REGIONAL AND HISTOGRAM ANALYSIS OF T2 MAPS OF INTERVERTEBRAL LUMBAR DISCS

T2 maps from a healthy volunteer collected at four different time instances during a day

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Abstract

In this master thesis, lumbar discs were evaluated by creating analysis tools in MATLAB (MathWorks, Natick, Massachusetts, U.S.A) for analysing T2-map images of the spine.

Purpose The purpose of this study was to examine how the time instance of the examination with and without axial loaded Magnetic Resonance Imaging (alMRI) influences the T2 value of intervertebral lumbar discs.

Method alMRI was performed at four different time instances during a day separated by approximately 4 h on a healthy volunteer. In-house analysis tools that performed regional disc analysis, with mean T2 values of subvolumes calculated, were written in MATLAB. Histogram analysis of the T2-value distribution, with skewness and kurtosis of the distribution calculated, were also performed with these analysis tools.

Results There were great differences in T2 values between hydrated and dehydrated discs, visible in both the regional analysis and the histogram analysis. Differences in the T2 values between different time points of the day were modest. The study showed small effect of loading of the spine in all discs of the healthy volunteer. When the spine was axially loaded, the variation in the T2 value was low for both regional and histogram analysis, indicating a more robust measurement situation with alMRI.

Conclusions

• Generally, the T2 value of the disc decreased over the day, where the decrease tended to be larger in the anterior subregions.
• There were modest differences in T2 value between unloaded and loaded state of the spine as well as in between the different time points during the day.
• Great differences in T2 value of the discs between hydrated and dehydrated discs were seen in both regional analysis and histogram analysis.
• For unloaded state of the spine, large variations in the T2 value of the disc and in the subvolumes of the discs were seen between different time points during the day, while smaller variations were seen for the loaded state. The same effect was seen in the histograms, where the kurtosis and skewness of the histograms varied less during the loaded state.
• Quantitative parameters from the analysis in this work can be useful for determine the level of disc degeneration since the parameters are continuous variables and therefore offers a more detailed division of disc degeneration.
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1 Introduction

Low back pain (LBP) is a problem with a high prevalence in the general population. The pathogenesis is indefinite, but has been associated with degenerative changes of the intervertebral discs (IVD) [1]-[3]. IVD degeneration is a natural part of aging, starting already in the second decade in life with small IVD fissures. The interface between the nucleus pulposus (NP) and the annular fibrosus (AF) then reduces with NP leaking out into the AF, or even outside the disc. Not everyone with degenerative IVD changes suffer or show signs of symptoms, but for those who do, the psychological and physiological consequences are severe and not to neglect. LBP is thus a world wide problem with high socioeconomically costs [4, 5]. The best diagnostic imaging method for LBP patients is magnetic resonance imaging (MRI). However, the conventional scan protocols cannot distinguish between IVDs of a symptomatic patient and IVDs of an asymptomatic individual. A diagnostic method with high specificity to evaluate patients with non-specific LBP is today not clinically available [6]-[9].

A problem when scanning LBP patients is that in the moment of imaging their back is in a resting state which causes their symptoms to decrease, or even disappear. Conventional supine imaging of the spine thus fails to represent the spine in a painful state. In this thesis, axial loaded MRI (aMRS) is combined with T2-mapping, see Chapter 2 Section 2.2, to evaluate the IVDs in the lumbar spine in a resting state but also in a state that simulates standing position and, thus, a state of pain.

aMRS is a method with potential to induce spinal/IVD changes not displayed on supine MRI. At the moment aMRS is a novel method regarding the application on LBP patients, and therefore, validation is required before becoming a routinely used method for these patients. Amongst other things, validation needs to be performed to study the dependence on when the MRI is performed during the day. It has previously been shown that in supine unloaded position, the T2 value of the discs decreases during the day, however the time dependence for aMRS has, to our knowledge, not yet been studied [4]. It is reasonable, though, to hypothesize that with aMRS, the T2 value of the disc also displays similar time dependence. Moreover, to our knowledge, the time dependence of how the T2 values changes during a day has only been studied using global analysis, where changes in the mean value over the entire disc is determined, without regional or histogram analysis.

Small regional IVD changes can be a cause of pain and it is therefore important to perform a more specific regional IVD analysis, with analysis of subvolumes, to
1. Introduction

detect even bio-dynamical effects in smaller regions. The histogram analysis may also have the feasibility to detect small changes in the discs.

The primary aim of the feasibility study was to investigate how the T2 value varies in both the entire IVD as well as in IVD subvolumes, with and without axial loading of the spine at different time instances during one day. Secondary aims were to investigate the histogram of the T2-value distribution of the IVD, with the purpose to find new promising parameters for diagnostic and longitudinal assessments of IVDs.
2 Theory

2.1 Intervertebral Discs

Intervertebral discs (IVD) are composed of nucleus pulposus (NP) and annulus fibrosus (AF). NP is the core of the discs which is high in water content and the surrounding AF is mostly composed by collagen fibers. A non-degenerated disc has a well defined interface between AF and NP.

2.1.1 Epidemiology of Disc Degeneration

Disc degeneration occurs as a natural part of ageing and appears from the second decade in life. It is also associated with LBP which is a disease with high prevalence. With increasing age, and/or spinal trauma, small annular fissures occur and the interface between NP and AF reduces. Sometimes the gelatinous NP leaks out to AF. Degenerated discs can later lead to disc herniation, spinal stenosis, and degenerative spondylolisthesis as secondary problems.

2.2 Magnetic Resonance Imaging

In this chapter fundamental principles of Magnetic Resonance Imaging (MRI) are described. T1 relaxation and T2 relaxation are briefly explained as is the method referred to as T2 mapping.

2.2.1 MRI Physics

MRI is a non-ionization method to image an object with several contrast options. In the human body, the high density of $^1$H enables imaging with MRI. In MRI, a static magnetic field, $B_0$, causes the protons ($^1$H) to precess around the axis of the $B_0$ field. The precession occurs due to the magnetic dipole moment of the proton. By adding an radio frequent (RF) pulse, i.e. an excitation pulse, to a volume element in the object of study, the protons in the volume will flip from precessing around the $B_0$ direction to precess in the direction of the $B_0 + B_1$ field, which is the combination of the static field and the magnetization component of the RF pulse. After an RF pulse with flip angle 90 degrees, all the magnetization in the volume element will be in the transverse plane, perpendicular to the main magnetic field. The flip angle for the magnetization is dependent on the total amount of energy in the applied RF pulse. The frequency of the RF pulse must obey Larmor’s equation:
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\[
f_0 = B_0 \cdot \gamma
\]  \hspace{1cm} (2.1)

where \(f_0\) is the resonance frequency, \(B_0\) is the static magnetic field strength and \(\gamma\) is the gyromagnetic constant. The gyromagnetic constant is unique for every element and provides the element’s resonance frequency for a given magnetic field strength.

### 2.2.2 Relaxation

T1 relaxation is the phenomena of rebuilding the magnetization in the \(B_0\) direction after an excitation, \(M_z\). T1 relaxation describes how the protons deposit excess energy to the surrounding molecules and reverts back to equilibrium state, i.e. aligns with \(B_0\), due to the conversion to thermal energy. The process of transferring energy to surrounding molecules, and therefore the T1 value, is specific for every tissue. T1 relaxation describes the time for the magnetisation, \(M_z\), to rebuild to 63% of its initial value after a 90 degrees pulse. The T1 value is derived from equation (2.2)

\[
M_z = M_0 \left(1 - e^{-t/T_1}\right),
\]  \hspace{1cm} (2.2)

where \(t\) is the time from excitation to signal collection and \(M_0\) is the initial magnetisation. T2 relaxation, on the other hand, is the reduction of magnetization in the transverse plane perpendicular to \(B_0\), \(M_{xy}\). \(M_{xy}\) is reduced as the protons loses their initial spin coherence. The T2 value is not affected by \(B_0\). The T2 value depends on the mobility of the protons in different tissues. In water, the protons can move freely, which increases the time it takes for the protons to interact with each other compared to protons in lipids. T2 relaxation time describes the time it takes for the transverse magnetization to reduce to 37% of its initial value after a 90 degree pulse and is derived from equation (2.3).

\[
M_{xy} = M_0 e^{-t/T_2}
\]  \hspace{1cm} (2.3)

### 2.2.3 T2 mapping

T2 mapping is a quantitative MRI method where each pixel value in the image represents a calculated T2 value. The image is calculated voxel-by-voxel from the signal intensity for several echo times. The echo times are optimized for a certain T2 value, the signal intensity is exponentially fitted, and from this the individual voxels T2 value is determined. For voxels with low signal the mathematical fit will be insufficient and the T2 map will show false values.
Method

3.1 MRI Scanning

A male, healthy volunteer (27 years) without back pain was the control person for this study. During one day, the same scan protocol were repeated four times with approximately 4 h separation between the measurements. The examination included T1-weighted and T2-mapping sequences, before and after axial loading of the spine. alMRI was used to simulate an upright standing position while lying down in the scanner. The alMRI was performed with a DynaWell compression device (Dynawell diagnostics AB, Las Vegas, NV, U.S.A), in which the person wears a vest over the shoulders and upper chest with two straps parallel to each side of the body. 50% of the persons body weight is applied by tightening the straps to the footplate of the compression device. The change of the spine during loading is shown in Figure 3.2.

Imaging of the spine was performed in both unloaded and loaded state with a Siemens MAGNETOM Aera 1.5 T, using Spine 32 and Body 18 receiver coils. The T2 mapping was carried out with a multi-echo spin echo sequence with six echo times spanning from 11 ms to 89 ms. The T2 values were calculated with a mono-exponential fitting of the different signal intensities for each echo time. A T2-map image is shown in Figure 3.1. For scan sequence details, see Table 3.

Table 3.1: MRI and alMRI protocol details.

<table>
<thead>
<tr>
<th>Sequence</th>
<th>NSA</th>
<th>Flip (°)</th>
<th>TR (ms)</th>
<th>TE (ms)</th>
<th>Slice (mm)</th>
<th>Matrix size</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSE T1 sag</td>
<td>2</td>
<td>150</td>
<td>480</td>
<td>9</td>
<td>3.5</td>
<td>320x320</td>
</tr>
<tr>
<td>FSE T2 sag</td>
<td>1</td>
<td>150</td>
<td>3500</td>
<td>95</td>
<td>3.5</td>
<td>384x384</td>
</tr>
<tr>
<td>FSE T2 ax</td>
<td>2</td>
<td>150</td>
<td>5330</td>
<td>97</td>
<td>3.5</td>
<td>320x320</td>
</tr>
<tr>
<td>SE T2-map</td>
<td>1</td>
<td>180</td>
<td>1400</td>
<td>11-89</td>
<td>3.5</td>
<td>256x256</td>
</tr>
</tbody>
</table>

1NSA: Number of Signal Averages
2Flip: Refocusing flip angle
3TR: Repetition time
4TE: Echo time
5Slice: Slice thickness
3. Method

**Figure 3.1:** A T2-map image of the spine in unloaded state. The colorbar shows a relative scale where 1 is the longest T2-value.

**Figure 3.2:** T2-weighted images of the spine in unloaded state (left) and in axial loaded state (right). An increased lordosis in loaded state can be seen when axial loading is applied.
3. Method

3.2 Disc Segmentation

Before regional and histogram analysis, each lumbar disc was segmented. The segmentation was applied on each disc separately to simplify the disc manipulation and calculations. A transformation of the T1-weighted (T1W) images was made to match the matrix size and the field of view (FOV) to the T2-map images. The T1W matrices were cut asymmetrically to match the image center position to the same coordinate as in the T2-map images. The mask images were manually created and based on the morphological T1W images using MATLAB’s built-in application `imageSegmenter`. An example of how a region of interest (ROI) was drawn can be seen in Figure 3.3. Each mask image was then imported as a logical file to MATLAB’s workspace. The logical matrices for each slice and disc were then multiplied with the corresponding slice in the T2-map image stack and fused to a 3D matrix which only contained information about one disc, while the rest of the matrix was set to zero.

![Figure 3.3: An example of a region of interest (marked in purple) of a lumbar disc.](image-url)
3.3 Regional Analysis

For the regional analysis the images were first aligned row-wise, so each lumbar disc would have the same angular dependence as input for the analysis. After the rotation each disc was divided in five subvolumes. This rotation of matrices simplified the creation of new matrices for each subvolume. The discs were also numbered for a reference system as seen in Figure 3.4.

![Figure 3.4: The order of reference of the lumbar discs.](image)

3.3.1 Rotation of Images

After the segmentation of the discs, the 3D matrices were individually rotated. A function was implemented that searches for a specific degree that gives a maximum width of the disc. This function initially finds the row in the 3D matrix with the most non-zero elements, i.e. the maximum length of the disc for the current rotation in the original segmented image. The function then rotates the original 3D image matrix iteratively with a cumulative variable of the rotation degree. For iterations when the function found a row in the new rotated matrix, where the length of a row with non-zero elements would be longer than the previous, the new length of the
row with the maximum number of non-zeros elements, and the coordinates as well, was updated and saved. The cumulative rotation variable was increased for each iteration with one degree for each iteration and spanned from -1:-180 degrees. An example of how a disc was rotated is showed in Figure 3.5.

![Original image vs. Rotated image]

**Figure 3.5:** An example of the rotation of a lumbar disc.

### 3.3.2 Creation of Subvolumes

The matrices of the rotated discs were automatically divided into subvolumes for a regional resolved analysis to be able to detect variations in reaction from anterior to posterior of the IVD. Before splitting the discs into subvolumes the matrices were linearly interpolated symmetrically in two dimensions to increase the matrix size in-plane. The number of slices were unchanged. The interpolation does not provide new information or improves statistical power of the analysis but has process related advantages. The splitting into subvolumes is dependent on the number of columns in the disc and an enlarged matrix will be less prone to errors in the determination of the width of each subvolume.

After rotation, the discs were divided into five equally wide VOIs (volumes of interest) in the sagittal plane. If the length of the disc was not a multiple of five, the central VOI was narrowed and the other four VOIs were kept symmetrical regarding the width. The splitting of the matrix was done using the central column in the
3. Method

disc as initial position. When the length was an even number, i.e. when there were two central columns, the mid-column of the disc was chosen to be the column to the anterior direction of the two central columns. In Figure 3.6, the division of a disc into subvolumes is shown.

Figure 3.6: The reference order of the subvolumes in the lumbar discs, where A is the most anterior positioned subvolume.

3.3.3 Analysis of the T2 values

All zero elements outside the discs in each subvolume were removed and new matrices were produced which only contained T2 values within the subvolumes of the discs. These matrices were then evaluated for mean T2 value.

3.4 Histogram

From the segmented disc matrices, a vector was created with all zero values removed so the vector only contained the different T2 values. The histogram distribution of T2 values in each segmented disc was then plotted from this vector including the constraint that all T2-values over 500 ms were removed, since T2 values above 500 ms are not clinically relevant.

3.4.1 Gaussian Two Peak-Fitting

After the bin-size had been regulated, the histogram was normalized with respect to the chosen bin-size and the number of occurring T2 values. A non-linear least square Gaussian fitting was applied to search for two peaks in the histogram, with the hypothesis that for a non-degenerated IVD, the T2 values of AF and NP will occur as two separate peaks in the histogram.
3. Method

3.4.2 Kurtosis and Skewness

For each disc, kurtosis and skewness of the histogram were calculated and studied at every time instance for the matrices in unloaded and loaded state. The kurtosis and skewness for the histogram data from all discs at all time instances were evaluated separately. The result of the difference in kurtosis, as well as skewness, between the loaded and unloaded state was also studied.
3. Method
4

Results

4.1 Regional Analysis

An overall decrease of the T2 value during the day was seen in the discs for both regional analysis of subvolumes, Figure 4.1 - 4.2, and for the analysis of the whole discs, Figure 4.4 - 4.5. The effect of loading decreased during the day and the difference in the mean T2 value between unloaded and loaded state decreased for every time instance, Figure 4.3 and 4.6. The different subvolumes responded differently on loading depending on the position in the anterior-posterior direction.

The mean T2 value in the different subvolumes in the discs for unloaded state is shown in Figure 4.1. The average for all subvolumes, showed a small reduction of T2 value over the day. This trend for the average was also seen for the loaded state, Figure 4.2, and is evident in Figure 4.3.

Subvolume C and D had higher average in their mean T2-value in both unloaded and loaded state for all time instances compared to the other subvolumes. Subvolume B and E displayed the opposite pattern.

Figure 4.1: The mean T2 value of the different subvolumes for all discs in unloaded state for different time instances. The black solid line represents the average T2 values for all subvolumes and the colored dotted lines represents the mean T2 values for the subvolumes separately.
4. Results

Figure 4.2: The mean T2 value of the different subvolumes for all discs, in loaded state for different time instances. The black solid line represents the average T2 values for all subvolumes and the colored dotted lines represents the mean T2 values for the subvolumes separately.

Figure 4.3: Subtraction plot of the difference in the mean T2 values of the subvolumes between unloaded and loaded state for all discs for different time instances. The black solid line represents the average T2 values for all subvolumes and the colored dotted lines represents the mean T2 values for the subvolumes separately.
A decrease of the mean T2 value of the whole disc was shown for both unloaded, Figure 4.4, and loaded state, Figure 4.5. The average for all discs was higher for loaded state than for unloaded state. The subtraction plot in Figure 4.6 shows that the difference became smaller for every time instance. Disc 1 and disc 2 displayed the same pattern for the T2 value decrease over the day, as well as how the loading affects regarding the mean T2 value, see Figure 4.6. The mean T2 values for disc 5 were substantially lower for all time instances for unloaded as well as for loaded state, see Figure 4.4 and 4.5.

**Figure 4.4:** The mean T2 value of the lumbar discs in unloaded state for different time instances. The black solid line represents average T2 values for all discs and the colored dotted lines represents the mean T2 values for the discs separately.

**Figure 4.5:** The mean T2 value of lumbar discs in loaded state for different time instances. The black solid line represents the average T2 values for all discs and the colored dotted lines represents the mean T2 values for the discs separately.
4. Results

Figure 4.6: Subtraction plot of the difference in the mean T2 values of the lumbar discs between unloaded and loaded state for all discs for different time instances. The black solid line represents the average T2 values for all discs and the colored dotted lines represents the mean T2 values for the discs separately.
4. Results

4.2 Histogram Analysis

The histogram of all non-degenerated discs (disc 1-4) at all four time instances for both unloaded and loaded state can be seen in Figure 4.7. The corresponding histogram for the dehydrated disc (disc 5) can be seen in Figure 4.8. In both histograms, a difference between loaded and unloaded state appears. The hydrated discs displayed a wider distribution including higher T2 values than the dehydrated disc. The peak at lower T2 values is flattened as loading is applied and the slope becomes slightly reduced, i.e. a number of pixels was translated to a slightly larger T2 value. The skewness for all hydrated discs were 1.67 in unloaded state, and 1.72 in loaded state. For the dehydrated disc, the skewness was 1.37 in unloaded state, and 0.77 in loaded state.

![Figure 4.7](image_url)

**Figure 4.7:** The histogram of the T2-value distribution for all non-degenerated discs for all four time instances. The blue bars represent unloaded state and the red bars represent loaded state, while the black regions are where they overlap.

![Figure 4.8](image_url)

**Figure 4.8:** The histogram of the T2-value distribution for the dehydrated disc for all four time instances. The blue bars represent unloaded state and the red bars represent loaded state, while the black regions are where they overlap.
4. Results

4.2.1 Gaussian Two Peak-Fitting

For non-degenerated discs, two peaks could be detected in the histogram, shown in Figure 4.9. The number of bins was 35 which corresponds to a bin size of 14.25 ms. There was a difference of the area under the Gaussian two peak-fitting curves. The area beneath the first peak (the left in Figure 4.9) is smaller than the area beneath the second peak (the right in Figure 4.9).

![Figure 4.9: A histogram of the T2-value distribution with a two peak-Gaussian fitting applied on the third lumbar disc for the third time instance examination in loaded state.](image)
4. Results

4.2.2 Kurtosis and Skewness

The kurtosis plotted against time instance is displayed for unloaded respectively loaded state in Figure 4.10 and Figure 4.11. The kurtosis for disc 5 fluctuated significantly more compared to the other discs in the unloaded state. For the non-degenerated discs (disc 1-4) the kurtosis was more stable and varied less over the day. Less fluctuations of the kurtosis occurred over the day for the non-degenerated discs, but the average value was not significantly changed.

For disc 5, the fluctuations in kurtosis in loaded state over the day was smaller compared to the kurtosis in unloaded state for this disc. The subtraction plot between unloaded and loaded state, Figure 4.12, shows that the average for all discs was close to zero and that kurtosis for disc 5 shows great variation depending on time instance.

![Image of Figure 4.10](image-url)

**Figure 4.10:** The kurtosis for the discs for each time instance in unloaded state. The colored dotted lines represent the discs separately and the solid black line represents the average kurtosis for disc 1-4.
4. Results

**Figure 4.11:** The kurtosis for the discs for each time instance in loaded state. The colored dotted lines represent the discs separately and the solid black line represents the average kurtosis for disc 1-4.

**Figure 4.12:** Subtraction plot between the kurtosis for the discs for each time instance in unloaded state subtracted with the values for loaded state. The colored dotted lines represent the discs separately and the solid black line represents the average kurtosis for disc 1-4.

In Figure 4.13 the skewness of the histogram data of the discs is displayed, where skewness were plotted against time instance for unloaded state. The skewness for disc 5 fluctuated more than the skewness for disc 1-4. Disc 5 also experienced a lower skewness value compared to the other discs, in general. The non-degenerated discs (disc 1-4) were more stable in the skewness value and varies less over the day.
In Figure 4.14 the skewness was plotted against time instance in loaded state. For the non-degenerated discs, less fluctuations in the skewness value occurred for the different time instances in loaded state. The average value for disc 1-4 did not significantly changed from the average skewness value in the unloaded state.

For disc 5, a difference in skewness value from loaded state compared to unloaded state could be seen as less fluctuations for different time instances.

The subtraction plot, Figure 4.15, shows that the average for all discs were close to zero and that disc 5 showed great variation depending on time instance in unloaded state.

**Figure 4.13:** The skewness for the discs for each time instance in unloaded state. The colored dotted lines represent the discs separately and the solid black line represents the average skewness for disc 1-4.
4. Results

Figure 4.14: The skewness for the discs for each time instance in loaded state. The colored dotted lines represent the discs separately and the solid black line represents the average skewness for disc 1-4.

Figure 4.15: Subtraction plot between the skewness for the discs for each time instance in unloaded state subtracted with the values for loaded state. The colored dotted lines represent the discs separately and the solid black line represents the average skewness for disc 1-4.
5 Discussion

5.1 Spatial Analysis

The different subvolumes in the discs responded differently to loading regarding their T2 values. This indicates a redistribution of water molecules within the disc, where the T2 values get affected differently depending on how the molecules moved. Subvolume C-D had an overall higher mean T2 value, maybe due to the fact that NP is included in these VOIs. This, in turn, implies that NP is not centered in the disc but is positioned slightly more posteriorly. A decrease of the mean T2 value for the entire disc was shown over the day, in concordance with previous studies [4]. According to the subtraction plot of the mean T2 value for all discs in Figure 4.6, the response to the loading was decreased over the day. Some of the discs had a lower mean T2 value at the first time instance than for the following time instance. This effect was more distinct in unloaded state than in loaded state and could be the result from a transient loading effect from when the person got out of bed to upright standing position in the morning. This effect needs be statistically verified.

5.2 Histogram Analysis

The histogram in Figure 4.7 showed no clear difference between loaded and unloaded distribution of the higher T2 values. Pixels with lower T2 values, however, were affected by loading. The T2 values below 75 ms seemed to be the ones that are most affected by the axial load. Since these are non-degenerated discs, no great differences was expected. A non-degenerated disc does not have many fissures in the IVD where NP can leak into during the aMRI. However, there was a smoothing effect for the high frequency peak at low T2 values for the loaded state. This indicates that even non-degenerated discs experiences effects of loading and redistribution of T2 values. The corresponding histogram for the dehydrated disc, Figure 4.8, showed that there were almost no T2 values above 100 ms present. As loading was applied, the peak experienced a smoothing effect, causing a lower peak height and an increased peak width.
5. Discussion

5.2.1 Kurtosis and Skewness

The results seemed to be more stable on disc-level for all discs in the loaded state when analysing the kurtosis and skewness for the histogram of the T2-value distribution. In the evaluation of the non-degenerated discs, with the parameters kurtosis and skewness, it could be more relevant to focus on the lower T2 values of the histogram since it appears to be that part of the histogram where the loading affects the T2-value distribution.

5.3 The Effect of Loading

In this study, one focus was to determine what happens to the disc when the spine is axially loaded. The effect of loading is small and the difference between unloaded and loaded state, which was shown to fluctuate over the day, is not a promising parameter for evaluating discs since it is sensitive to the imaging in unloaded state and therefore affecting the result.

The imaging in unloaded state reflects the loading the spine has experienced during the day up until the moment of imaging, which could fluctuate a lot depending on what the person have done previously that day. This might be the reason why the results vary more in unloaded state compared to the results in loaded state, for both the regional analysis and the histogram analysis. When knowing more about how to interpret the results from the analysis and how the corresponding variables reacts in spectrum of different level of disc degeneration, it could be used as parameters to longitudinal follow up how the discs changes for patients with LBP.

5.4 Limitations

The feasibility study carried out in this Master’s thesis displays variation in response to loading as well as trends over the day, however, this must be statistically verified by increasing the sample size. Due to the small sample size of one control person, the trends found in this work could be pure statical variations in the measurements, and therefore fail to reflect actual behavior of the discs. To determine if the previously mentioned trends are reflections of a physiological behavior of the disc content or not, the analysis carried out in this thesis has to be done on a larger sample, consisting of control persons with discs of the same degeneration grades.

The uncertainty in the results is still unknown, and the variation of the signal-to-noise ratio (SNR) in the image is yet to be evaluated. Knowledge of the SNR variations could be useful since such a variation may influence the sensitivity of the analysis regarding the mean T2-values in the different subvolumes. The constancy of the measurement is yet to be investigated as well. Such an investigation could be done by repeating the same measurement several times in a row and scanning one control person repeatedly, while keeping the conditions unchanged.
Another limitation was the small range of disc degeneration. The healthy volunteer only had discs of Pfirrmann grade 2 and 4 [10]. The responses and trends seem to depend highly on the disc-status, and therefore it is of high interest to evaluate a broader range of disc-statuses, from non-degenerated to completely degenerated, with the purpose to evaluate how these parameters respond continuously.
5. Discussion
6 Conclusion

In this master thesis, lumbar discs were evaluated by creating several analysis tools in MATLAB for both regional and histogram analysis on T2-map images of the spine. The work concluded the following:

- Generally, the T2-value of the disc decreased over the day, where the decrease tend to be larger in the anterior subvolumes.
- There were modest differences in T2-value between unloaded and loaded state of the spine as well as in between the different time points during the day.
- Great differences in T2-value of the discs between hydrated and dehydrated discs were seen in both regional analysis and histogram analysis.
- For unloaded state of the spine, large variations in the T2-value of the disc and in the subvolumes of the discs were seen between different time points during the day, while smaller variations were seen for the loaded state. The same effect was seen in the histograms, where the kurtosis and skewness of the histograms varied less during the loaded state.
- Quantitative parameters from the analysis in this work can be useful for determine the level of disc degeneration since the parameters are continuous variables and therefore offers a more detailed division of discs-statuses.

Future work The results in this study need to be statistically verified in a larger study where a wider range of disc degeneration is included to get more knowledge of how the analysis works continually, from a non-degenerated disc to a degenerated disc. It is also of interest to do repeated measurements of the T2-map sequence at one time point to get a perception of how the measurement varies with unchanged conditions.
6. Conclusion
Bibliography
