy endplates. The core acts as a spacer between the two endplates and works to mimic the normal motion of the disk between the two vertebrae. CHARITE, ProDisc, and other prosthesis differ in how the endplates are anchored to the vertebrae and the amount of movement they allow. The surgeon will decide which implant is best, based on the needs of the patients and correct angle for optimal lordosis. Figure taken from (Marco et al., 2007).

**Interspinous Spacer**

Interspinous spacers have become another way to decompress the lumbar spine, without the need for extensive spinal surgery. As mentioned previously, one specific side effect of lumbar stenosis is neurogenic intermittent claudication, or NS. NS is a specific symptom complex where the patient remains relatively asymptomatic while sitting, but upon standing experiences aggressive pain, numbness, and weakness in the legs. These symptoms are caused by dynamic neuroischemia, brought about through an increased pressure on the peripheral nerves while standing (Verbiest et al., 1975).
Interspinous spacers correct this problem though the insertion of an oval spacer between spinous processes, thus preventing excessive extension and lordosis of the spinal vertebrae while standing (Lindsey et al., 2003). Currently the most widely used spacer is the X STOP implant (Figure 21). During surgery, implants are placed between adjacent spinous processes while the patient is under local anesthetic and lying in the flexed right lateral decubitus position (Figure 22). Post-operative movement is allowed the same day. (Anderson et al., 2006).

Since interspinous spacers implementation in the field, the literature has suggested that surgical outcomes using spacers are similar to lumbar decompression at a four year follow up period, albeit with less hospital costs (Joaquim et al., 2009). In a recent retrospective study conducted by Zucherman, 71% of patients who had received spacers were satisfied with their treatment (Zucherman et al., 2004). Moreover, biomechanical studies using cadaveric spines have found that X STOP significantly increased spinal canal area by 18%, and foraminal width by 41, both contributing to less NC symptoms (Lindsey et al., 2005). The current literature on interspinous spacers appears promising, however, positive outcomes depend largely on both the stability of the implant and strength of the spinous processes. When used correctly in carefully selected patients, interspinous spacers may soon prove to be a more commonly used, effective alternative to non-instrumented lumbar decompression (Anderson et al., 2006; Yerby et al., 2001).
Figure 21: X STOP Interspinous Spacer
Shown above is an artist rendering of the X STOP interspinous spacer implant. Figure taken from (Anderson et al., 2006).

Figure 22: Surgical Placement of X STOP Implant
After administering of a local anesthetic, the correct implant location is determined by fluoroscopy. Once found, the skin is incised, and the paraspinal muscles are elevated while carefully protecting the supraspinous ligament. Then starting just posterior to the lamina, interspinous implant devices (ranging from 6-14 mm) are sized for insertion. The correct sized device is then inserted and locked into place. Figure taken from (Anderson et al., 2006).
**Dynamic Stabilization**

Dynamic stabilization (DS), also called the Dynesys system, is a new method available to treat LS that offers an almost pseudo-fusion of the lumbar spine by decompressing the central and foraminal canals in the absence of a rigid fusion cage. This system works through a combination of pedicle screws, polycarbonate urethane spacers, and polyethylene cords, which eliminate pain by decompressing the spinal canal and stabilizing the spinal vertebrae without fusion (Figure 23) (Farr et al., 2014).

The surgical procedure is very similar to PLIF, albeit with some key differences. While PLIF is successful in reducing back pain through the fusion of adjacent spinal vertebrae, it does come at a cost by limiting the flexibility and motion of the spine. Dynamic stabilization excels by reducing stenosis though hardware that not only reduces pain but also allows patients to maintain some spinal flexibility and natural function (Figure 24) (Robbins et al., 2014). Complications are also less frequent in DS. Since no bone grafting is necessary, working in favor of motion preservation, the iliac crest remains undisturbed. Accelerated degeneration of adjacent vertebrae is also avoided, as the spinal joints are more movable as opposed to a solid structure representative of fusion procedures (Welch et al., 2007).
Figure 23: The Dynesys System
The Dynesys System, commonly referred to as dynamic stabilization, works to decompress the central canal through a series of spacers, pedicle screws and polyethylene cords. Figure taken from (Farr et al., 2014).

Figure 24: Multiple Level Dynamic Stabilization Procedure
Pictured is a multiple level dynamic stabilization performed on the L3-L5 vertebrae. The patient benefits from the procedure by reducing stenosis while maintaining some natural flexibility around the joints. This degree of flexibility would not be attainable if traditional fusion was performed. Figure taken from (Robbins et al., 2014).
**Nucleus Pulposus Replacement**

The goal of nucleus pulposus replacement surgery is simple – to replace the damaged disc’s nucleus pulposus with a synthetic material. This is done in order to maintain disc height, preserve natural functional motion, and sustain a material capable of absorbing impact between the two spinal vertebrae (Siepe et al., 2006). Replacement of the nucleus pulposus achieves this goal through injectable hydrogel pellets encased in polyethylene jackets (Figure 25) (Braithwaite et al., 2010). Although still under preliminary analysis, present data suggest ProDisc II as a viable option for highly specific patient populations wanting to maintain a natural range of motion without the complications and limitations of traditional arthrodesis (Siepe et al., 2006).

**Figure 25: Nucleus Pulposus Replacement**
Above is an illustration depicting the injection of synthetic hydrogel solution within the confines of the annulus. This is done after surgically removing any remaining nucleus pulposus. Figure taken from (Braithwaite et al., 2010).
CHAPTER 4: CONCLUSION AND FUTURE DIRECTIONS

Lumbar spinal stenosis has a large spectrum of potential treatment options since the disease itself has a wide range of severities. As discussed, an accurate patient history and diagnosis is of paramount importance in order to achieve good clinical results. When examining a patient, it is recommended that both CT and MRI scans are used, as well as standing x-ray films if positive sagittal balance is suspected. Neurophysiological EMG testing, while necessary in some patients to rule out suspected pre-existing neuropathies, appears to be unnecessary in accurately diagnosing the general LS population.

Physical exams are also of the utmost importance. While radiological findings are necessary to confirm the presence of LS, the definitive diagnostic is essentially clinical. Thus, when LS is suspected, patients should be extensively examined by their physician at the time of visit using the Laseque test and accurate administration of the Oswestry Disability Index to confirm their diagnosis. Although LS currently lacks a “gold standard” diagnosis, clinical symptoms such as lower back and leg pain, thigh pain, and a wide based gait should point to a possible LS diagnosis, prompting the physician to move forward with imaging studies. These highly sensitive and specific diagnostic procedures are important as they provide a definitive LS diagnosis while eliminating possible differential diagnoses such as hip osteoarthritis, trochanteric bursitis, and peripheral neuropathy. Prior to imaging, if the physician believes any of these other conditions may be contributing to a patient’s pain, a corticosteroid injection should be given in order to help clarify the diagnosis.
The patient’s physical and socioeconomic status should also be taken into account when diagnosing LS. Today, most LS patients are between 50 and 60 years old with their condition commonly arising alongside age-associated degeneration of the lumbar and facet joints. However, females, heavy manual laborers, smokers, and individuals with a BMI above 30 are at an increased risk for developing LS (Abbas et al., 2013). An extensive patient history is very important to the diagnostic strategy as treatment should be tailored specifically to the individual based on their age, sex, and expected quality of life.

Conservative treatment, while an important first step in the management of LS, seems limited to a first line of defense lasting only a short period of time. Physical therapy appears to be successful clinically in alleviating some symptoms for up to a year. While sometimes beneficial, NSAIDs and anticonvulsants/depressants have had only limited success. And despite their increased use in recent years, there is still very little evidence of the benefits epidural corticosteroid injections provide, thus explaining the current controversy regarding their increased use. In one recent study it was even shown that ESIs were associated with significantly less improvement among eventual surgical candidates and resulted in longer surgical times and lengthier hospital stays (Radcliff et al., 2013). However the largest problem with today’s current methods of conservative treatment as a whole is that they fail to correct the underlying condition of LS, while remaining only meagerly effective in reducing symptoms.

As a result, it would appear that surgery is currently the best single option for patients who fit the clinical and radiographic findings indicative of LS. However, despite
surgery’s proven benefit, patients have shown considerable aversion to spinal surgery, perhaps due to the complex operative nature of the procedures and potential for severe complications. This aversion has resulted in a lack of surgical referrals, and an increasing patient preference to symptom management over surgical treatment. This unfortunately has led to extensive, often unnecessary, steroid injections and frequent use of pain medications - thus explaining the high rates of opiate use and addiction among LS patients (Manchikanti et al., 2010).

To help remedy this issue and provide comfort to patients considering surgical treatment for stenosis; LS and total hip arthroplasty operations were recently compared for positive clinical outcomes (Reindl et al, 2003). This comparison is important as total hip arthroplasty has gained widespread acceptance in the medical community as a safe operation with predictable results that leads to a significantly improved quality of life in patients.

It was found that although complex, lumbar spinal decompression, arthrodesis, and associated instrumentation posed no greater risk to patients than would be expected from a total hip arthroplasty procedure. Major complication rates post-operatively were similar (Hip: 12, Spine: 14) among 68 patients, as were reoperation rates (Hip: 7.5-27%, Spine: 17-27%). It was also found, as many other studies have confirmed, that the use of fusion significantly reduces the number of reoperations (Reindl et al, 2003). This study, among others, has confirmed the safety of LS operations and will hopefully encourage more patients to undergo surgical treatment.
Of all the currently available surgical techniques used to treat LS, TLIF and XLIF procedures appear to be the most promising. When performed by an experienced surgeon, these procedures provide benefit over traditional PLIF/ALIF procedures in their minimally invasive approach, surgical avoidance of the thecal sac and abdominal aorta, decreased operating times, and minimal blood loss/decreased hospital stays. The only downside appears to be the extensive surgical training needed to successfully complete these procedures – possibly further sub-specializing an already specialized field.

Although in recent years the rates of fusion have been increasing, with BMP/interbody device use nearly doubling, the current literature is beginning to suggest use of instrumentation in the absence of arthrodesis (Lad et al., 2014; Bae et al., 2013, Modhia et al., 2013). This approach is favored as it is believed to be the best foreseeable future of surgical LS treatment. Hopefully by providing a minimally invasive procedure that decompresses and stabilizes the spine, yet still allows for natural range of motion, will lead more LS patients to undergo surgical correction.

On the whole, the judicious use of conservative measures is recommended, but surgical management is heavily encouraged when these no longer prove effective. Although more long-term studies will be needed, it appears that lumbar disk replacement and minimally invasive dynamic stabilization are the optimal treatments and the future of surgical LS procedures.
APPENDIX

Medical Definitions

- **Arthrodesis**: The surgical fixation of a joint by a procedure designed to accomplish fusion of the joint surfaces by promoting the proliferation of bone cells.

- **Autogenous Bone Grafting**: A bone graft taken from bone from the patient’s own body.

- **Cauda Equina**: A descriptive Latin term referring to the bundle of nerve roots from the lumbar and sacral levels that branch off the bottom of the spinal cord. Also known as the “Horse’s tail”.

- **Chondrometaplastic Changes (Chondrometaplasia)**: A condition characterized by the metaplastic activity of the chondroblasts.

- **Degenerative Spondylolisthesis**: Latin for “slipped vertebral body”, this is a condition where one vertebra slips forward over the one below it.

- **Dynamic Neuroischemia**: Deficient supply of blood to the brain that is due to obstruction of the inflow of arterial blood.

- **Facetectomy**: An operation to remove part of the facet. To prevent a degenerated facet from pinching a nerve.

- **Foraminotomy**: An operation to make the foramen larger to provide more space for the nerves and blood vessels.

- **Hypertrophic Osteoarthritis**: A chronic arthropathy characterized by disruption and potential loss of joint cartilage along with osteophyte formation along the joint.

- **Laminectomy**: An operation to remove the lamina to allow more room for the spinal cord and nerves.

- **Ligamentum Flavum**: Any series of ligaments of yellow elastic tissue connecting the laminae of adjacent vertebrae from the axis to the sacrum.

- **Lordosis**: Excessive inward curvature of the spine.

- **Lumbar Plexus**: A nervous plexus (a branching network of intersecting nerves) in the lumbar region of the body which forms part of the lumbosacral plexus.

- **Neural Foramina Stenosis**: the compression of a spinal nerve as it leaves the spinal canal through the foramen (the opening between the vertebrae through which spinal nerve roots travel and exit to other parts of the body).

- **Neurogenic Claudication**: A condition in which spinal nerves become compressed by stenosis resulting in weakness, discomfort, and difficulty walking.

- **Osteoconductive**: The process by which bone forms on the surface. This is a natural passive process.
- **Osteoinductive**: the process by which osteogenesis is induced. It is a phenomenon regularly seen in any type of bone healing process. Osteoinduction implies the recruitment of immature cells and the stimulation of these cells to develop into preosteoblasts.

- **Pars Interarticularis**: A small segment of bone that joins the facets joints in the back of the spine.

- **Pedicle**: The stub of bone that connects the lamina to the vertebral body to form the vertebral arch.

- **Peripheral Neuropathy**: Weakness, numbness, and pain from nerve damage, usually in the hands and feet.

- **Sagittal Imbalance**: Sagittal imbalance implies a patient is unable to maintain a normal weight-bearing line between their head and their pelvis when viewed from the side. In basic terms, they cannot stand up straight.

- **Stenosis**: An abnormal narrowing of a passage in the body, in this case the spinal canal.

- **Subluxation**: The incomplete or partial dislocation of a joint.

- **Transcutaneous Electrical Stimulation**: The use of electric current produced by a device to stimulate nerves for therapeutic purposes.

- **Trochanteric Bursitis**: Inflammation of the bursa at the outside point of the hip known as the greater trochanter.

- **Vascular Claudication**: A cramping pain in the buttock or leg muscles caused by poor circulation of the blood to the afflicted area.

- **Zygapophyseal Joints (Facet Joints)**: are a set of synovial, plane joints between the articular processes of two adjacent vertebrae. There are two facet joints in each spinal motion segment.
REFERENCES


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- Determined the 2011 rise in radioactive Iodine in Philadelphia’s water supply. The research conducted focused on two of radioactive isotopes: $^{129}$I and $^{131}$I. The purpose of the project was to discover the source of radioactivity; i.e., isotope 129 from nuclear waste from the 2011 Fukushima disaster and isotope 131 from thyroid treatment waste.
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