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VENTILATION KINEMATICS OF ADULT PATIENTS WITH A MEDIAN STERNOTOMY INCISION FOLLOWING CARDIOTHORACIC SURGERY

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A research report submitted to the Faculty of Health Sciences, University of the Witwatersrand, Johannesburg, in fulfilment of the requirements for the degree of Master of Science in Physiotherapy

Johannesburg, 2020

DECLARATION

I, Cary-Anne Gissing, declare that this research is my own work. It is being submitted for a degree in the Master of Science in Physiotherapy at the University of the Witwatersrand in Johannesburg. This research report has not been submitted before for any degree or examination at this or any other institution.



Cary-Anne Gissing
19/06/2020

DEDICATION

"*We do not need magic to change the world, we carry all the power we need inside ourselves already; we have the power to imagine better"* – J.K. Rowling

To my patients, for their resilient fight.

To my family, "clean-family", friends and colleagues, for their continued support, endless love, motivation sessions and shaping me into the person I am today, thank you.

To Dad, you left us too soon, thank you for undeniable belief in me. Thank you for teaching me that education is the one thing nobody can take away from you.
"*To have been loved so deeply, even though the person who loved us is gone, will give us some protection forever"* – J.K. Rowling

To Tamar Reyneke, thank you that you believed in me in the times I didn't. Always.
"*After all this time? Always*." – J.K. Rowling

ABSTRACT

Introduction:

Cardiovascular diseases contribute significantly to the burden of diseases in South Africa and internationally. A standard intervention is open-heart surgery to repair and improve the functioning of the heart and a median sternotomy is the most commonly used incision during cardiothoracic surgery as it allows for optimal access to the heart and surrounding vessels. To date, few studies have described the effect of cardiothoracic surgery on ventilation kinematics as assessed by clinical bedside physiotherapy outcome measures.

Aim: The aim of this research was to determine the impact of a median sternotomy on the ventilation kinematics and to describe the changes from admission to discharge from hospital.

Methods:

A longitudinal observational study was conducted at a private hospital in Gauteng. Male and female patients undergoing elective cardiothoracic surgery between the ages of 18 to 70 years were consecutively sampled. Participants were assessed pre-operatively and again at hospital discharge. The demographic and clinical profile of study participants were determined. Ventilation kinematics were assessed by measuring upper and lower thoracic expansion and respiratory muscle strength (Maximum Inspiratory Pressure [MIP] and Peak Inspiratory Flow [PIF]). Lastly, it was determined whether a relationship exists between the ventilation kinematics and specific demographic and clinical variables. Analysis included descriptive statistics and the Shapiro-Wilks and Wilcoxon Signed-Rank Tests, Spearman's Rank-order and Pearson's Product-Moment correlations. Statistical significance was set at $p \leq 0.05$.

Results:

The study population consisted of 61 participants and most (n=35, 57%) underwent coronary artery bypass graft surgery with the mean amount of time spent in theatre being 5.85 (SD1.30) hours, median mechanical ventilation hours 17.33 (IQR 11.21) and median days in intensive care five (IQR 2.75). Forty-seven (77%) participants were male and seventeen (27%) females with a median age of 59 (IQR 22) years. The median length of stay in hospital was nine (IQR 7) days. All participants were independently mobile at hospital admission but 5 (8.2%) required a mobility aid for independent mobility at hospital discharge. There was a significant difference between upper thoracic and lower thoracic expansion between admission and discharge (Upper: 104.51cm vs 102.51cm; $p<0.001$, Lower: 100.03cm vs. 98.70cm, $p=0.0001$). There was a significant difference between MIP and PIF between admission and discharge (MIP: $55cmH_20$ vs $30.66cmH_20$, $p<0.001$; PIF: 2.70l/s vs. 1.66l/s, $p<0.001$). There was also a significant difference between the predicted MIP achieved between admission and discharge (%Pred MIP: $58.66cmH_20$ vs. $33.26cmH_20$, $p<0.001$). There was a significant difference between admission and discharge for VAS pain scores and chest X-ray total scores ($p<0.001$). Oxygen saturation ($p<0.001$), temperature ($p<0.001$) and diastolic blood pressure ($p=0.004$) were significantly different from admission to discharge from hospital. There was a fair

negative correlation between predicted MIP and age (r=-0.319, p=0.012). There was a fair positive correlation between lower thoracic expansion and age (r=0.286, p=0.031). There was a fair negative correlation between upper thoracic expansion and length of time intubated (r=-0.261, p=0.05). There was a fair negative correlation between MIP and PIF between chest X-ray scores at admission (PIF: r=-0.278, p=0.03; MIP: r=-0.356, p=0.004).

Conclusion

There is significant alteration that happens to the respiratory pump that affects ventilation kinematics following a median sternotomy incision during cardiothoracic surgery when changes are evaluated from admission to discharge. Physiotherapy practice should continue with postoperative care after hospital discharge considering the presence of respiratory muscles weakness and presence of mobility dysfunction.

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LIST OF ABBREVIATIONS

6MWT	- Six-Minute Walk Test
ACBT	- Active Cycle of Breathing Technique
BMI	- Body Mass Index
CABG	- Coronary Artery Bypass Grafting
COPD	- Chronic Obstructive Pulmonary Disease
CPB	- Cardiopulmonary Bypass
CVD	- Cardiovascular Disease
DBE'S	- Deep Breathing Exercises
ECMO	- Extracorporeal Membrane Oxygenation
FET	- Forced Expiratory Technique
FEV1	- Forced expiratory volume in one second
FVC	- Forced Vital Capacity
IABP	- Intra-aortic Balloon Pump
ICC	- Intra-class Correlation coefficient
IHD	- Ischaemic Heart Disease
IMA	- Internal Mammary Artery
IMT	- Inspiratory Muscle Training
IQR	- Interquartile Range
LOS	- Length of Stay
MIP	- Maximum Inspiratory Pressure
MEP	- Maximum Expiratory Pressure
MVV	- Maximum Voluntary Ventilation
PEFR	- Peak Expiratory Flow Rate
PEEP	- Positive End expiratory Pressure
PIF	- Peak Inspiratory Flow
PPC'S	- Postoperative Pulmonary Complications
PPD	- Post-operative Pulmonary Dysfunction
VAS	- Visual Analogue Scale
WHO	- World Health Organisation

CHAPTER 1

1. BACKGROUND AND NEED

1.1 INTRODUCTION

Cardiovascular disease (CVD) contributes significantly to the burden of disease in South Africa but also internationally. Cardiovascular disease has become one of the largest causes of non-communicable disease worldwide, causing over 50% of deaths (McAloon et al. 2016). The World Health Organization (WHO) estimated that over 17.6 million people died worldwide of CVD in 2012. This accounts for 31.3% of global mortality, with ischaemic heart disease (IHD) accounting for 7.4 million deaths (13.2%) (McAloon et al. 2016). In lower to middle income countries the global burden of CVD accounts for over 80% of deaths (Bowry et al. 2015). In 2015, there were an estimated 422.7 million cases of CVD and 17.92million CVD deaths. Ischaemic heart disease remained the leading cause of CVD globally, followed by strokes (Bowry et al. 2015).

In South Africa, diseases of the circulatory system accounted for 84315 (18,5%) of total deaths between 2014 and 2016. In 2016, other forms of heart disease (5,1%), hypertensive diseases (4,4%) and IHD (2,8%) were listed among the top ten causes of natural deaths in South Africa according to Statistics South Africa (Statistics South Africa, 2016). The WHO suggests that three times more deaths occur from CVH in low-income countries compared to those with high income. CVH affect males and females equally but occur mostly within the working class population (Bowry et al. 2015). Furthermore, the number of deaths caused by non-communicable diseases are expected to increase by 15% by 2020 (Bowry et al. 2015).

The primary prevention of CVD is lifestyle modification and in the event that this intervention is unsuccessful, surgery may be considered. Cardiothoracic surgery, including coronary artery bypass grafting (CABG) and valve replacements, are commonly used in the treatment of heart diseases. A median sternotomy is the most commonly used incision when undergoing cardiac surgery (Ther et al. 2011). This technique is most advantageous as it allows optimal access to the heart and its surrounding vessels. A median sternotomy involves using retractors to divide the sternum and manubrium centrally, the sternum is then closed using stainless steel wires (Cahalin et al. 2011). When no complications occur, the average the time spent under anaesthesia during open heart surgery can take four and a half hours (Dowling et al. 2003). Acute pain is common following cardiac surgery and often limit patients from participating in activities that can prevent postoperative complications. Pain has been described as the most intense during the first two days post-operatively and was significantly lower by day seven (Milgrom et al. 2004).

Multiple studies have indicated that post-operative pulmonary complications (PPCs) often develop in patients following cardiothoracic surgery. Post-operative pulmonary complications are widely documented, an estimated 230 major surgical procedures occur worldwide every year, where the incidence of PPCs range from 1% to 23%. Postoperative pulmonary complications include respiratory infection, respiratory failure, pleural effusion, atelectasis, pneumothorax, bronchospasm and aspiration pneumonitis (Miskovic & Lumb, 2017). These complications include changes in respiratory symptoms such as cough frequency, sputum production, dyspnoea level and experience of chest tightness e.g. wheeze (Miskovic & Lumb, 2017).

Ventilation is described as the movement of air into and out of the lungs (Wilkins, Stoller & Kacmarek, 2009). During inspiration, a muscular effort is required to overcome lung and chest wall compliance and airway resistance to ensure the thoracic cavity enlarges for lung expansion to occur (Wilkins, Stoller & Kacmarek, 2009). Expiration is generally a passive process which involves the relaxation of the inspiratory muscles during which the thoracic cage recoils (Wilkins, Stoller & Kacmarek, 2009). The process of ventilation is thus dependent on the 'respiratory pump': contraction of muscles of ventilation, movement of the rib cage (ribs and sternum) and mobility in the thoracic spine (Norkin & Levangie, 1992). Biomechanics is the study of mechanics of the human body and can include two concepts: kinematics and kinetics (Norkin & Levangie, 1992). A kinematic analysis describes the position and displacement of a segment during movement (Norkin & Levangie, 1992). Ventilation kinematics can thus be defined as the changes observed in the 'respiratory pump' during ventilation. Therefore, once a component of the 'respiratory pump' of normal ventilation kinematics is injured or altered, an altered breathing pattern can be expected.

To date, few studies have reported on the effect of cardiothoracic surgery on ventilation kinematics and/or PPCs. Ragnarsdottir et al. (2004) showed that bilateral abdominal respiratory movements and lung volumes three months post-operatively were still decreased in patients when an internal mammary artery retractor was used during surgery. Authors noted that these changes could be due to an injury to the ribcage and diaphragm muscle (Ragnarsdottir et al. 2004). Kristjansdottir et al. (2004b) additionally reported that patients who had a median sternotomy often still presented with a restrictive type of breathing pattern three months following surgery and this was attributed to injury suffered by the motor system of the respiratory organs (Kristjansdottir, et al. 2004b). Morsch et al. (2009) noted that patients had a significant reduction in pulmonary volume and capacity as well as decreased ventilatory muscle strength during the postoperative period. Locke et al. (1990) examined participants pre-operatively and three months post-operatively. They found all patients presented with a reduction in lung volume as well as dysfunction between airflow and rib

cage motion in more than one plane of movement. This finding was still present three months post-operatively. This study further supported the findings of restrictive ventilator patterns as it proved uncoordinated and reduced rib cage motion (Locke et al. 1990).

Physiotherapy forms an important part of the management of patients following cardiothoracic surgery as it can address certain PPCs. The main aim of post-operative physiotherapy is to restore the normal functional abilities of the patient and to achieve appropriate levels of physical activity post discharge (Hirschhorn et al. 2012). Current physiotherapy management includes deep breathing exercises, inspiratory muscle training, manual chest clearing techniques, intermittent positive pressure breathing to prevent post-operative atelectasis, pneumonia and improve pulmonary function (Westerdahl et al. 2005; Westerdahl et al. 2009; Hermes et al. 2015). Early rehabilitation after cardiac surgery has been proven to significantly improve the functional outcomes of patients (Dong et al. 2016). Rehabilitation following surgery can include early mobilization (including sitting, sitting in a chair, walking on the spot and distance walking), aerobic exercises and resistance training to improve the functional ability of the patient (Kirkeby-Garstad et al. 2006; Hirschhorn et al. 2012).

1.2 PROBLEM STATEMENT

To date, there are no clear studies that have determined the effect of a median sternotomy incision on the ventilation kinematics defined by chest wall expansion (movement of the rib cage) and inspiratory respiratory muscle strength of adult patients following cardiothoracic surgery. The relationship between possible ventilation kinematics alteration of such patients and their demographic and clinical profiles is also unknown. The implication of potentially altered ventilation kinematics following cardiothoracic surgery on clinical practice needs to be explored.

1.3 RESEARCH QUESTION

What is the impact of a median sternotomy incision on the ventilation kinematics of adult patients following cardiothoracic surgery?

1.4 AIM OF RESEARCH

To determine the impact of a median sternotomy incision on the ventilation kinematics of adult patients following cardiothoracic surgery.

1.4.1 Objectives of Research

The objectives of the study are:

- To determine the demographic profiles, including gender, age and physical activity, of adult patients undergoing cardiothoracic surgery via median sternotomy incision.

- To determine the clinical profiles of adult patient undergoing cardiothoracic surgery via a median sternotomy incision (Length of stay (LOS) in intensive care unit (ICU), LOS in ward, LOS in theatre, number of hospital days, pain level, chest X-ray score.)
- To determine the effects of a median sternotomy on ventilation kinematics of adult patients by determining their chest wall expansion and inspiratory respiratory muscle strength pre-operatively and at hospital discharge and establish the change that occurred in these parameters.
- To determine if a relationship exists between the ventilation kinematics and the demographic and clinical profiles of adult patients following a median sternotomy incision in cardiothoracic surgery.

1.5 SIGNIFICANCE OF RESEARCH

This study may determine the effects of a median sternotomy on ventilation kinematics and may improve our understanding and knowledge of how patients present clinically. This study may also indicate any clinical correlations that may exist between ventilation kinematics and the demographic and clinical profiles of adult patients following a median sternotomy incision. This may allow us to identify risk factors and early complications pre- and post-operatively and determine a pattern in the clinical profiles of patients undergoing cardiac surgery.

Chapter two consists of a discussion of the literature on the normal ventilation kinematics, assessment of ventilation kinematics, the procedure, closure and complications of a median sternotomy, the changes in ventilation kinematics following a median sternotomy and the role of physiotherapy addressing the changes in ventilation kinematics.

CHAPTER 2

2. LITERATURE REVIEW

2.1 INTRODUCTION

The following sources were used to collect the literature included in this review; Google Scholar, Elsevier, Pubmed, Cochrane and EBSCO host.

The keywords used during this strategy were: “ventilation” “normal ventilation” “anatomy” “chest wall” “chest wall movement” “thoracic biomechanics” “respiratory muscles” “respiratory muscle function” “ventilation abnormalities” “ventilation kinematics” “post-operative pulmonary complications” “thoracic movement” “thoracic expansion” “cardiac surgery” “coronary artery bypass graft surgery” “median sternotomy” “median sternotomy technique” “median sternotomy procedure” “median sternotomy closure” “complications median sternotomy” “risk factors” “sternal complications” “sternal precautions” “sternotomy precautions” “movement assessment thoracic cage” “maximum inspiratory pressure” “peak inspiratory flow” “respiratory muscle strength” “predicted maximum inspiratory pressure” “ventilation changes” “spirometry changes” “physiotherapy” “deep breathing exercises” “physiotherapy post cardiac surgery” “cardiac rehabilitation” “inpatient cardiac rehabilitation”

The literature discussed in this chapter is structured under the following main headings to provide the background to the study:

2.2. Ventilation Kinematics.
2.3. Median Sternotomy.
2.4. Ventilation kinematic changes following a median sternotomy.
2.4. Role of physiotherapy in addressing ventilation kinematics following a median sternotomy procedure.

2.2 VENTILATION KINEMATICS

Ventilation can be described as the process of moving air in and out of the lungs (Kacmarek et al. 2017). Ventilation occurs as a cyclic activity that consists of an active inspiratory phase and a passive expiratory phase during relaxed breathing (Kacmarek et al. 2017). The process of ventilation is dependent on the ‘respiratory pump’: contraction of muscles of ventilation and movement of the rib cage (ribs and sternum) (Norkin & Levangie, 2011). Ventilation kinematics can thus be defined as the changes observed in the ‘respiratory pump’ during ventilation.

Ventilation kinematics change during physical activity and exercise to adapt to the increase in energy demand. During most exercise or increased workload situations, an increase in energy demand requires an increase in the availability of oxygen to provide aerobic energy production. To adapt to these changes, pulmonary ventilation increases by increasing the frequency of breathing and therefor the pulmonary minute ventilation and tidal volume increases gradually (Plowman & Smith, 2014).

2.2.1 **Movement of the Thoracic Cage**

The thoracic cage consists of various anatomical structures that contribute to its function. These structures include: the bony thoracic girdle consisting of the sternum anteriorly, attached to the clavicles via the manubrium of the sternum superiorly, with the ribs attaching onto the sternum anteriorly spanning around in a circular manner to attach to the thoracic vertebrae posteriorly (Moore et al. 2010). To induce movement of the bony structures, the muscles of respiration further encircle and attach the thoracic cage to various structures above and below to ensure multiple planes of movement (Moore et al. 2010; Main & Denehy, 2016).

The thoracic cage consists of 12 pairs of ribs. Ribs 1-7 are true ribs as they attach directly on to the sternum anteriorly. Ribs 8-12 are false ribs as they indirectly attach to the sternum or not at all (Moore et al. 2010). Ribs 8,9,10 attach to the sternum via a common cartilaginous strap, while ribs 11 and 12 are floating ribs as they have no attachment to the sternum (Moore et al. 2010). Structurally each rib contains a sternal end, a long curved flat body and a head attaching to the thoracic spine (Moore et al. 2010; Main & Denehy, 2016). Ribs biomechanically can rotate around two axis. Firstly, ribs 2-5 rotate around the axis of their neck causing their sternal end to rise and fall (Moore et al. 2010). This increases the antero-posterior diameter of the chest demonstrating the same action as a “pump-handle” (Main & Denehy, 2016; Kacmarek et al. 2017). Simultaneously, the ribs move around their axis from their angle at the sternum causing the middle part to move upwards and outwards, simulating a bucket-handle effect (Main & Denehy, 2016). Ribs 6-7 are capable of both movements, where-as ribs 8-10 will increase the transverse diameter of the chest. Ribs 11-12 are minimally involved in changing the diameter of the thorax as they have no anterior attachment to the sternum (Moore et al. 2010; Main & Denehy, 2016).

The thoracic cavity consists of multiple joints, each joint only allowing for small ranges of movement and are critical in allowing normal movement during ventilation. Consequently, any disturbance in the mobility of these joints may influence normal ventilation. Posteriorly, the thoracic cage attaches to the spine via the costovertebral joints (Moore et al. 2010). A typical rib will span from anterior to posterior attaching to the vertebral column via two joints, namely the joints of the heads and the costovertebral joints (Moore et al. 2010; Main &

Denehy, 2016). The head of the rib will articulate with the superior costal facet of the same vertebra, the inferior costal facet of the vertebra superior to it as well as the intervertebral disc (Moore et al. 2010). Multiple ligaments and connective tissue span this joint, only slight gliding movements occur at the facets, more movement may cause a large excursion of the sternal end of a rib (Moore et al. 2010). The costotransverse joint is located posteriorly where the transverse process of the same rib is met by the tubercle of the rib (Moore et al. 2010; Kacmarek et al. 2017). Anatomically, the superior six ribs have convex surfaces on their tubercles, therefore rotation occurs mostly around a transverse axis (Kacmarek et al. 2017). This allows for elevation and depression of the sternal end of the ribs and the sternum in the sagittal plane, therefore causing a pump handle movement, as previously stated (Kacmarek et al. 2017). Ribs 7-10 have more flattened tubercles that articulate with flattened transverse processes which allow for gliding movements. This results in the action of a bucket-handle movement causing the most lateral part of the rib to elevate or depress in the transverse plane (Kacmarek et al. 2017).

Inflation and deflation of the lungs resultantly occur from changes of the dimensions of the chest wall/ thoracic cage (Kacmarek et al. 2017; Main & Denehy, 2016).

2.2.2 Role of the Respiratory Muscles during Ventilation Kinematics

Changes in the thoracic cavity dimensions during normal ventilation are due to the tension developed by the muscles of ventilation (Main & Denehy, 2016). The diaphragm and intercostal muscles are the primary muscles of ventilation (Main & Denehy, 2016; Kacmarek et al. 2017). The diaphragm is a large, dome-shaped muscle that contains three sets of muscle fibres. The sternal fibres originate on the posterior surface of the xiphoid process, the fibres run upwards and medially and insert onto the anterior border of its central tendon (Main & Denehy 2016). The costal fibres are attached to the inner surface of the lower six ribs and their costal cartilages (Main & Denehy, 2016). The costal fibres make up the bulk majority of the diaphragm and run upwards and medially where they attach onto the anterolateral part of the central tendon (Main & Denehy, 2016; Kacmarek et al. 2017). The lumbar fibres are divided into two crura where they originate on the anterolateral vertebral bodies and intervertebral discs of L1-3 (Main & Denehy, 2016). The left and right crural fibres arch to form the median arcuate ligament and insert onto the central tendon (Main & Denehy, 2016). During normal inspiration the diaphragm moves inferiorly increasing the vertical diameter of the chest during normal tidal breathing (Main & Denehy, 2016; Kacmarek et al. 2017). With deep inspiratory efforts the diaphragm contracts around a central fixed point, causing it to move the ribs upward and outwards and causing forward movement of the sternum (Main & Denehy, 2016; Kacmarek et al. 2017).

The intercostal muscles that encircle the thoracic cavity span the distance between the superior and inferior ribs. They are further divided into three muscular layers. The external intercostals forming the outer layer, they attach the inferior border of the rib above to the superior border of the rib below (Moore et al. 2010; Main & Denehy, 2016). The external intercostals cause the simulation of the pump and bucket handle movement as they are able to pull the rib below to the rib above (Main & Denehy, 2016). The second layer compromises of the internal intercostals and play a bigger role as muscles of expiration. Contraction of these muscles as a unit have the ability to draw the ribs together and depress the rib cage with a forced expiration (Main & Denehy, 2016). The deepest layer is formed by the innermost intercostals (Moore et al. 2010), they play a larger role in the stability of the chest wall (Main & Denehy, 2016). They prevent the intercostal spaces from being drawn in during inspiration and being pushed out laterally during expiration (Moore et al. 2010). Accessory muscles of respiration are activated when a larger inspiratory effort is required.

Therefore, once a component of the 'respiratory pump' of normal ventilation kinematics is injured or altered, an altered type of breathing pattern can be expected.

2.2.3 **Assessment of Ventilation Kinematics**

2.2.3.1 **Movement assessment of the thoracic cage**

Assessing the movement or mobility of the thoracic cage can be useful in determining either thoracic mobility or chest expansion. Measurements of chest wall motion can be a useful tool to assess respiratory airflow and volume changes via a non-invasive technique, monitor breathing changes over a long period of time and to identify patterns of chest wall movement in different segments of the chest wall (Seddon, 2015). Thoracic or chest expansion is used by physiotherapists in a variety of different conditions including asthma, chronic obstructive pulmonary disease (COPD), thoracic scoliosis, ankylosing spondylitis, impaired pulmonary function, dyspnoea, decreased exercise tolerance, following thoracic surgery or trauma caused to the thorax and rib cage (Olsén et al. 2011; Debouche et al. 2016). In clinical practise there are different methods to assess thoracic mobility, these can include the Respiratory Movement Measuring Instrument, inductive or opto-electronic plethysmography, compute tomography, video systems for movement and a cloth tape measure (Olsén et al. 2011).

Physiotherapists often use a cloth tape measure for evaluation and treatment purposes, this method offers a simple, quick, inexpensive, valuable and reproducible way to assess thoracic excursion (Olsén et al. 2011; Debouche et al. 2016). This technique uses the tape measure to measure the circumference around the chest or thorax using specific landmarks during maximal inspiration and maximal expiration (Bockenhauer et al. 2007; Debouche et al. 2016). Multiple landmarks have been previously described to measure chest expansion, the two

most recent frequently used and described landmarks use the upper and lower anatomical markers. The upper anatomical markers include the third intercostal space in the middle of the clavicular line and the spinous process of the fifth thoracic vertebrae posteriorly, the lower anatomical landmarks include the xiphoid process anteriorly and the spinous process of the tenth thoracic vertebrae posteriorly (Bockenhauer et al. 2007; Olsén et al. 2011; Debouche et al. 2016). Different positioning for evaluations have been used in different studies, Olsen et al. (2011) placed subjects in a standing position with their arms raised above their head for assessment purposes. Bockenhauer et al. (2007) and Mohan et al. (2012) both assessed their control group in a standing position with their arms placed next to their sides (Bockenhauer et al. 2007; Olsén et al. 2011; Mohan et al. 2012).

While assessing most authors chose to use a “cross-over” technique, the cloth tape measure is held tightly and the tape is crossed by crossing one’s hands, ensuring the tape is kept flat against the subject’s skin. The instructions given to the patient have recently been found to be more effective to use “breathe in as deeply as possible and make yourself as big as possible” for inspiration and “breathe out as deeply as possible and make yourself as small as possible” for expiration (Olsén et al. 2011). Using these specific instructions were proven to measure the maximal range of motion of the thorax. Olsen et al. (2011) proved that when comparing the two different instructions, there was a significant difference of 0.9 – 1.4cm at both thoracic levels ($p<0.001$) (Olsén et al. 2011).

Multiple authors have proved that using a cloth tape measure for assessing chest expansion is reliable and can be used as an effective outcome measure. Bockenhauer et al. (2007) proved that using a cloth tape measure had a intraclass correlation coefficient (ICC) for measuring thoracic excursion ranged from 0.81 to 0.91 (95% CI, 0.69-0.99) (Bockenhauer et al. 2007). Mohan et al. (2012) had similar results with ICC ranges of between 0.95 to 0.97 measuring thoracic excursion at three different levels (Mohan et al. 2012). The total chest expansion or thoracic excursion is calculated by the difference of the value of maximal inspiration and maximal expiration (Debouche et al. 2016).

Chest expansion and thoracic cage mobility may vary in different populations, the normal ranges are between four to seven centimetres in healthy subjects. The normal range of chest expansion tends to decline with age (decline of up to 50% to 60% between the ages of 15 and 75 years) and tend to be 20% greater in men (Debouche et al. 2016).

2.2.3.2 **Assessment of Respiratory Muscle Strength**

Impairment in the respiratory muscles has the ability to compromise ventilation, gas exchange and oxygen delivery to tissues. The most frequently used test to assess respiratory muscle strength at the bedside include maximum inspiratory pressure (MIP), maximum

expiratory pressure (MEP), forced vital capacity (FVC) and maximum voluntary ventilation (MVV) (Kacmarek et al. 2017). Maximum inspiratory pressure can be measured invasively and non-invasively. Non-invasive measures can either be measured at the mouth or via nasal pressure, they are frequently used as a quick and reliable bedside assessments that can be reproduced and is widely accepted.

Maximum inspiratory pressure is there for an inexpensive and simple clinical measurement that can be used to assess respiratory muscle strength, including the diaphragm, abdominal, intercostal and accessory muscles. Maximum inspiratory pressure is not routinely tested during pulmonary function testing, but may be indicated when respiratory muscle weakness is suspected to be a cause of abnormal respiratory mechanics (Jalan et al. 2015). Maximum inspiratory pressure is frequently assessed in patients with neuromuscular disease (Myasthenia Gravis, Guillain-Barre syndrome, amyotrophic lateral sclerosis, stroke, polio or quadriplegia). In addition this assessment is also done to monitor rapid loss of inspiratory muscle strength or to follow the progress of patients suffering from chronic diseases (COPD, Asthma or muscular dystrophy) and lastly to detect muscle weakness in high risk patients e.g. critical care survivors (Jalan et al. 2015).

Maximum inspiratory pressure can be defined as the greatest sub-atmospheric pressure that can be generated against an occluded mouthpiece during maximal inspiration. This can be defined as the Muller manoeuvre (Minahan et al. 2015). It is started with forced expiration and then followed by an attempt at full inspiration with the mouth and the nose closed, this causes the pressure to become more negative in the chest and lungs (Lee et al. 2016). The MIP is the ability of the respiratory muscles to work synergistically to produce a volitional force output, it is an established and reliable outcome of global respiratory muscle strength (Caruso et al. 2015).

Peak inspiratory flow (PIF) can be defined as the maximal amount of flow achievable from a maximal inspiratory effort starting from full expiration. Peak inspiratory flow is dependent on two characteristics, namely the strength of the respiratory muscles and the airway resistance of a patient. This measure is partially dependent on the ability and the strength of the inspiratory muscles to shorten to facilitate a maximal inspiratory effort (Lee et al. 2016).

Multiple threshold devises are available to test respiratory muscle strength, the measurements can be made with an analogue or digital manometer. The POWERbreathe device is an example of a digital manometer. The POWERbreathe device is a threshold inspiratory muscle training device that originated in the United Kingdom, it is widely available internationally via the internet (Hart et al. 2001). This device is able to provide instant automatically processed information on inspiratory muscle strength (including MIP and PIF)

(Lee et al. 2016). It is recommended for testing purposes that patients are seated comfortably in a chair with their feet supported on the ground, with their back supported and an angle of 90 degrees between the hips and trunk (Lee et al. 2016). Participants are then instructed to perform maximal inspiration against an obstructed mouthpiece at near residual volume, a pressure that is sustained for 2-3 seconds can be recorded (Lee et al. 2016). To minimize an air leak during the technique a conventional mouthpiece and nose clip can be used. It is suggested that participants should be allowed two trial attempts and an average of three attempts should be recorded. Lee et al. (2016) have proved that measuring different pulmonary variables with a POWERbreathe device in stroke patients showed to have good intra- and inter-examiner reliability (Lee et al. 2016). The POWERbreathe device has been used safely in patient's undergoing cardiac surgery by Turky & Afify (2016), although the device was used as a treatment modality, no adverse effects or negative comments were made (Turky & Afify, 2016).

During a study performed by Langer et al. (2015), they measured the validity of an electronic inspiratory loading device during a loaded breathing task in patients with COPD, it was compared to an external laboratory system that was used as "gold standard". They successfully concluded that the device is able to provide automatically processed and valid estimates of physical units of energy during any loaded breathing task (ICC 0.97 for average mean inspiratory power, 0.98 for average mean pressure, 0.98 for average duty cycle and 0.99 for total work, al $p<0.0001$.)

The POWERbreathe device has been used in other various conditions. Langer et al. (2015) used the POWERbreathe device to study the effects of a short home-based inspiratory muscle training (IMT) program in patients with COPD. They showed that this population group benefitted by showing significant improvements in inspiratory muscle strength and endurance. Further research uses the POWERbreathe device in a large mulit-centered randomised control trial for COPD patients as it applies a variable resistance that is controlled by an electronic valve. They suggest that when compared to traditional threshold loading devices, the POWERbreathe device is able to offer variable flow resistive load and is specifically challenging for inspiratory muscles at higher lung volumes, thus adding the potential of greater training effects in patients. Another added benefit of this device used in both studies, that it is able to store home-based training data for up to 40 sessions. This is specifically important for home-based programs and essential continuation of care (Charususin et al. 2013).

2.3 MEDIAN STERNOTOMY

2.3.1 Definition, Indication and Uses of a Median Sternotomy

Open heart surgery can be defined as the operative procedure that is performed on an exposed heart with a retracted chest, and commonly requires the use of cardiopulmonary

bypass. Open heart surgery still uses the standard surgical approach, namely a median sternotomy (Main & Denehy, 2016). A median sternotomy can be defined as a surgical incision, involving both tissue and bone, where a midline incision is made anteriorly to expose the heart via sternal retractors (Oda, 2010). The incision is commonly used for CABG, valve replacements, limited pulmonary surgeries, tumor resections (McGregor et al. 2003) and more recently thyroidectomies (deep retrosternal goiter) (Ahmed et al. 2006). Although many techniques have evolved allowing minimally invasive cardiac surgeries, the median sternotomy is still favoured worldwide as it allows optimal visualization during surgery (McGregor et al. 2003). This allows for safe central cannulisation for cardiopulmonary bypass and has been well tolerated by a large population group (McGregor et al. 2003).

Cardiopulmonary bypass (CPB) is a type of extracorporeal circulation used when performing surgery of the heart or great vessels and is used as it maintains circulatory and respiratory support as well as temperature management. During CPB venous blood is drained from the heart via cannulas into a reservoir. A pump moves the blood to an oxygenator via a heat exchanger after which it is returned to arterial circulation. Blood is oxygenated via a membrane oxygenator that is responsible to maintain adequate saturation levels to perfuse vital organs. For intra-cardiac repair, the aorta is cross-clamped to cause an ischaemic heart, this is called cardioplegia. Cardioplegia is necessary for myocardial protection, as it reduces myocardial oxygen consumption (Sarkar & Prabhu, 2017).

Before closure of the sternum, CPB is weaned and the heart starts to take over normal circulation again. During this phase, mechanical ventilation is started via a ventilator. Cardiopulmonary bypass is weaned when the perfusionist gradually occludes venous return, filling the heart and reducing pump flows. Failure to wean of CPB during surgery may need the assistance of further mechanical support devices, ranging from intra-aortic balloon pump (IABP), ventricular assist devices or extracorporeal membranous oxygenators (ECMO) (Sarkar & Prabhu, 2017)

2.3.2 **Procedure of a Median Sternotomy**

The procedure of a median sternotomy involves the patient being placed in a supine position with arms placed laterally next to their sides (Oda, 2010). An incision is made 2cm below the sternal notch travelling downward 3cm below the xiphoid process (Oda, 2010). An incision is then performed on the midline of the sternum, the lateral margins of the sternum are first identified by palpation of the intercostal spaces laterally. An oscillating saw is used to gain access through the sternum, once the sternum is halved, a sternal retractor is place and the ribs are spread laterally and posteriorly (Oda, 2010; Main & Denehy, 2016). Once the sternum has been successfully retracted, the patient can be placed on cardiopulmonary bypass. Before closure of the chest is performed, the patient is rewarmed and sinus rhythm

is restored. Depending on the nature of the surgery, pleural and or mediastinal drains are inserted via stab incisions inferior and laterally to the median sternotomy (Main & Denehy, 2016).

The length of a procedure typically depends on the complexity of the surgery required. A CABG procedure usually takes between 2-3 hours compared to an aortic or mitral valve replacement requiring more than 3 hours with a minimum of 80 minutes of cardiopulmonary bypass (Main & Denehy, 2016). Patients are therefore placed in a specific sustained position during surgery with increased strain placed on the back, chest, neck and shoulders due to sternal retraction, this has the potential to lead to musculoskeletal and neurological implications.

2.3.3 **Closure of the Sternum**

The process of closing the sternum after cardiac surgery is crucial for the recovery of the patient. Unlike other fractures, the sternum is unable to be completely immobilised. It is constantly challenged by movement from the thoracic cage during breathing, increased intrathoracic pressure during coughing and sneezing as well as upper limb movements. This directly affects the healing ability, especially in high-risk patients (Allen et al. 2017).

The standard sternal closure is attained by the use of stainless steel wires, they are commonly used as they are cost effective and have a low rate of sternal complications (Cataneoa et al. 2019). The amount of wires used may vary according to the surgeon's preference and the amount of risk factors the patient has for sternal instability. The amount of wires can range from four to eight wires. According to a review by Cataneoa et al. 2019, many authors believe that at least six or more wires should be used standardly and eight or more in high-risk patients. The more wires used causes better distribution of forces acting on each wire and decreases pressure on an individual wire. Better force distributions can decrease the amount of sternal cutting and fractures caused by wires during activities that cause increased intrathoracic pressure such as coughing (Cataneoa et al. 2019).

Multiple techniques have been developed clinically for adequate closure, these include transsternal, peristernal, figure of eight and a combination of sutures (Losanoff et al. 2004; Schimmer et al. 2006; Schimmer et al. 2008). Sharjeel et al. (2017) proposed that figure of eight sternal steel wires decrease the incidence of sternal instability as they distribute shear stress over a greater area. They also reduce lateral and longitudinal stress more effectively (Sharjeel et al. 2017). Single wire fixation has however found to be better tolerated when subjective pain levels were measured at 14 and 30 days post CABG when compared to using figure of eight or combination wiring. Lower pain levels can lead to faster rehabilitation and increased quality of life post-surgery (Kukulski et al. 2018).

Before the wires are set, adequate alignment of the sternum is crucial. For successful osteotomy and fracture management, bony approximation, compression and stabilization of the fracture site is necessary. Approximation and rigid fixation are necessary for the formation of good bony union. This is essential for the formation of blood vessels to carry nutrients to the injury site to initiate the repair process (Elghonemy & Hussein, 2016). Sternal approximation is obtained by twisting or crimping the wires until an optimal level of tension is felt by the surgeon (Losanoff et al. 2016). Rigid sternal closure decreases the probability of haematoma formation in peri-sternal tissue, decreasing the risk of bleeding, infection and the need for re-look sternotomy (Randecker 2005). There are many complications that can arise from poor sternal closure, these include sternal instability, sternal dehiscence, osteomyelitis, mediastinitis as well as deep and superficial sternal wound infections (Elsaify et al. 2019).

Other sternal fixation techniques have been developed that are used for rigid fixation to decrease the amount of sternal separation or dehiscence. These include titanium plates, hooks and cables; thermal-reactive nitinol clips; flat wire sternal closure systems and plastic zip-tie based systems. These techniques are not always used due to their increased cost and prolonged surgery time (Cataneoa et al. 2019).

Some of these techniques are based on fracture management from elsewhere in the body and try to attain better rigid fixation. During a randomised control trial by Allen et al. (2017), they proved that rigid plate fixation (titanium plates) had better sternal healing scores at three and six months post-operatively ($P < .0001$ & $P < .0007$). The study also proved greater sternal union rates at three and six months (41% vs 16%, $P < .0001$) (80% vs 67%, $P = 0.03$), fewer sternal complications throughout six months as well as significantly less pain sensation with fewer use of narcotics (Allen et al. 2017). The consensus is that rigid plate fixation may enhance sternal stabilization and can reduce the risk of sternal infections, especially in high-risk patients. However, during a systematic review and meta-analysis performed by Cataneo et al. (2019) they concluded that there was only moderate evidence to show that new sternal closure methods make little to no difference compared to standard closure methods (Cataneoa et al. 2019).

2.3.4 **Complications Following a Median Sternotomy**

Complications following a median sternotomy occur in 1-5% of cases, although it occurs infrequently these complications are associated with a high morbidity and mortality rate (10-40%) (Brocki et al. 2010; Bek et al. 2010). Complications may vary between sternal instability, sternal dehiscence, non-union and infections. Instability and non-union of the sternum post-surgery compromises wound integrity and may increase the risk of bacterial infections (Losanoff et al. 2002). Infections can vary between superficial infections, deep wound

dehiscence and mediastinitis. Most infections are late onset and occur most frequently after more than two weeks of discharge (Douville et al. 2004).

Common risk factors that have been described that increase the risk of sternal complications include prolonged surgery time, the use of mammary arteries, re-operations for bleeding, prolonged mechanical ventilation, age (> 75 years), history of osteoporosis, obesity (body mass index >30) and hospital-acquired pneumonia as well as COPD (Careaga et al. 2010; Bek et al. 2010). Sternal complications are commonly associated with extended hospitalizations, prolonged use of antibiotics, high costs, multiple operative procedures and prolonged pain (Douville et al. 2004).

Post-operative pain is an unavoidable complication of a median sternotomy due to the nature of the procedure. Patients experience acute pain immediately post-operatively that is treated with adequate pain control measures. Musculoskeletal complications occur due to the nature of the surgery, some patients may experience shoulder, chest and upper limb pain for up until three months post-surgery (Bellet et al. 2017). Non-neuropathic pain is frequently contributed to tissue damage and may be caused by a thermal, chemical or mechanical nature during surgery. Non-neuropathic pain generally subsides as the injured tissues start to heal (Markman et al. 2010). Normal healing of the skin and incision site generally occurs within 10 days post-operatively (Lorenz & Longaker, 2008). Normal sternal/bone healing occurs within 28-35 days post-operatively, but may vary according to patient and surgery related conditions (Brocki et al. 2010).

Patients that experience non-anginal type pain post-operatively for more than three months can be classified to have chronic post-sternotomy pain. This can occur between 11% and 56% of patients at one year post-operatively, with patients describing their pain to decrease over time. Chronic post sternotomy pain has variable presentations and may have multiple sites, but predominantly affects the thorax. This pain may affect the thorax, which can be divided into three different sites including anterior chest pain on the left side, midline scar pain or right sided chest wall pain. This pain can also affect the upper and lower extremities as well as the neck and the back (Meyerson et al. 2001).

Chronic post-sternotomy pain is said to be caused by the up-regulation, activation and neural sensitization during the acute pain phase. Aggravating factors normally include pressure at the wound site, clothes rubbing against the wound, any movement, deep breathing and coughing, changes in weather and temperature as well as personal stress. Many causes have been speculated to cause pain post-operatively. Persistent neuropathic pain can be caused by entrapment of the anterior intercostal nerve or injury caused by mammillary artery harvest (Mazzeffi & Khelemsky 2011). Patients may experience a neuropathic or dysesthesia

type pain causing areas of numbness and/or hypersensitivity predominantly on the anterior chest wall (Markman et al. 2010). This pain is commonly caused by an injury or trauma to the intercostal nerves during the grafting of the internal mammillary arteries, the nature of the injury may be mechanical, ischaemic or thermal (Markman et al. 2010).

Sternal arthritis or hypersensitivity caused by sternal wires may also lead to chronic pain (Mazzeffi & Khelemsky, 2011; Abo El Nasr & Taha, 2017a). Sternal and rib fractures are a common complication during cardiac surgery due to sternal retraction. Rib fractures occur in 5% of patients and occur mainly in the upper thorax. This pain may refer into arm or neck and mimic angina type pain (Mazzeffi & Khelemsky, 2011). The first rib is the most frequent fracture, if displaced posteriorly during surgery it may further cause a brachial plexus injury. If the brachial plexus is involved, it commonly affects the C8-T1 nerve roots, this can in turn cause pain, dysthesia and hand weakness (Mazzeffi & Khelemsky, 2011). A brachial plexus injury can also occur due to traction or compression of the nerve roots between the clavicle and the first rib. Deep wound infections and non-union of the sternum may also predispose a patient to develop chronic sternotomy pain. Due to prolonged inflammatory changes in the area after deep wounds infections, it may lead to chronic tissue damage, wound dehiscence and scarring (Mazzeffi & Khelemsky, 2011). With non-union of the sternum, patients typically report pain, popping or grinding of the sternum that effects activities of daily living (Chepla et al. 2011). This includes high levels of pain still experienced by patients post discharge.

2.3.5 **Risk Factors for Sternal Complications**

Risk factors are widely described in various types of patients. The development of dehiscence, non-union and infection may have multiple causes. These factors are associated with patient characteristics, pre- and post-operative conditions as well as operative variables (Brocki et al. 2010).

2.3.5.1 **Patient Centred Factors**

Patient centred risk factors for developing sternal complications include: obesity (body mass index [BMI] > 30kg/m), having insulin dependent diabetes mellitus or COPD, an increased age, smoking, gender (female>male due to added breast tissue) osteoporosis and chronic heart failure (Cahalin et al. 2011; Fu et al. 2016). Age has a significant influence on multiple factors, including ventilation kinematics. Age-related functional changes in the respiratory system are caused physiologically by a progressive decrease in chest wall compliance, elastic recoil of the lung as well as respiratory muscle strength (Joshua et al. 2014).

Obesity and female gender may cause increased tension across the median sternotomy incision due to an increased chest circumference owing to adipose tissue or increased bra cup size (macromastia). In women with unsupported macromastia it is postulated that they

are subjected to increased inferolateral tension, placing the median sternotomy wound under strain which may lead to the development of sternal dehiscence or infection (Balachandran et al. 2016). Obesity also has the ability to cause altered chest wall mechanics with reduced lung volumes, increased respiratory resistance and increased work of breathing. Respiratory muscle function may be more severely impaired with increasing obesity, this impairment can either be caused due to a diaphragm myopathy or the burden of obesity on the diaphragm itself (Severin, 2019).

Diabetes mellitus and elevated blood glucose levels places patients undergoing cardiac surgery at risk of developing a sternal infection due to the nature of the effects of hyperglycaemia on wound healing. Hyperglycaemia is known to impair the natural host immunity and increase the probability of an infection (Balachandran et al. 2016).

2.3.5.2 **Operative Factors**

Operative and post-operative developments might also place the patient at risk for developing sternal complications. Perioperative risk factors include the usage of bilateral internal mammary artery (IMA) grafts (Balachandran et al. 2016; Fu et al. 2016). The IMA is one of the main blood vessels that supply the sternum of oxygenated blood along with its collateral system, it is also the graft choice of many surgeons due to its long-term patency results (Balachandran et al. 2016). To minimize the risk associated with bilateral IMA grafting, surgical technique has been optimized to use skeletonized grafts to preserve collateral blood supply to maintain adequate healing of the sternum (Balachandran et al. 2016). Post-operative complications that include respiratory failure, low cardiac output states and mediastinal re-exploration for bleeding (re-look sternotomy) and the requirement of blood products may place any patient at further risk to develop sternal complications (Cahalin et al. 2011).

Intra-operative risk factors that have been associated with sternal infection include length of CPB, cross clamp times, use of intra-aortic balloon pump support post-operatively, low output states. Strategies are used intra-operatively to reduce CPB risk for deep sternal wound infection for adequate myocardial protection and to prevent low output states. Avoiding re-operation and delayed closure is another strategy to prevent infections (Sajja, 2015).

Reoperations after postoperative complications requires the surgeon to reopen the surgical site and sternum, this exposes the mediastinal structures including the skin, sternum and heart to airborne and environmental pathogens and may increase the risk of sternal infections. Due to the nature of the surgery, post-operative bleeding is always a risk and may require the transfusion of blood products. In rare cases, the replacement of blood products

may cause host immunosuppression placing the patient under further risk to develop a sternal infection (Balachandran et al. 2016).

2.3.5.3 **Activity Related Factors**

A literature review performed by Brocki et al. (2010) identified a further six possible mechanisms that may also provoke sternal dehiscence, instability and sternal pain. These include frequent coughing, tension on the sternum during resisted movements of the arms, skin strain that may lead to separation of the surgical site, skin strain due to hypertrophy mamma in female patients as well as the activation of abdominal muscles during bed mobility activities such as moving from supine to sitting (Brocki et al. 2010).

A cough is a normal protective mechanism to enable a person to clear secretions, foreign bodies and particulate matter and is necessary to avoid post-operative complications (Main & Denehy, 2016). Before an optimal cough can be obtained, a full deep inspiratory effort is required causing a considerable increase in intrathoracic pressure. Before commencing a coughing mechanism, the expiratory muscles are at the most advantageous length to generate a large enough force to expel air at an accelerated pace (Brocki et al. 2010).

Coughing therefore produces a considerable amount of pain in patient post median sternotomy and places the sternal wires under severe strain. Lateral stress is the most prevalent occurrence during coughing and is described widely by many authors that the lower half of the sternum is more vulnerable to lateral stresses than the upper manubrium (Casha et al. 2014). Parker et al. (2008) concluded in a study comparing forces exerted on a median sternotomy while performing a cough compared to lifting activities that a cough was able to exert a force of a mean mass of 27.5kg on a sternotomy incision. Similarly, Adams et al. (2014) concluded that a sneeze (also the use of force-expelled air) was able to exert a mean force of 41.0 kg on the sternum. Post sternotomy coughing is one of the most frequent causes of increased pain levels. Frequent coughing is also a major risk factor for sternal dehiscence and sternal instability. Due to the increase in the frequency of the lateral and distraction forces placed on the sternum during coughing, the sternal closure site is placed under high stress. In biological models, sternal separation occurred due to sternal wires cutting through the bone and rather than fractures sites occurring adjacent to the wires (Balachandran et al. 2016). Coughing produces a significant increase in sternal separation of the sternal edges in the lateral direction (0.01 to 0.02cm) when evaluated with real-time live ultrasound at 7 days, as well as 6 and 12 weeks post-operatively ($p<0.01$) (Balachandran et al. 2018).

Another mechanism that may predispose patients to sternal instability is bilateral or unilateral movements of the upper limbs. Forward and lateral movements of the upper limbs also cause a lateral distraction force of sternum. The pectoralis major muscle attaches via its

sternocostal head to the anterior surface of the sternum, the superior six costal cartilages and the aponeurosis of the external oblique muscle, although it's main function is flexion, adduction and medial rotation of the humerus (Moore et al. 2010). When the pectoralis is eccentrically loaded in shoulder abduction or scapular retraction the pectoralis muscle causes a lateral force in the direct opposite direction of the sternal wires. Therefore any forward or lateral movement may cause significant lateral forces on the sternal wires as well as the surgical incision site (Brocki et al. 2010). Sternal strain is there for much higher when both arms are moved sideways or forwards.

Consequently precautions can be described to prevent the following from causing sternal complications.

2.3.6 **Precautions Following a Median Sternotomy**

Sternal precautions are widely documented and vary between countries and institutions offering cardiac surgery. Most precautions are set by the discretion of the operating surgeon or the treating therapist. The most common universal sternal precautions include full restriction of bilateral shoulder exercises, pushing up with arms from a seated position, weight bearing through upper limbs for bed mobility, scapular adduction (also known as retraction) and lifting any heavy objects (2-5kg) (Brocki et al. 2010; Overend et al. 2010; Cahalin et al. 2011; Tuyl et al. 2011). The time frame set for these precautions is 6-8 weeks, but can also be limited up to 12 weeks. Further sternal support is encouraged by placing one's hands on the sternal wound during any coughing or sneezing (Brocki et al. 2010). A recent study suggested that sternal precautions should not all be standardized but should be adapted according to the patient's characteristics, including risk factors, comorbidities and previous level of activity (Cahalin et al. 2011).

When sternal precautions are prescribed, the forces acting on the sternum are the most important guiding factor. The most common forces that may cause sternal disruption include; the action of normal respiration and the muscles responsible, simultaneous activation of pectoralis muscle (as with bilateral upper limb movement), and the changes in volume that occur during normal respiration causing intrathoracic changes to become more negative (Brocki et al. 2010). The above mentioned forces will cause a lateral pull or vector on the sternum, thus the force to the sternum is applied in the opposite direction to the pull of the sternal wires (Robicsek et al. 2000; Brocki et al. 2010).

The greatest forces known to cause sternal dehiscence are distraction forces and any simultaneous strain of the sternum in a lateral direction (Parker et al. 2008; Brocki et al. 2010). During any bilateral upper limb movements, the lateral vector will cause severe strain on the sternal wires and the overlying incisional site (Brocki et al. 2010). Upward movements

of the upper limbs will have both an axial and lateral vector therefor straining the sternum even further. The inspiratory mechanism will cause an anterior-posterior displacement of the chest wall, this will in turn cause a bending movement and will pivot around the sternotomy suture line (Robicsek et al. 2000; Brocki et al. 2010). During normal transfers, the activation of the abdominal muscles (including mostly rectus abdominus and obliques) will exert an axial and diagonal pull on the sternum and costal area (Adams et al. 2006; Brocki et al. 2010).

Many authors have started to question whether sternal precautions are too limiting and need to be reviewed according to specific patient characteristics. Cahalin et al. (2011) hypothesized in a literature review that sternal precautions were too limiting (Cahalin et al. 2011). A sternal precautions algorithm as proposed assessing the risk of sternal complications by evaluating a patient's number of primary and secondary risk factors, assessing patients on the sternal instability score and evaluating a patient according to their characteristics and clinical profile. It is proposed that low risk patients follow moderate activity guidelines and the progress to progressive activity guidelines after two weeks. High risk patients should follow conservative activity guidelines for at least two to four weeks and thereafter they can progress to moderate activity guidelines. Patients are educated regarding normal sternal healing which includes improved sternal pain, no clicking or popping of the sternum, no crepitus on palpation, complete cutaneous healing as well as no symptoms of local or systemic infection. During the different phases of conservative to progressive activity guidelines, patients are encouraged to perform shoulder and scapular movements in pain-free ranges, keep shoulder in a neutral position during transfers and progress the amount of weight lifted weekly (Cahalin et al. 2011).

Similarly, Adams et al. (2016) suggested that the increased limitations of certain activities may lead to fear of activity, in return casing short-term disuse muscle atrophy (Adams et al. 2016). They also commented that severe activity limitations may delay a patient's return to work, especially patients whom need to perform physically demanding jobs and whom are expected to be able to handle a certain amount of load. This has financial implications for a family and the economy in return. Adams et al. (2016) therefor devised a sternal precaution protocol called "Keep your move in the tube" and is based on the kinesiology and ergonomics to shorten the length of the outstretched arm and therefore enables patients to perform movements that were previously not allowed. The authors hypothesised that if patients keep their arms as close to their body as possible and imagine if there was a tube around their trunk, they could avoid excessive stress on the sternum by modifying load-bearing movements. By stabilizing the movement of the humerus, less lateral stress is placed on the sternum therefore decreasing the forces causing sternal distraction, patients are there for encouraged to use their arms within limitations and perform bed mobility and transfer

activities more independently which may in return increase their time to discharge (Adams et al. 2016).

Katijjahbe et al. (2017) have also hypothesised that patients who receive modified sternal precautions may have increased potential to earlier improved physical function when compared to patients following standard sternal precautions four weeks after surgery. Their trial is named the “The Sternal Management Accelerated Recovery Trial” (S.M.A.R.T) and propose the use of modified and adapted sternal precautions. These include: using pain and discomfort as a guideline to use arms safely, avoid using one arm to push or pull any objects or stretching one and/or both arms simultaneously backwards. During any lifting activities as well as usage of arms, arms should be kept in close proximity to the body. Techniques used to preserve the sternum during coughing should be used with a pillow or anything similar as well as during transfers. Adapted transferring techniques include when a patient transitions from lying to sitting, patients were advised to first roll onto their sides, thereafter easing their legs over the side of the bed and then very cautiously using their arms to move into sitting.

In 2018, the S.M.A.R.T. trial was concluded and there was no statistically significant difference between modified sternal precautions versus standard precautions when comparing physical function at four weeks (MD 1.0, 95% CI -0.2 to 2.3) and 12 weeks (MD 0.4, 95% CI -0.9 to 1.6) postoperatively, when assessed by the Short Physical Performance Battery. Therefor modified or less limiting sternal precautions for patients following a median sternotomy performed during cardiac surgery had related outcomes on physical recovery, pain as well as health-related quality of life when compared to standard sternal precautions (Katijjahbe et al. 2018).

In contradiction to commonly used sternal precautions, Sturgess et al. (2014) established that exercises that included the trunk and upper limb had a significantly positive effect on reducing the incidence of sternal pain during the first 6 weeks post-operatively. The exercises included in the study were individualised to each participant, the program was modified by the patient’s response to each exercise and altered accordingly (including pain, quality of movement and fatigue). Each patient received a booklet containing normal sternal precautions. The outcome measures used to evaluate the range of motion of the chest wall included normal posture, thoracic extension, thoracic rotation and side-flexion as well as shoulder flexion This further contradicts the use of normal sternotomy precautions (Sturgess et al. 2014).

2.4 VENTILATION KINEMATIC CHANGES FOLLOWING A MEDIAN STERNOTOMY

Mechanical properties of the chest wall following a median sternotomy have been proven to be altered post-operatively. Due to the nature of the surgical intervention which includes a

median sternotomy with rib resection, the motor system or the pulmonary pump is said to undergo an overstretch injury, resulting in altered movement patterns (Kristjansdottir et al. 2004a). The surgery is speculated to alter the spinocostal angles that results in the reduction of mobility of the ribs and consequently decreased lateral thoracic expansion (Kristjansdottir et al. 2004a; Ragnarsdottir et al. 2004) . Increased stress is placed on the costotransverse and costovertebral joints and cause structures surrounding the joints to stretch, these joints are then forced to recover in an elongated positions and cause an increase in movement (Kristjansdottir et al. 2004a).

The intercostal muscles subsequently need to adapt to perform in a new range allowed to them. The diaphragm gradually also regains its original strength and length (Kristjansdottir et al. 2004a). The connective tissue of the costovertebral and costotransverse joints remain elongated due a percentage of permanent loss of elasticity and decreased contraction prevails. This finding is supported by increased upper thoracic movements 12 months post-operatively after cardiac surgery found by a study performed by Kristjansdottir et al. (2004b). During the grafting of the internal mammillary arteries additional trauma to and a decreased blood supply to the intercostal muscles is speculate to cause decreased contractile ability therefore decreasing ventilatory muscle strength. The pulmonary pump therefore undergoes significant injury to cause a decrease in chest wall movements (Kristjansdottir et al. 2004b).

The pulmonary pump is associated with a restrictive defect and is due to decreased movement and displacement of the thoracic cavity during inspiration and expiration. Lock et al. (1990) found a significant decrease in the displacement of the sternum at the manubrial and xiphisternal levels as well as lateral displacement of the chest in patients who had undergone a CABG surgery (Locke et al. 1990). A reduction in chest wall expansion was correlated with a reduction in vital capacity (Locke et al. 1990). Acutely after surgery, bilateral abdominal wall motion was described with left abdominal movement being significantly more impaired than right abdominal movement, therefor indicating that the left thoracic wall undergoes more injury than the right. Kristjansdottir et al. (2004a) found acutely that average abdominal movements were decreased on the left as well as the right, these changes persisted until three months post-operatively (Kristjansdottir et al. 2004a). The changes included asymmetrical respiratory movements between the abdominal and upper thoracic movements during breathing. Locke et al. (1990) found similarly that reduced abdominal wall displacement was still present three months post-operatively, but values were significantly better than at discharge. Abnormalities still present at three months post-operatively were suggested to be due to decreased timing of the onset of lateral wall displacement as well as the reversal of direction of all or parts of the sternum during breathing (Locke et al. 1990).

Diaphragmatic function has been linked to a decrease in respiratory function. Elevated diaphragm are seen on at least 13% of post-operative cardiac patients according to Weismann et al. (1999). This can be due to a number of causes including atelectasis, phrenic damage and a reflex mediated decrease in diaphragm dysfunction (Weissman, 1999). Phrenic nerve injury is a well-known complication following cardiac surgery that can lead to diaphragm dysfunction.

Various mechanics have been described that may cause a phrenic nerve injury including hypothermia, mechanical trauma and ischaemia (McCool & Tzelepis, 2012). Diaphragm dysfunction can lead to debilitating symptoms such as dyspnoea, decreased exercise tolerance, sleep-disordered breathing, hypersomnia, reduced quality of life, atelectasis and respiratory failure (McCool & Tzelepis, 2012). Paradoxical movements during breathing, elevated diaphragm on a chest X-ray, decreased vital capacity and difficulty weaning off mechanical ventilation post-operatively are further symptoms that phrenic nerve investigations need to be done (Kristjansdottiret et al. 2004b). Phrenic nerve injuries predominantly occur on the left side and are usually caused by the irrigation of the pericardial space with cold solution (including either ice slush or cold saline) for myocardial preservation during cardiopulmonary bypass (Ragnarsdottir et al. 2004; Kristjansdottir et al. 2004b).

Further post-operative complications following a median sternotomy is associated with alterations in gaseous exchange and lung mechanics. Post-operative pulmonary dysfunction (PPD) is a well-documented feature post cardiac surgery and CPB. Post-operative pulmonary dysfunction is the expected alterations experienced by patients including increased work of breathing, shallow respiration, ineffective cough and hypoxemia. Post-operative pulmonary dysfunction has the ability to develop into major PPCs. Post-operative pulmonary dysfunction is caused mainly by two factors; abnormalities in gaseous exchange, alterations in lung mechanics, or both (Wynne & Botti, 2004). Abnormalities in gaseous exchange are mainly caused by a widening of the alveolar-arterial oxygen gradient, increased microvascular permeability, increased pulmonary shunt fraction, and intrapulmonary aggregation of leukocytes and platelets. Alterations in lung mechanics include decreased static and dynamic lung compliance, reduced vital capacity and functional residual capacity (Wynne & Botti, 2004; Badenes et al. 2015).

The causes of developing PPD and further complications can be divided into preoperative, intraoperative and postoperative. Preoperative factors include patients of increased age, COPD, history of smoking, obesity, previous cardiac surgery and heart failure. Intraoperative factors include respiratory depression, CPB and duration of bypass time, lung deflation, topical cooling, internal mammary artery dissection, sternotomy incision, increased number of grafts and lower core temperature. Postoperative factors include pain, immobility, chest

tubes, pleural effusions, atelectasis, impaired mucocilliary clearance, fluid imbalance, respiratory depression associated with anaesthesia and pulmonary oedema (Wynne & Botti, 2004; Badenes et al. 2015).

The side-effects of general anaesthesia have been widely described in various amounts of surgical cases. Anaesthesia in combination with prolonged supine positioning results in a relaxation of the chest wall, an upward shift of the diaphragm, decreased lung compliance and a shift in blood volume from the thorax to the abdomen (Wynne & Botti, 2004). This feature alone can result in a ventilation-perfusion mismatch as well an abnormal shunt-fraction. In combination with anaesthesia and prolonged supine positioning, cardiac surgery then progresses to using a median sternotomy, grafting of mammillary arteries and other viable grafts, initiating cardiopulmonary bypass and myocardial hypothermia (Apostolakis et al. 2010).

Once CPB is initiated, pulmonary ventilation is stopped and results in the collapse of both lungs. Pulmonary circulation is therefor also stopped exposing blood to hypothermic conditions. During cardiopulmonary bypass the lungs metabolic demands are totally dependent on the oxygen supply from the bronchial arteries, which normally contribute 3% to 5% of total blood supply to the lungs (Apostolakis et al. 2010). This predisposes the lungs to pulmonary ischemia, injury to the capillary walls, release of inflammatory mediators, increased pulmonary capillary permeability, flooding of the pulmonary interstitium, formation of micro-thrombi, insufficient alveolar distention to activate the production of surfactant (Wynne & Botti 2004). This all has the potential to lead to abnormalities in gaseous exchange, lead to closure of small airways causing either severe pulmonary congestion, atelectasis and sputum retention.

There is currently a widespread conclusion that patients following cardiac surgery present with a restrictive lung function post-operatively (Weissman, 1999; Kristjansdottir et al. 2004a,b; Morsch et al. 2009). A restrictive pattern can be defined as both forced expiratory volume in one second (FEV1) and forced vital capacity (FVC) are diminished and the FEV1/FVC ratio is preserved or even above normal. The primary problems of restrictive lung functions is either decreased lung compliance, thoracic compliance or both (Kacmarek et al. 2017). Common findings post cardiac surgery indicate that patients present with decreased forced vital capacity (FVC), decreased forced expiratory volume over 1 second (FEV1), decreased Peak Expiratory Flow Rate (PEFR) and decreased Maximum Voluntary Ventilation (MVV) (Weissman 1999).

These changes were described by two studies to still be present at discharge and resolved within three months following cardiac surgery via a median sternotomy incision

(Kristjansdottir et al. 2004b). Maximum inspiratory Pressure as well as MEP were significantly decreased on the 6th day post-operatively, concluding a further restrictive disorder. Weissman et al. (1999) described a further restriction in ventilatory profiles (decreased FVC and FEV1) in patients who had undergone harvesting of internal mammillary arteries, the authors concluded the finding to extensive dissection of the interior portion of the anterior chest wall (Weissman 1999).

A contributing factor to a decrease in FEV1 post-operatively is also due to the friction caused during respiratory movements caused by chest drains (Morsch et al. 2009). Intercostal and subxiphoid drains are commonly inserted after cardiac surgery to drain excess fluid and blood in the thoracic cavity. Pleural drains are frequently inserted after the harvesting of the left or right internal mammillary arteries. Intercostal drains more so than subxipohoidal drains cause a drop in the FEV1 (Morsch et al. 2009). Further contributing factors to restrictive lung function is using a method called rib retraction, it is said to decrease airway pressures and increase lung compliance, leading to increased airway resistance (Morsch et al. 2009).

Westerdahl et al. (2014) performed a study to assess breathing exercises two months post cardiac surgery. During the assessments lung function measurements were performed pre-operatively and two months post-operatively. They found that two months post-operatively, patients had a mean decrease in vital capacity to 94 ± 11% (P<.001) and in FEV1 to 93 ± 12% (P<.001). The study also included the measurement of thoracic excursion with a tape measure around the circumference of the chest at the level of the xiphoid process. The patients were asked to stand with their hands placed on their head, the difference between maximal inspiration and expiration was calculated. They found that thoracic mobility did not differ significantly between the groups either before or 2 months after surgery (Westerdahl et al. 2014).

2.5 ROLE OF PHYSIOTHERAPY IN ADDRESSING VENTILATION KINEMATICS FOLLOWING A MEDIAN STERNOTOMY PROCEDURE

2.5.1 Role of Physiotherapy

Physiotherapy is a widely used modality following cardiac surgery. Physiotherapy is provided in different phases when cardiac patients are involved and multiple treatment strategies are used to influence positive outcomes. Physiotherapy interventions are provided pre-operatively, immediately post-operatively and after discharge cardiac rehabilitation is initiated (Mampuya 2012). Physiotherapy is thought to reduce the risk of pulmonary complications such as pneumonia or atelectasis (Westerdahl et al. 2014).

Physiotherapy pre-operatively is not routinely provided, but may be provided to identify high risk patients. These patients include high risk for developing PPCs and sternal complications. Assessing mobility status and the risk for falls pre-operatively may indicate the need for exercise interventions pre-operatively.

Post-operative physiotherapy or otherwise referred to as cardiopulmonary rehabilitation occurs in four phases. Phase one of cardiopulmonary rehabilitation occurs during in hospitalization and entitles the assessment of cardiorespiratory function, mobility review, monitoring of pain management and risk of sternal complications (Mampuya, 2012). The role of physiotherapy during this phase is to maintain and restore cardiorespiratory function to baseline function. Respiratory care is indicated to prevent pulmonary complications and improve pulmonary function. Alongside with respiratory care, restoring functional capacity is integral to the success of cardiac surgery. The role of exercise is a crucial component in phase 1 of cardiac rehabilitation to improve physical function, walking ability, functional independence and endurance (Mampuya, 2012).

2.5.2 **Physiotherapy Practice as per Survey Feedback from Different Countries**

Table 2.1: Comparison between Countries for Mobilization and Exercises

Study/author	**Overend et al.**	**Westerdahl et al.**	**Roos et al.**	**Filbay et al.**	**Seo et al.**	**Lomi & Westerdahl**
Country	Canada	Sweden	South Africa	New Zealand, Australia	Korea	Greece
Year of study	2010	2010	2011	2011	2013	2013
Sample size	18(18)	8(29)	142	64 (56)	9 (9)	45 (58)
Respondent	Physiotherapist	Physiotherapist	Physiotherapist	Physiotherapist	Nurses, physiotherapist	Physiotherapist
Response Rate	100%	88%	76%	88%	90%	78
Data collection	Telephone survey	Postal survey	Postal and Electronic	Postal	E-mail survey	Postal Survey
No. of surgeries/week	21 (6-24)	Not collected	Not Collected	Not collected	18.7 (5-70)	Not collected
LOS (day)	6.4 (4-10.6)	Not collected	Not Collected	Not collected	8.8 (5-14)	Not collected
Sit on side of bed	Not collected	POD 1 (97%)	Not collected	POD 1 (100%)	Not Collected	POD 1 (60%)
Sit to stand by bed	POD 1 (94%)	POD 1 (97%)	Not collected	Not collected	POD 1 (78%)	POD 1 (18%)
Sit to stand by chair	POD 1 (50%)	POD 1 (97%)	Not collected	Not collected	POD 1 (67%)	POD 1 (60%)
Walking in the ward	POD 1 (22%)	POD 2 (79%)	Not collected	Not collected	POD 1 (33%)	POD 2 (44%)
Walking in the corridor	POD 2 (50%)	POD 3 (93%)	Not collected	Not collected	POD 3 (33%)	POD 3 (51%)
Stairs up and down	Not collected	POD 4 (38%)	Not collected	POD 4 (96%)	POD 5 (23%)	Not collected
Mobilization (general)			86%	94%		
Exercises for lower extremities	Not collected	POD1 (41%)	82%	79%	Not collected	POD 2 (67%)
Thoracic/upper extremities ROM exercises unilateral	Not collected	POD3 (34%)	Not collected	Not collected	Not collected	POD 4 (31%)
Thoracic/upper extremities ROM exercises bilateral	Not collected	POD 3 (76%)	Not collected	Not collected	Not collected	POD 4 (51%)

POD – Post-Operative Day

2.5.3 Interventions that Aim to Address Ventilation Kinematics

Pre-operative physiotherapy has been described in few studies, including questionnaire based surveys. Multiple surveys indicated that patients received preoperative information including topics of breathing exercises, early mobilization, coughing techniques, exercises for thrombosis prophylaxis. Most physiotherapists also covered sternal restrictions (Lomi & Westerdahl, 2013). During these sessions high risk patients were able to be identified before surgery, these commonly included patients that smoked, had COPD, renal failure, previous cardiac surgery and severe heart disease (Lomi & Westerdahl, 2013). Interventions previously used in pre-operative cardiac surgery patients include inspiratory muscle training (IMT) as well as prehabilitation programmes.

Hulzebos et al. (2006) concluded that preoperative IMT reduced the prevalence of PPC's and shortened the length of stay in hospital post-operatively in patients undergoing cardiac surgery that are at increased risk of developing pulmonary complications (Hulzebos et al. 2006). The intervention included inspiratory muscle training commencing at 30% of the patient's MIP, each day for 20 minutes a day for at least two weeks. One session per week was supervised, the other six sessions were unsupervised. If the rate of perceived exertion was below five, the resistance was increased incrementally by 2cm H_20 (Hulzebos et al. 2006). Karanfill & Moller (2018) concluded in a systematic review evaluating preoperative IMT and preventing pulmonary complications following cardiac surgery, that preoperative IMT results in a significant reduction in atelectasis as well as the incidence of pneumonia when performed in patients undergoing CABG or valve surgery (P=0.01) (Karanfil & Moller 2018).

Sawatzky et al. (2016) performed a pilot randomized control trial for prehabilitation program for elective coronary artery bypass graft surgery patients. Patients participated in a structured exercise program for 60-minutes with the minimum amount of sessions being twice weekly, in addition patients attended further voluntary exercises sessions at the same facility. Types of exercises included were based and varied according to patients' leisure activities and physical capabilities, these included a variety of activities including walking, stationary bicycle, stretching, stretching exercises that included light resistance with either body weight or resistance bands. Aerobic exercise was prescribed at 85% of their maximal oxygen consumption based on stress test results performed at baseline, the intensity and progression was increased based in communication between healthcare professionals. The patients also attended twelve group-based education sessions that included medication usage, exercise, dietary advice, stress- and risk management. The study included a small sample size, but the Prehab was able to allow patients to improve on their physical fitness as assessed by the six minute walk test before surgery and to maintain the same outcome postoperatively as compared to standard care. Similarly, the prehab group showed

improvement in 5-meter gait speed preoperatively that was able to be maintained post-operatively (Sawatzky et al. 2016).

Similarly, Waite et al. (2017) performed a home-based preoperative rehabilitation to improve physical function and reduce hospital length of stay for frail patients undergoing coronary artery bypass graft and valve surgery, this included a home-based exercise program that included balance and strength training exercises. The exercise program were progressed on models developed from the “Otago exercise program to prevent fails in older people”. This program consists of exercises focusing mainly on balance and strength, each patient is evaluated individually and exercises are prescribed accordingly. Significant differences were observed in the Clinical Frailty Score (P=0.003), 6MWT (P=0.0005), 6MWT walking speed (P=0.001) and Short Physical Performance Battery total score (P=0.0002) (Waite et al. 2017)

Post-operatively cardiac patients are frequently assisted by mechanical ventilation. Fast track regimes aim to extubate patients as early as possible with time-directed extubation protocols (Lai et al. 2016) . Interventions that have been reported during the intubation phases include suctioning, manual hyperinflation, positioning, thoracic expansion exercises and upper- and lower limb exercises. Patman et al. (2001) performed a randomized control trial to establish the effectives and need for physiotherapy during the intubation phase. They concluded that physiotherapy during intubation did not improve any patient outcomes (Patman et al, 2001). For patients being mechanically ventilated for longer than 24 hours, physiotherapy interventions should include techniques for routinely ventilated patients.

Post-operative physiotherapy normally includes early mobilization, upper and lower-limb exercises, breathing exercises, supported coughing and incentive spirometry. Early mobilization and its benefits have been well-described in ICU-settings, although limited evidence is available for post-surgical cardiac patients. During a national survey in Sweden, most physiotherapists included early mobilization techniques during physiotherapy. On post-operative day 1 patients were mobilized to either sitting on the edge of the bed or in a chair, this was then progressed to walking in the room on day 2 and walking in the corridor on day 3 and 4. Stair climbing was assessed and completed by only few patients (Westerdahl & Moller, 2010). These results were similar to surveys performed in Australia and New Zealand (Tucker et al, 1995), the United Kingdom (Reeve & Ewan, 2000) and Canada (Overend et al, 2006). During the same surveys upper limb exercises using bilateral exercises were more commonly performed than lower limb exercises and were frequently only started on post-operative day two and three.

A recent systematic review by Santos et al. (2017), mentioned that early mobilization following cardiac surgery is necessary in preventing postoperative complications, improving

functional capacity of patients and reducing the length of hospitalization. Each trial showed differences in techniques administered to achieve mobilization as well as when to start the intervention performed, early mobilization groups showed improved outcomes when compared to the control groups who did not receive treatment, although the advantages showed minimal difference when the interventions were compared (Santos et al. 2017).

A major component post-surgery is early mobilization and restoration of baseline mobility function. Internationally, most research points in the direction of early mobilization in the ICU. The complications of prolonged bedrest and immobility are widely documented and have been proven to have deterious effects on pulmonary function. During a randomised control trial performed by Mohmoudi et al. (2017), they concluded that early mobilization post CABG reduces the incidence of atelectasis and pleural effusions and improves oxygenation in the post-operative patient (Mahmoudi et al. 2017). A further benefit of early mobilization and exercise based rehabilitation significantly improves cardiac autonomic function when assessing heart rate variability during in-patients following CABG surgery (Mendes et al. 2010).

To restore normal ventilation kinematics, physiotherapists globally use different treatment modalities to address abnormalities and restore normal respiratory function. These treatment modalities used address two main problems experienced by patients post cardiac surgery, these include sputum retention due to anaesthesia and decreased coughing ability as well as decreased pulmonary function and atelectasis. Treatments used to address sputum retention include manual therapy (percussions, vibrations and shacking), coughing techniques including huffing and PEEP exercises (Main & Denehy, 2016). Treatments aimed at restoring pulmonary function, preventing atelectasis and improving gaseous exchange include deep breathing exercises, active cycle of breathing, sustained inspiratory effort, spirometry, positioning, inspiratory muscle training, PEP breathing and diaphragmatic breathing (Westerdahl, et al. 2005; Olsén et al. 2015; Main & Denehy, 2016).

Manual chest therapy techniques are thought to loosen secretions, reduce fatigue and increase the effectiveness of other respiratory techniques. Physiologically, manual techniques cause an intermittent positive pressure applied to the chest wall. This pressure is transmitted through the airways and lungs and causes air to oscillate during the expiratory phase. This is thought to aid in the clearance of secretions (Main & Denehy, 2016). There is however very limited evidence to prove that manual techniques show any effectiveness (McCool & Rosen, 2006).

Deep breathing exercises (DBE's) are frequently used to treat post-operative pulmonary impairments as well as to prevent any further complications. The aim of DBE's is to reduce

post-operative atelectasis, improve lung volumes, increase sputum clearance and improve gaseous exchange. In a study performed by Westerdahl et al. 2005 found that chest physiotherapy including deep breathing exercises significantly decreased atelectasis and improved spirometry values compared to a regime without breathing instructions following CABG surgery (Westerdahl et al. 2005).

Atelectasis is a commonly noted complication during cardiac surgery, Westerdahl et al. (2015) noted during a randomized control trial that all patients presented with atelectasis on the fourth day post-operatively, with the largest areas affected the basal segments of the lungs. During deep breathing exercises, physiotherapists encourage patients to take slow deep inspiratory breaths to improve basal ventilation. Increasing basal ventilation will favour more dependant lung regions where perfusion is greater than ventilation, therefor directly targeting to improve oxygenation and prevent further atelectasis (Westerdahl & Olsén, 2015). Active cycle of breathing technique (ACBT) and the forced expiration techniques (FET) are more frequently used in the management of patients with chronic pulmonary conditions that include sputum retention (Lewis et al. 2012). As cardiac patients may suffer from an ineffective cough and sputum retention, these techniques are optimally sought to increase with treatment effectivity. A typical cycle of ACBT normally consists breathing control, three to four thoracic expansion exercises and the FET. FET normally consists of one to two forced expirations or huffs (low and high volume) promote secretion clearance due to changes in thoracic pressures (Lewis et al. 2012). Thoracic expansion exercises are useful in cardiac patients to promote slow deep breaths to prevent atelectasis as well as to loosen and clear secretions and to improve collateral ventilation. The exact effect of ACBT on cardiac patients has not yet been established, but research shows good effect for short term improvements in sputum clearance in a wide variety of pulmonary conditions (Lewis et al. 2012).

In conjunction with deep breathing exercises, assistive devices and techniques are used to aid in achieving baseline respiratory values, these commonly include PEP therapy and incentive spirometry. PEP therapy is commonly used in many different surgical cases. PEP therapy also known as positive expiratory pressure entails breathing against an expiratory resistance through a variety of different applications. Pursed lip breathing or resistance created by a device are used to create a positive expiratory pressure and is used to increase lung volumes (including FRC and Vt), to reduce the amount of hyperinflation, slow down the rate of expiration and improve airway clearance (Urell et al. 2010).

Incentive spirometry is used to aid in deep breathing exercises to improve and restore normal lung volumes. The spirometer is a handheld device that imitates deep breathing and the patients are encouraged to take slow deep inspiratory breaths that increase inflation of the lungs. This is thought to be especially beneficial in post-operative patients to enhance

inspiration to increase normal low postoperative FRC values and reverse atelectasis and hypoxaemia. During a search of Cochrane Library, there is poor evidence to support the use of incentive spirometry to prevent pulmonary complications post- upper abdominal surgery (do Nascimento Junior et al. 2014) and coronary artery bypass graft surgery (Freitas et al. 2012).

Petterson et al. (2015) combined the use of breathing exercises, PEP therapy and upright positioning in standing in patients that underwent cardiac surgery. They found that a combination of techniques in standing versus sitting, oxygenation improved significantly in the standing group compared with controls directly after breathing exercises ($p<0.001$) and after 15 minutes of rest ($p=0.027$). Performing breathing exercises in standing also significantly improved subjective breathing ability ($P=0.004$).

This concludes that no single technique alone is effective, but combinations of techniques and treatments can benefit cardiac patients to restore normal ventilation kinematics as well as their cardiopulmonary and functional status. Treating patients with a holistic approach emphasizing patient and therapist goals is the most important way to achieve success post-surgery.

Chapter 3 consists of an outline of the methodology used to design and conclude the study.

CHAPTER 3

3. METHODOLOGY

3.1 INTRODUCTION

This chapter will include a discussion of the methodology followed to answer the objectives of the study.

3.2 STUDY DESIGN

The study design was a longitudinal observational study design. Each participant underwent two assessments, one at baseline pre-operatively and the second at discharge from the hospital post-operatively.

3.3 SUBJECTS

3.3.1 Source of Subjects

Participants for this study were selected when undergoing an elective cardiothoracic procedure requiring a median sternotomy incision at the cardiothoracic unit at a private hospital in Gauteng. Consecutive sampling was used during this study in which every participant meeting the inclusion criteria was used until the required sample size was achieved. They were approached following admission to the cardiac ward or cardiothoracic ICU. The aim of the study was discussed and informed consent was obtained.

3.3.2 Sample Size

The study sample was calculated to be 61 participants using an electronic sample size calculator available at http://www.sample-size.net/sample-size-conf-interval-mean/. (Hulley et al. 2011).

Sample size = N = $4Z_{\alpha}^{2}S^{2}/W^{2}$ = 61

Literature sourced from Morsch et al. (2009) was used to assist with the sample size calculation. The authors evaluated the ventilatory profile of patients undergoing CABG surgery using MIP pre- and post-operatively as outcome measure. The study noted the change in MIP of study participants using Manovacuometry was: pre-operatively MIP 65.8 ± 28.6 cmH_2O and a significant drop was noted post-operatively to 42,4 ±19.9 cmH_2O (Morsch et al. 2009). Using an electronic calculation, a confidence interval of 95% was accepted, the desired width of the confidence level was accepted at 12 and the accepted mean of the standard deviation of the variable was set at 24.25.

3.3.3 Sample Selection

3.3.3.1 Inclusion criteria

The inclusion criteria for this study were:

- Male and female patients undergoing elective cardiothoracic surgery requiring a median sternotomy incision.
- Patients aged 18-65 years.

3.3.3.2 Exclusion criteria

The exclusion criteria of the study were:

- Patients who had a previous median sternotomy or any other thoracic wall surgery.
- Patients who were admitted for emergency procedures and were unable to undergo pre-operative assessments.
- Patients admitted who required immediate balloon-pump management who were unable to complete a thorough pre-operative assessment.
- If a median sternotomy procedure was to be done for lung pathology.
- Patients who participated in another clinical trial at the time.
- Patients with a history of spontaneous pneumothorax.

3.3.4 Variables

3.3.4.1 Dependent variables

- Ventilation kinematics determined by the following: rib mobility measured by chest expansion and inspiratory muscle strength recorded by MIP and PIF.
- Demographical and clinical profiles of participants.

3.3.4.2 Independent variables

- Patients undergoing cardiothoracic surgery via a median sternotomy incision.

3.3.4.3 Cofounding variables

- Vital signs, Visual Analogue Scale (VAS) score (pain), Radiograph analysis

3.4 MEASUREMENT TOOLS AND OUTCOME MEASURES

A summary of the measurement tools and outcome measures used in the study can be seen in table 3.1 below.

Table 3.1: Outcome Measures and Measurement Tools

Variables	Measurement Tool	Score/Value
Demographic and clinical profiles	Demographic questionnaire (Appendix 1) Assessment sheet (Appendix 2)	
Chest expansion	Non-stretch tape measure	Centimetres
Inspiratory respiratory muscle strength	KH1 POWERbreathe device	MIP in cmH_2O PIF in l/s
Pain	VAS score for pain	Score ranging from 1-10
Radiographic analysis	Chest X-ray score	Score out of 12

3.4.1 Maximum Inspiratory Pressure and Peak Inspiratory Flow

The measurement of inspiratory muscle strength is widely documented as a reliable measure, using the MIP and PIF. These tests have the advantage that they are non-invasive and can be performed at the bedside of a patient and normal values have been established. Maximal inspiratory pressure is typically obtained by measuring mouth pressure during a maximal isometric inspiratory effort performed at residual lung volume, otherwise known as the Mueller manoeuvre. This manoeuvre is seen as the gold standard when measuring MIP and several authors have proven the reliability and validity (Minahan et al. 2015).

The POWERbreathe device is a handheld device designed for respiratory muscle training with the additional benefit of being able to measure MIP and PIF. The POWERbreathe device is a valve which only allows inspiratory airflow once a threshold negative pressure is generated at the mouth, once the valve has opened the resistance to inspiratory airflow is minimal (Hart et al. 2001). The POWERbreathe device was used in a study testing the reliability of an electronic inspiratory loading device for assessing pulmonary function in post-stroke patients. They significantly proved the intra- and inter-reliability of pulmonary function measurements evaluating MIP and PIF for the post-stroke patients were very high, ICCs ranged from 0.933 to 0.986 in variables. Authors suggested the handheld device would be useful for clinical rehabilitative assessment of pulmonary function (Lee et al. 2016). Langer et al. (2015) measured the validity of the POWERbreathe device during a loaded breath task in patients with COPD. During this study, the results from the handheld device were compared to an external laboratory system that provided the “gold standard” reference. The ICC for average MIP was 0.97. This study concluded that clinicians would be able to establish the load on inspiratory muscles in these tests in daily practice (Langer et al. 2013).

The following steps were undertaken to assess MIP and PIF:

- Study participants were comfortably seated in a chair with their feet supported on the ground, their back supported and hips at a 90 degree angle. The participant had a nose piece on to ensure no air leakage occurred (Lee et al. 2016).

- The instruction given to the participant was to first exhale to residual lung volume and then to maximally and forcefully inhale against an obstructed mouthpiece for 1.5 – 3.0 seconds (Minahan et al. 2015).
- Participants practiced twice and then immediately after they were asked to repeat the trial three times, until three acceptable measurements were obtained. The test was repeated and the maximum of three values that vary by less than 20% was accepted (Lee et al. 2016). They relaxed for 1min between efforts. A measurement was considered effective if they were maintained without an air leak for a duration of 1.5 – 3.0 seconds and if two readings were taken with a maximum difference of 10% (Lee et al. 2016).
- The MIP instructions were: 'breathe out slowly until your lungs are completely empty and squeeze the air out of your lungs. Now breathe in hard and hold your effort for at least two seconds' (Lee et al. 2016).
- The PIF instructions were: 'breathe out slowly until your lungs are completely empty, now breathe in as hard and as fast as possible until your lungs are full' (Lee et al. 2016).
- The following equations were used to calculate the predicted MIP for each participant, according to Evans & Whitelaw (2009):
  - Male MIP = 120 - (0.41 x age)
  - Female MIP = 108 – (0.61 x age)

3.4.2 Chest Expansion using a Tape Measure

To measure chest expansion, a cloth tape measure was used with a range from 0cm – 150cm. A recent study conducted by Bockenhauer et al. (2007) proved that using a cloth tape measure to assess thoracic excursion was highly reliable in men and resulted in ICCs (95% CI, 0.81- .0.91) of substantial reliability. This study proved that measuring thoracic excursion at two levels is reliable in the clinical setting especially when changes in thoracic excursion are expected to be greater than approximately 0.6cm. Authors suggested that the mean of three measurements at each thoracic level for each phase of the respiratory cycle be done (Bockenhauer et al. 2007). Instructions given to the study participants in the authors' study were: "make yourself as big/small as possible" as opposed to the traditional instruction of "breathe in/out maximally". These instructions resulted in a significant increase in thoracic excursion, 1.4cm in the upper thorax and 0.9cm in the lower thorax when measured with a tape measure ($p<0.001$) (Olsén et al. 2011).

The following steps were undertaken to evaluate chest expansion of study participants:

- The upper and lower thoracic expansion were measured, each of these measurements had an anterior and posterior landmark and was marked with an eye pencil.

- Upper thoracic expansion using the landmarks of the fifth thoracic spinous process and the third intercostal space at the midclavicular line was used.
- Lower thoracic expansion was measured from the 10th thoracic spinous process and the xiphoid process.
- The circumference of peak inhalation and peak expiration was measured.
- The verbal instructions given to the participants were to “breathe in/out maximally” but also to make themselves as “big or as small” as they possibly can.
- With regards to holding the tape measure, the tape measure was crossed over by crossing over one’s hands while keeping the tape measure flat against the participant’s skin. When crossing over the tape caution was taken as to not contour the skin to prevent any discomfort to the patient.
- For calculation purposes the total thoracic excursion was equal to the thoracic circumference at the end of forced inspiration minus thoracic circumference at the end of forced expiration (Bockenhauer et al, 2007).
- Once the correct procedure was explained to the study participant and the relevant anatomical points marked with an eyeliner pencil, the participant performed one repetition of maximal inspiration to maximal expiration and the recording was written down. The participant rested for two minutes, and the manoeuvre was repeated. Three circumference assessments were conducted and the mean of these three used for data analysis.

3.4.3 **VAS Score for Analysing Pain Levels**

Every participant evaluated pre-operatively and post-operatively were asked to assess their pain level. The VAS is well documented in the evaluation of acute and chronic pain. The VAS is represented on a 10cm line and patients are asked to mark a point between ‘no pain’ and ‘worst imaginable pain’ to indicate pain intensity. The VAS was administered on paper and the distance from the start was measured to obtain the pain level of a participant. Bijur et al. (2001) evaluated the reliability of the VAS scale in an acute setting assessed by ICC were high (ICC = 0.97 [95% CI = 0.96 to 0.98]) and therefore suggested that the VAS pain scale is sufficiently reliable to assess acute pain (Bijur et al. 2001).

3.4.4 **Analysing Radiographs**

Table 3.2 refers to the radiograph evaluation tool used during the study. All radiographs were evaluated on a scale of 1-4, a score of 1 indicated no pleural effusion, atelectasis or elevated left diaphragm, a score of 4 indicated noticeable signs of one or more of the aforementioned. No limitations were listed during this study concerning the radiographic evaluation (Kristjansdottir et al. 2004a).

Table 3.2: Radiograph Evaluation Tool

Radiographic Evaluation (X-rays)	**Score**
Atelectasis of the left lung 1= None 2= Minor. Little shadowing in the retrocardial area. No significant reduction in lung volume. 3= Medium. Significant shadowing in the retrocardial area and at the base of the lung. No major reduction of lung volume. 4= Major. Near total collapse of the inferior lobe. There is an opaque area in the basal/medial part of the lung with sharp lateral border. Significant reduction of the left hemi thorax.	
Pleural Fluid 1= Normal. 2= Minor. Some filling of the costophrenic angle. 3= Medium. Near total filling of the costophrenic angle. Fluid is seen running up the lateral chest wall and/or shadowing of the lower part of the left lung. 4= Major. Fluid fills the lower part of the left hemi thorax and/or shadowing of the whole left lung.	
The position of the diaphragm 1= Normal. 2= Minor. Left diaphragm is slightly higher than the right diaphragm. 3= Medium. Left diaphragm is elevated up to half the height of the left heart border. 4= Major. Left diaphragm is elevated above half the height of the left heart border.	
Total score	/12

Source: Kristjansdottir et al. 2004

3.4.5 Assessment Forms

An assessment form was created by the researcher and used for each participant to capture their information. The content was informed by published literature (Locket et al. (1990), Kristjansdottir et al. (2004) and Morsch et al. (2009).The face validity of the assessment form was evaluated by the supervisor involved in this study to ensure it aligned with the objectives of the study. Vital data of each patient was recorded before and after each evaluation to ensure each procedure was done safely. Equipment used to record vital data was standard to every participant as portable monitors were readily available and easily accessible at the current hospital the study was performed at. Each participant was discharged from the same unit, therefore all vital data recorded was performed by the same equipment. The following were included in the assessment forms for admission and discharge:

- Vital data (including heart rate, respiratory rate, blood pressure, oxygen saturation and blood glucose levels)
- VAS score for pain.
- Chest X-ray score including radiographic evaluation tool.
- Chest expansion (including upper and lower expansion).
- Inspiratory muscle strength including predicted values.
- Peak inspiratory flow measurements.

3.4.6 **Demographical Data**

The demographical data collected for this study included age, gender, height, weight, diagnosis, type of surgery, social history, past medical history, co-morbidities and surgical history. During this assessment the participant's length of stay in ICU and hospital was calculated. Theatre details were also recorded as well as the length of time the patient was ventilated in ICU. Details regarding the participant's ICU stay were also recorded and any complications were noted. See Appendix 1 for the demographical data assessment form.

The face and content validity of the assessment and demographical forms were reviewed by the researcher and the supervisor of this study. It was also approved by the assessors group. Content was added according to similar research articles including Locket et al. (1990), Kristjansdottir et al. (2004) and Morsch et al. (2009).

3.5 **ETHICAL CONSIDERATIONS**

- The Research Committee of the private hospital approved the study. Approval number *UNIV-2017-0027 (Appendix 3)*.
- Ethical clearance was granted by the Human Research Ethics Committee of the University of the Witwatersrand. Clearance certificate *NO. M160957* (Appendix 4).
- The cardiothoracic surgeons performing the elective surgeries gave written consent to evaluate their patients for research purposes.
- Each participant gave informed consent (Appendix 5 and Appendix 6).
- The dignity of each person was preserved when any chest measurements were taken. The curtains were drawn for each patient to ensure privacy, all visitors and nursing staff were asked to wait outside for the duration of the evaluation.
- All unit managers, shift leaders, cardiologist and physicians of relevant wards and ICU's were informed and gave verbal consent to perform this study.
- Lastly, a clinical trial number was obtained from the South African Clinical Trial Registry. Trial number: *DOH-27-1217-5912*.

3.6 **PROCEDURE**

3.6.1 **Pilot Study**

3.6.1.1 **Aim of the pilot study**

During the pilot study the aim was to determine the following:

- Intra-rater reliability of the researcher when doing the physical assessments.
- Evaluating the demographic and clinical evaluation forms for understandability.
- To determine the time needed to perform the testing procedure.

3.6.1.2 **Sample size of the pilot study**

Participants were identified through daily theatre lists available in the ICU and in the cardiac ward. Six eligible participants meeting the inclusion criteria were selected. This was calculated at 10% of the total sample size calculation (Hertzog, 2008).

3.6.1.3 **Methodology of the pilot study**

Participants for the study were identified via theatre lists and bed bookings available the day before in the cardiothoracic ICU and cardiac ward. Patients are frequently admitted the night before or early in the morning before their surgery. Most surgeries are scheduled to start at 07:30. Once the patient was admitted to the hospital, an arrangement was made with the shift leader of the cardiac ward to contact the researcher. Due to human error, frequent phone calls were made to enquire whether the patient had been admitted or not. Most often, most participants were evaluated between 06:00 to 06:30 of the morning of their surgery, prior to an anti-anxiety tablet was given before surgery.

Once first contact had been made with the participant, they were given information regarding the type, objectives and structure of the study. Clear expectations were made in terms of the participant and the clinician. Once the patient had received all of the necessary information of the study, written consent was obtained via a signature on the consent form.

Once written consent was obtained, the demographics form was completed which included a subjective interview and objective assessment. The participant was evaluated in the ward they were admitted to, the curtains were drawn to ensure that the dignity of the participant was maintained. Participants were asked to sit in a chair next to their bed with their hips at a ninety degree angle, their backs supported and feet supported on the floor. Once all of the demographical data was obtained, the vital signs were taken to ensure that the participant was stable and the VAS score was analysed. To analyse if the participant was in any pain a 10cm line was placed in front of the patient and the patient was asked to document their pain level with “0” being no pain at all and “10” being the worst imaginable pain. The length of the line was then recorded and documented as a score out of ten.

To assess chest expansion, the participant was asked to expose their chest. Two anatomical markers were obtained and marked with a skin pencil. These markers included the upper thoracic excursion using the fifth thoracic spinous process and the third intercostal space at the midclavicular line. Lower thoracic excursion used the landmarks of the 10^{th} thoracic spinous process and the xiphoid process anteriorly. The soft tape cloth was first placed over the upper and then the lower landmark. The tape measure was crossed over by crossing of the hands and was kept flat against the patient’s skin as to avoid any skin folds. The

participant was then asked to breathe in and out as maximally as they could, the total circumference at maximal inspiration and expiration was recorded. The participant was allowed one practice round, there after three recordings were made and an average was calculated. Sufficient time was given between upper and lower excursion measurements to ensure that the participant did not get tired.

Thereafter, it was explained to the participant how the MIP and PIF were to be recorded. The patient remained in the same seated position, and a nose piece was placed over the nose to ensure no leakage of air. The participant was then instructed place their mouth over the mouthpiece and seal their lips tightly. Maximum inspiratory pressure was measured first, the participant was instructed to exhale or empty their lungs fully and then take a deep breath in lasting for two to three seconds. One practice effort was allowed for the patient to familiarise themselves with both of the tests. The tests for both MIP and PIF were performed three times by each patient, an average score and a predicted score were calculated to compare results.

To evaluate the chest radiograph score, all X-rays that are currently taken at the private hospital are uploaded onto a digital system, namely the Picture Archiving and Communication System (PACS system). All X-rays are easily accessible and any patient's history of radiographs can be searched with either their name, surname or hospital number. The radiograph score was calculated from the chest X-ray that was taken pre-operatively and was not completed in front of the patient.

Once a participant had come out of theatre, all clinical theatre results were obtained from theatre notes that were available in the patients file post-operatively. If they were not available in the file, they were obtained from the theatre staff that keep records separately. The ventilation time was calculated from the time out of theatre until when they were extubated. All extubations are documented on the ICU chart with an exact time the patient was extubated.

During the pilot study three measurements were taken for each physical variable. The participant patient was then allowed to rest for five minutes, a new set of vital data was recorded to ensure the patient remained stable. Thereafter, the whole process was performed a second time in the same sequence. These results were then compared to one another and an intra-rater reliability could be calculated from the results.

All six patients completed all of the assessment pre-operatively and at the day of their discharge to home. Average length of stay in hospital and ICU were then calculated. No dropouts were recorded during the pilot study phase. During the study each participant

received physiotherapy treatment for the duration of their stay. The services were rendered by two private physiotherapy practices whom the cardiothoracic surgeons refer patients to.

3.6.1.4 **Statistical analysis of the results of the pilot study**

All data collected were captured on the evaluation forms during the participant's assessments. All data were then transferred to a Microsoft Excel spreadsheet. The Microsoft Excel spreadsheet was reviewed by the supervisor of the study. The data were imported into IBM SPSS version 24 (IBM Corp. 2016) for analysis. A Spearman correlation coefficient was used due to the small sample size of the pilot study. A p-value of less than 0.05 was considered to be significant.

3.6.1.5 **Results of the pilot study**

Table 3.3: Intra-Rater Reliability Scores for Assessments at Admission

Variable	N	Mean ± SD	Spearman Correlation	P-value
Upper chest expansion ▪ Recording 1 ▪ Recording 2	6	 103,06 (±8,59) cm 102,89 (±8,54) cm	1,00	0.00
Lower chest expansion ▪ Recording 1 ▪ Recording 2	6	 99,71 (±12,33) cm 99,61 (±12,24) cm	1,00	0.00
Maximum Inspiratory Pressure ▪ Recording 1 ▪ Recording 2 ▪ Predicted	6	 58,66 (±14,81) 61,66 (±19,80) 84,65 (±18,50)	0.978	0.001
Peak Inspiratory Flow ▪ Recording 1 ▪ Recording 2	6	 2,68 (±1,4) 2,73 (±1,68)	0.989	0.005

The above mentioned data was used from admission results, for the outcome measures upper thoracic expansion, lower thoracic expansion, MIP and PIF all demonstrated very high correlations as well as statistical significance.

3.6.1.6 **Implications of the pilot study**

The pilot study was beneficial to determine whether the researcher had a good intra-rater reliability when performing the physical assessments of study participants. During the pilot study, a major limitation was noted in terms of age. Initially the inclusion criteria for age was 65, after discussions with my supervisor, it was decided that patients up until the age of 70 would be included in the main study. The reason being that there was already a significant age range with many patient being operated being between the ages of 55 to 70 years of age. Many of the patients ranged between the ages of 65 to 70, were still part of the working class and were deemed healthy and fit individuals to participate in this study.

The assessment forms were tested and were kept as is in the main study as no difficulties occurred during completion of the assessment forms. In total, to complete one full assessment ranged between twelve to twenty minutes. Time was often dependent on participants asking a lot of questions regarding the surgery.

3.6.2 Main Study

The main study followed the pilot study. During the main study all recordings were only taken once compared to the pilot study as reliability of the researcher needed to be tested. After the pilot study, the data was analysed and all readings were deemed reliable. Each participant underwent two assessments, one at baseline pre-operatively and the second at discharge from the hospital post-operatively.

The only difference between the pilot and main study was the inclusion criteria of age was increased to 70 years from 65 years. This decision was made by the researcher and supervisor, as many patients were being excluded due to their age ranging from 65-70. Many patients in this age category were still very active and contributing to a working society and we therefore decided to include them into this study. The pilot study took place in February 2018. The main study took place from March 2018 until March 2019.

Challenges experienced during data collection were:

- The hospital is also a transplant centre that performs heart and lung transplantation surgeries. Elective surgeries are often cancelled as to allow for emergency transplant surgery.
- Beds are often blocked by long-term patients that include transplant patients, Extracorporeal Membranous Oxygenation (ECMO) and Left Ventricular Assistive Device (LVAD) patients.
- The hospital is also a 24 hour emergency cardiology centre. Many cardiac emergencies are admitted which require the insertion of either an ECMO or a balloon-pump, these patients are then excluded from the study.
- Due to the experience of the cardiothoracic surgeons, many patients referred to this centre are complex cases and have had multiple cardiac surgeries before.

3.7 DATA ANALYSIS OF THE MAIN STUDY

Data of the main study were captured into a Microsoft Excel spreadsheet. The data were imported into IBM SPSS version 24 for further analysis.

- To determine whether data was normally distributed, a Shapiro-Wilks test was used. If the p-value was less than 0.05, the data was seen as not normally distributed as it significantly deviated from normal distribution.

- For data that was normally distributed, means and standard deviations were calculated. For data that was not normally distributed, frequencies were calculated and the median and interquartile ranges were used.
- To determine pre and post test results, a Paired Samples T-test was used for parametrical data and a Wilcoxon Signed-Rank test was used for non-parametrical data.
- Subsequently to calculate correlations within the data, Spearman's Rank-Order Correlations were calculated for non-parametrical data and Pearson's Product-Moment correlations for parametrical or normally distributed data.
- The strength of association of the correlation coefficient between two valuable was measured and interpreted as follows (Portney & Watkins, 2008):
  - 0.00 to 0.25 = Little or no relationship
  - 0.25 to 0.50 = Fair Relationship
  - 0.50 to 0.70 = Moderate to fair relationship
  - Above 0.75 = Good to excellent relationship

The results from this study are presented in Chapter 4.

CHAPTER 4

4. RESULTS

4.1 INTRODUCTION

This chapter presents the results obtained through data collected from the observational study. The results relating to each of the research objectives will be presented. The findings of the study will be presented under the following subheadings:

- Objective 1: Demographic Profile of Participants
- Objective 2: Clinical Profile of Participants
- Objective 3: Ventilation kinematics results
- Objective 4: Correlations

Figure 4.1 is a flow diagram of the representation of the number of participants, from interest to participation in the study.

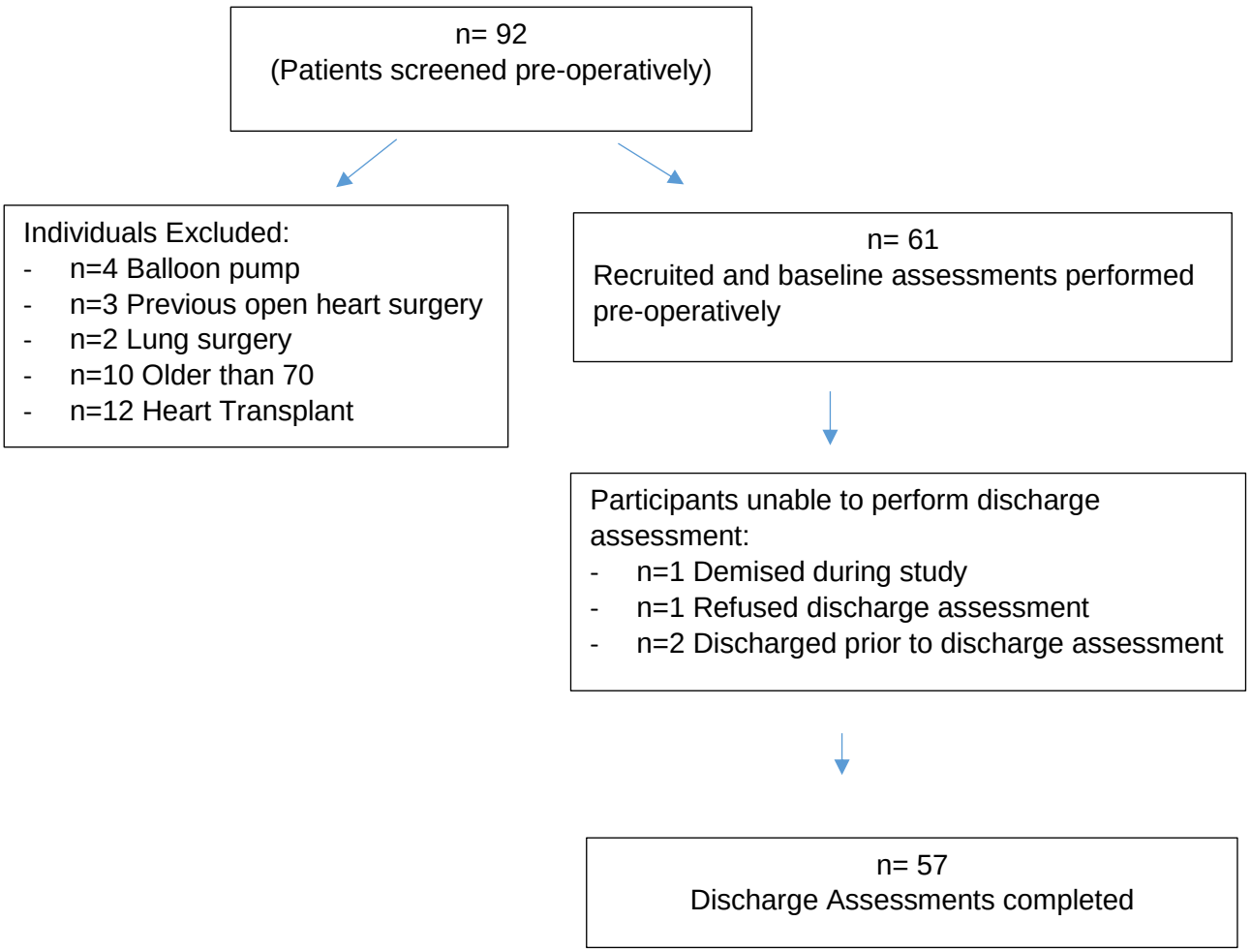


Figure 4.1: Flow Diagram for the Movement of Patients

4.2 OBJECTIVE 1: DEMOGRAPHIC PROFILES OF PARTICIPANTS

The age analysis of the study population of the 61 participants that participated in this study revealed a median age (IQR) of 59 (22). The youngest participant was 19 years of age and the oldest was 70 years of age. The study consisted of 72.10% (n=44) male and 27.90% (n=17) female participants.

4.3 OBJECTIVE 2: CLINICAL PROFILE OF PARTICIPANTS

4.3.1 Physical Function Status of Participants

All participants (n=61, 100%) that were included in this study were independently mobile pre-operatively without an assistive device. When re-evaluated at hospital discharge, five participants (8.20%) required a walking aid for independence while the rest (n=56, 91.80%) did not.

4.3.2 Height and Weight Distribution of Participants

Height and weight measurements were necessary to calculate the normal predicted value for MIP of each participant. The mean height (±SD) for the study population was 1.72m (±0.09) and weight was 81.99kg (±15.39).

4.3.3 Surgery Details of Participants

For all participants that underwent cardiac surgery, a median sternotomy procedure was performed (n=61, 100%). Figure 4.2 is an outline of the surgery types done.

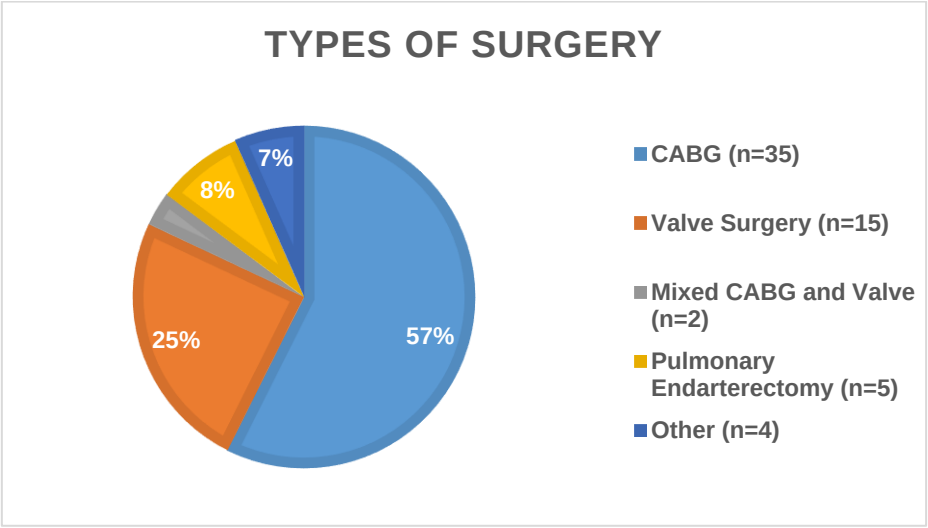


Figure 4.2: Types of Surgery (N=61)

Most study participants (n=35, 57%) underwent CABG. Other surgeries included thymectomies, mitral valve aneurysm repair and atrioseptal defect repair.

Individuals who undergo cardiac surgery often have surgical drains inserted post-operatively. Table 4.1 provides information regarding the drains present in patients post-operatively.

Table 4.1: Surgical Drains Present in Patients Post-Operatively

Type of Surgical Drain	**n (%)**
Mediastinal	61 (100%)
Pericardial	61 (100%)
Pleural No Drain Left Pleural Drain Left and Right Pleural Drains	 22 (36.10%) 33 (54.10%) 6 (9.80%)

All patients had mediastinal and pericardial drains inserted post-operatively (n=61, 100%). A left pleural drain (n=33, 54.10%) was often present post-operatively. Left pleural drain are commonly inserted due to the left mammillary artery grafting done to use as a potential grafting for CABG.

4.3.4 Theatre Information of Participants

The mean (±SD) amount of time each participant spent in theatre was 5.85 (±1.30) hours, with the minimum amount of time being 2.58 hours and the maximum 8.17 hours.

Table 4.2: Amount of time in Theatre, on Cardiac Bypass and Aortic Clamp

	Theatre Time (hours)	**Time on Bypass (hours)**	**Time on Aortic Clamp (hours)**
N	61	61	61
Mean (± S.D)	5.84 (±1.30)	n/a	n/a
Median (IQR)	n/a	2.01 (1.14)	1.36 (0.85)

Table 4.2 presents the amount of time each participant spent on cardiac bypass as well as aortic clamp. The median time spent on bypass was 2.01 (1.14) hours and on aortic clamp was 1.36 (0.85) hours.

4.3.5 ICU and Ward Information of Participants

The median (IQR) of time participants were ventilated was 17.33 (11.21) hours. The median amount of time participants spent in ICU was five (2.75) days. The minimum amount of time spent in ICU was one day and the maximum was 41 days. The median length of stay in hospital was nine (7) days with the minimum number of days four and the maximum 85 days.

4.3.6 Vital Signs of Participants at Admission and Discharge from Hospital

All vital signs were stable for all participants at admission and discharge before and after testing. No adverse vital signs were recorded during test procedures.

Table 4.3: Vital Signs of Participants at Admission and Discharge from Hospital

Variable	N	Mean	Standard Deviation	Normal range Main & Denehy, 2016)
Admission				
Heart Rate, bpm	61	77.98	16.01	50-100
Respiratory Rate, breaths/minute	61	16.43	2.34	12-16
Blood Pressure – Systolic, mmHg	61	121.57	17.12	95-140
Blood Pressure – Diastolic, mmHg	61	72.97	10.90	60-90
Temperature, degrees Celsius	61	36.28	0.47	36.5-37.5
Oxygen Saturation (SpO_2), %	61	95.34	2.81	97-100
Discharge				
Heart Rate, bpm	57	80.21	9.90	50-100
Respiratory Rate, breaths/min	57	16.70	1.97	12-16
Blood Pressure – Systolic, mmHg	57	118.42	14.62	95-140
Blood Pressure – Diastolic, mmHg	57	68.26	9.61	60-90
Temperature, degrees Celsius	57	36.63	0.45	36.5-37.5
Oxygen Saturation (SpO_2), %	57	93.35	2.77	97-100

Bpm (beats per minute), mmHg (millimetres mercury), % (percentage), SpO2 (Pulse oximetry saturation)

Oxygen saturation of study participants at discharge from hospital was below the admission finding and the suggested normal range for adult patients.

A paired-sample t-test was performed on vital signs. Oxygen saturation (p=0.001), temperature (p=0.001) and diastolic blood pressure (p=0.004) were significantly different from admission to discharge.

4.3.7 Chest X-Ray and VAS Pain Scores at Admission and Discharge from Hospital

Table 4.4 is a representation of the chest X-ray findings as assessed with the chest X-ray score proposed by Kristjansdottir et al. (2004).

Table 4.4: Chest X-ray Scores at Admission and Discharge from Hospital

	Admission	Discharge
CXR: Atelectasis		
None	61 (100%)	32 (52.5%)
Minor	0 (0%)	20 (32.8%)
Medium	0 (0%)	8 (13.1%)
Major	0 (0%)	0 (0%)
CXR: Pleural		
None	57 (93.4%)	34 (55.7%)
Minor	4 (6.6%)	26 (42.6%)
Medium	0 (0%)	0 (0%)
Major	0 (0%)	0 (0%)
CXR: Diaphragm		
None	59 (96.7%)	43 (70.5%)
Minor	2 (3.3%)	16 (26.2%)
Medium	0 (0%)	1 (1.6%)
Major	0 (0%)	0 (0%)

CXR (Chest X-Ray)

On admission, all participants presented with no atelectasis, 57 (93.4%) of participants showed no evidence of pleural effusions with four (6.6%) showing minor changes of the costophrenic angle pre-operatively. The majority (n=59, 96.7%) of participants had normal diaphragm height on chest x-rays with only two (3.3%) patients presenting with minor elevation of the diaphragm.

At discharge, 32 (52.5%) of the participants presented with no atelectasis, 20 (32.8%) presented with minor atelectasis and 8 (13.1%) of participants presented with medium atelectasis showing significant shadowing of at the basal segments of the lung and in the retrocardial area. When evaluating the pleural space on CXR, 34 (55.7%) showed no pleural changes and 26 (42.6%) participants showed minor filling of the costophrenic angle, no other major changes were found. The third component of the CXR score included the position of the diaphragm, 43 (70.5%) showed no changes on diaphragm height at discharge, 16 (26.2%) of participants presented with minor changes where the left diaphragm is only slightly more elevated compared to the right, and only 1 (1.6%) participant presented with the diaphragm elevated up to half of the height of the left heart border.

Table 4.5 is an outline of the VAS pain scores of study participants at admission and discharge from hospital.

Table 4.5: VAS Pain Scores of Study Participants at Admission and Discharge from Hospital

	Admission		Discharge	
Score /10	**Frequency**	**Percentage**	**Frequency**	**Percentage**
0	58	95.1%	5	8.2%
1	0	0%	1	1.6%
2	2	3.3%	7	11.5%
3	0	0%	8	13.1%
4	0	0%	21	34.4%
5	0	0%	6	9.8%
6	0	0%	3	4.9%
7	0	0%	3	4.9%
8	0	0%	2	3.3%
9	1	1.6%	1	1.6%
10	0	0%	0	0%
Total	61	100%	57	100%

Most participants, 58 out of 61 (95.1%) at admission presented with VAS scores of 0/10, two (3.3%) participants had pain scores of 2/10 and one participant presented with a pain score of 9/10. At the time of hospital discharge more study participants presented with pain: 21 (34.4%) presented with pain scores of 4/10, eight (13.1%) participants presented with pain scores of 3/10 and seven (11.5%) of participants presented with pain scores of 2/10. Participants that did experience pain described pain centrally over their median sternotomy wounds, especially when taking a deep breath or when coughing.

A Wilcoxon Signed Rank Test showed that there was a significant difference in chest x-ray scores as well as pain levels at discharge from hospital compared to admission findings. The difference between the chest x-ray total scores from admission to discharge changed from a median from 3/12 to 4/12, with the min-max scores changing from 3-4 to 3-5, this elicited a statistically significant change ($Z=-5.825$, $p<0.001$). As for pain levels, the median score at admission was 0/10 (min-max=0-9) and for discharge was 4 (min-max=0-9), this also elicited a statistically significant change ($Z=-5.867$, $p<0.001$).

4.4 OBJECTIVE 3: EFFECTS OF A MEDIAN STERNOTOMY ON VENTILATION KINEMATICS WHEN EVALUATING CHEST WALL EXPANSION AND INSPIRATORY RESPIRATORY MUSCLE STRENGTH

4.4.1 Chest Wall Expansion Results

The results for the participants upper and lower thoracic expansion are portrayed below in figure 4.3.

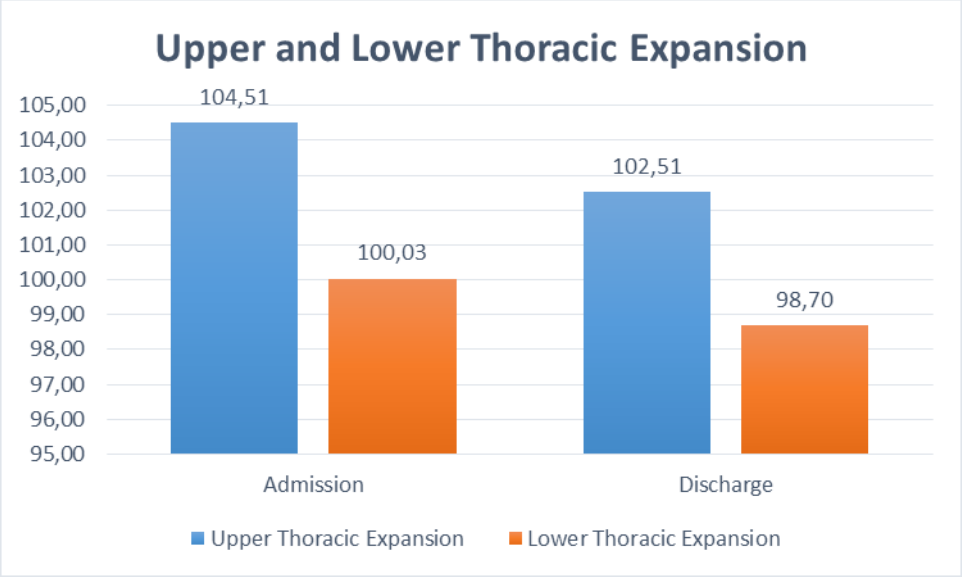


Figure 4.3: Upper and Lower Thoracic Expansion findings

The median (IQR) upper thoracic expansion for admission was 104.51cm (12.9) and showed a statistical significant difference to the discharge measurement of 102.51cm (12) when performing a Wilcoxon signed rank test ($p<0.001$). For lower thoracic expansion, the difference between mean (±SD) admission and mean (±SD) discharge (100.03cm (±12.04) vs. 98.70cm (±12.07)) showed a statistical significant difference when a Paired Samples T-test was performed ($p=0.001$).

4.4.2 MIP and PIF Results

Table 4.6 is an outline of the MIP and PIF findings of study participants at admission and discharge from hospital.

Table 4.6: Results for MIP and PIF of Study Participants at Admission and Discharge from Hospital

	Admission	% Predicted Admission	Discharge	% Predicted Discharge	Predicted
MIP (median (IQR)) ,cmH_20	55 (39.5)	58.66 (37.12)	30.66 (20)	33.26 (22.46)	94.69 ± 12.16
PIF (median (IQR)), l/s	2.70 (1.81)	n/a	1.66 (1.07)	n/a	n/a

The mean (±SD) predicted value of MIP for the study population was 94.69cmH_20 (±12.16). The median (IQR) MIP at admission was 55cmH_20 (39.5cmH20), with the percentage of the predicted MIP at 58.66cmH_20 (37.12cmH_20). There was a large distribution of values for the participants with the lowest MIP value of 8cmH_20 and the highest value of 127.33cmH_20. The discharge value was significantly lower than admission with MIP at 30.66cmH_20 (20cmH_20) and the percentage of the predicted MIP at 33.26cmH_20 (22.46cmH_20).

There was a statistical significant change for MIP of study participants when discharge values were compared with admission findings (Z=-4.75, p<0.001) and for the difference of the change for the percentage of the predicted MIP achieved at discharge (Z=-5.94, p<0.001). There was also a significant difference for PIF between admission and discharge (Z=-4.75, p<0.001).

4.5 OBJECTIVE 4: CORRELATIONS

4.5.1 Correlation between Outcomes and Age of Participants

A Spearman's rank-order correlation was run to determine the relationship between the outcomes measured and ages of the participants.

Table 4.7: Spearman's Correlations between Ventilation Kinematics and Ages of Participants at Admission and Discharge

	r-value	p-value
Admission		
Upper Thoracic Expansion	0.16	0.21
Lower Thoracic Expansion	0.22	0.078
Peak Inspiratory Flow	-0.086	0.510
Maximum Inspiratory Pressure	-0.062	0.637
Predicted MIP	-0.319	**0.012***
% Predicted MIP achieved	0.739	**0.044***
Discharge		
Upper thoracic expansion	0.195	0.147
Lower thoracic expansion	0.286	**0.031***
Peak Inspiratory Flow	-0.089	0.510
Maximum Inspiratory Pressure	-0.11	0.410
% Predicted MIP achieved	-0.005	0.969

**Statistically significant (p<0.05)*

There was a fair negative correlation between the predicted MIP and age, which was statistically significant (r=-0.319, p=0.012). At discharge, there was a fair, positive correlation between lower thoracic expansion and age (r=0.286, p=0.031). These results can be interpreted that as the age of the participants increases, the lower thoracic expansion also increases and the predicted MIP decreases. This can be attributed to the change that occurs to the thoracic cage in the natural process of aging, causing an increase in the diameter of the chest wall with associated decreased muscle strength.

4.5.2 Correlation between Ventilation Kinematics and Theatre Variables at Discharge

Table 4.8 presents the Spearman's correlations performed between the ventilation kinematic of the participants and the time in theatre, on bypass and aortic clamp.

Table 4.8: Spearman's Correlation between Ventilation Kinematics and Theatre Variables at Discharge

		Time Theatre	Time Bypass	Time Aortic Clamp
Upper Thoracic Expansion	Correlation Coefficient	0.129	-0.008	0.013
	p-value	0.340	0.954	0.923
Lower Thoracic Expansion	Correlation Coefficient	0.086	-0.104	-0.062
	p-value	0.524	0.441	0.648
Peak Inspiratory Flow	Correlation Coefficient	0.046	-0.056	-0.135
	p-value	0.732	0.676	0.316
Maximum Inspiratory Pressure	Correlation coefficient	0.098	0.054	-0.008
	p-value	0.467	0.690	0.954

There were no statistically significant correlation to suggest that theatre variables influenced any changes in ventilation kinematics at discharge evaluation.

4.5.3 Correlation between the Change in Ventilation Kinematics and ICU Variables

A Spearman's correlation was run to determine the relationship between upper thoracic expansion and length of time intubated post-operatively.

Table 4.9: Spearman's Correlation between discharge Outcomes and Length of Time Intubated, Length of Stay in ICU and Hospital

		LOT MV	LOS ICU	LOS HOSP
Upper Thoracic Expansion	Correlation Coefficient	-0.261	-0.139	-0.146
	p-value	**0.050***	0.302	0.277
Lower Thoracic Expansion	Correlation Coefficient	-0.195	-0.078	-0.028
	p-value	0.145	0.564	0.836
Peak Inspiratory Flow	Correlation Coefficient	-0.091	0.017	-0.025
	p-value	0.502	0.899	0.856
Maximum Inspiratory Pressure	Correlation coefficient	-0.065	0.014	-0.062
	p-value	0.629	0.920	0.646

LOT (Length of time), MV (Mechanical ventilation), LOS (Length of Stay), ICU (Intensive Care Unit), HOSP (Hospital).

There was a fair, negative correlation between these two variables which was statistically significant (r=-0.261, p=0.05). No other correlations were found between discharge ventilation kinematics and length of time intubated, length of stay in hospital and ICU as outlined above in Table 4.9.

4.5.4 Correlation between Ventilation Kinematics and Chest X-ray and VAS Pain Scores

A Spearman's Correlation was run to evaluate the relationship between ventilation kinematic findings at admission and discharge for Chest X-ray Total scores and VAS pain scores.

Table 4.10: Spearman's Correlation for Ventilation kinematics and Chest X-ray and VAS Scores at Admission and Discharge

		CXR Admission	VAS Admission	CXR Discharge	VAS Discharge
Admission Outcomes					
Upper Thoracic Expansion	Correlation Coefficient	-.0.156	-0.70	-0.133	0.004
	p-value	0.229	0.594	0.309	0.975
Lower Thoracic Expansion	Correlation Coefficient	-0.056	-0.106	-0.146	-0.053
	p-value	0.667	0.418	0.266	0.695
Peak Inspiratory Flow	Correlation Coefficient	-0.278	0.014	0.037	0.073
	p-value	**0.03***	0.913	0.776	p=0.587
Maximum Inspiratory Pressure	Correlation coefficient	-0.367	-0.051	0.003	0.08
	p-value	**0.004***	0.697	0.984	0.552
Predicted MIP	Correlation coefficient	-0.169	-0.077	-0.049	-0.050
	p-value	0.193	0.555	0.708	0.710
Discharge Outcomes					
Upper Thoracic Expansion	Correlation Coefficient	-0.195	-0.119	-0.088	0.047
	p-value	0.147	0.378	0.515	0.729
Lower Thoracic Expansion	Correlation Coefficient	-0.111	-0.119	-0.112	-0.006
	p-value	0.410	0.378	0.408	0.966
Peak Inspiratory Flow	Correlation Coefficient	-0.224	0.187	0.033	-0.004
	p-value	0.094	0.63	0.808	0.974
Maximum Inspiratory Pressure	Correlation coefficient	-0.202	0.129	0.056	-0.084
	p-value	0.133	0.341	0.680	0.535

CXR (Chest X-Ray), VAS (Visual Analogue Scale)

There was a fair, negative correlation, between admission PIF and MIP with Chest X-ray Total scores at admission, which was statistically significant (PIF; r=-.278, p=0.03) (MIP; r=-0.356, p=0.004). Detail regarding the results are outlined above in Table 4.10.

Chapter 5 will present the discussion chapter of the research report.

CHAPTER 5

5. DISCUSSION

5.1 INTRODUCTION

The precise effect of a median sternotomy incision used during cardiac surgery and how it effects ventilation kinematics post-operatively is still poorly understood. There are few studies that have evaluated chest expansion, spirometry values and MIP pre- and post-operatively following cardiac surgery. The published literature will be compared to the current study findings to assist in gaining an overall perspective of ventilation kinematics following a median sternotomy.

The main finding of the current study was that there was a significant difference of all clinical outcomes evaluated, namely thoracic expansion; MIP; PIF; chest x-ray scores when measured at admission and at discharge.

The discussion will be structured according to the objectives of this study, namely:

- Objective 1: Demographic Profiles
- Objective 2: Clinical Profiles
- Objective 3: Ventilation Kinematics

5.2 DEMOGRAPHIC PROFILES

5.2.1 Age

There was a wide range of age groups included in this study, the youngest patient was aged 19 and the oldest was aged 70, with the median age being 59. The reason for including a wide age range was to include the working population of South Africa. The age range was increased from 65 to 70 after the pilot study, as a large group of fit and working population were being excluded.

Cardiovascular disease is one of the main causes of premature death and disability. The underlying pathology of CVD and atherosclerosis develops over many years and usually becomes symptomatic by middle age (Sanchis-Gomar et al. 2016). The risk of developing therefore increases with age, especially over the age of 45 for men, and over the age of 55 for women (Maas & Appelman, 2010). Coronary heart disease is still the cause of one third of all deaths in people older than 35 (Sanchis-Gomar et al. 2016). In conjunction of coronary heart diseases, valvular diseases are becoming more prevalent accounting for more than 20% of all cardiac surgeries in Europe. Valvular disorders are most prevalent in young adolescents owing to congenital disorders and thereafter sharply increase after the age of 65 years due to degenerative causes (Lung & Vahanian, 2011). Heart diseases that require

intervention in the form of surgery affect a majority of age groups in the working population all over the world.

5.2.2 Gender

During the course of this study, more males (n=44, 72.10%) were included than females (n=17, 27.90%). Conventional risk factors for coronary heart disease place men at a higher risk of developing heart disease, especially when family history is prevalent (Hajar 2017).

Women are said to develop cardiovascular disease seven to 10 years later than men, but is still a major cause of mortality in women over the age of 65. This is due to the exposure of endogenous oestrogens during fertility years that delays the onset of atherosclerotic disease (Maas & Appelman 2010) .

5.3 CLINICAL PROFILES

5.3.1 Physical Function

All patients included in this study were independently mobile without any assistive device pre-operatively. Due to the nature of cardiac surgery being acute on sub-acute, most patients that undergo surgery do not have physical abnormalities. At discharge, only five (8.20%) patients required a walking aid for walking. Physical function is important to establish pre-operatively as it has a direct influence on the outcomes of surgery. Numerous studies have proved that frail patients, with multiple co-morbidities, experience higher rates of post-operative morbidity, mortality, increased length of hospital stay as well as increased economic burden. A lack of physical activity can therefore be very problematic when undergoing surgery (Stammers et al. 2015).

The five participant that required an assistive device at discharge, presented with an average age of 61.6 years, the youngest participant being 45 and the oldest 68. Four out of the five participant where above the age of 62 years. Two patients underwent CBG, one underwent an aortic valve replacement and two underwent pulmonary thromboendarterectomies. The youngest participant that required an aortic valve replacement, had comorbidities of cholesterol, hypertension and low left ventricular function (ejection fraction 40%) pre-operatively. The participant had an episode of cardiac arrest after extubation (length of time intubated was 22hours and 8mins) in ICU. The participant however only spent five days in ICU and eight days in hospital.

The other four patients were all over the age of 62 years, their average length of stay in ICU were 27.5 days and their average length of stay in hospital was 49.5 days. The participants were intubated for 342hours and 31minutes with the lowest being 37hours and 15minutes and the longest 629hours and 51minutes. The two patients undergoing pulmonary

endarterectomies (PEA) were ventilated for much longer respectively, with one patient undergoing a tracheostomy procedure. Both respective patients had no other co-morbidities except for chronic thromboembolic pulmonary hypertension. Both patients were also discharged with domiciliary and portable oxygen.

A pulmonary endarterectomy is deemed a complex procedure, out of the five patients that underwent this procedure, one patient sadly passed away and all others had increased length of hospital and ICU stay. Pulmonary endarterectomy surgery is aimed at improving symptoms of pulmonary hypertension, increasing exercise tolerance and improving overall quality of life (Taboada et al. 2014). Due to increased surgical techniques and knowledge, the mortality rate of PEA are similar to that of conventional cardiac surgeries, ranging from between 2.4-4.4% (Madani et al. 2016). Patients that presented with severe long-standing increased peripheral vascular resistance were specifically known to increase mortality rates. Reperfusion pulmonary oedema following surgery is a common phenomenon in the lobes where arteries have been endarterectomised, this occurs in 10-40% of cases within the first 72 hours after surgery (Sang et al. 2016). This may be linked to the severity of the pre-operative pulmonary hypertension (Sang et al. 2016).

During this study by Sang et al. (2016) the median amount of time ventilated was two days, the median amount of time in ICU was five days and in hospital was fifteen days. This is significantly less than the results found in the current study, although their study population was significantly larger. One could speculate in this study that persistent hypoxaemia due to reperfusion injury and damaged microvasculature caused increased ventilation times and length of stay in ICU, causing debilitating weakness requiring patients to require the use of an assistive device and domiciliary oxygen. Participants undergoing PEA that have suffered the consequences of pulmonary hypertension for a long amount of time, may be deconditioned preoperatively due to low exercise tolerance. This may cause deconditioning of patients as it presents as a chronic disease with declining functional ability, even though none of the participants required assistive devices preoperatively, patients may appear as frail by the time they are considered for surgery. Frail patients are at increased risk of mortality and prolonged hospitalisation after surgery (Lee et al. 2010).

The remaining two participants both underwent CABG surgeries for ischaemic heart disease. The one patient presented with full metabolic syndrome pre-operatively that included gout, hypertension, diabetes mellitus, obstructive sleep apnoea and an increased BMI. The patient was also subsequently in chronic renal failure and received dialysis three times a week at an outpatient facility. This specific participant spent 18 days in ICU and 29 days in hospital and was ventilated for 37hours and 15min. The participant received intermittent dialysis while in hospital. The other participant also presented with type 2 diabetes and hypertension, this

participant complicated on day two post-operatively due to a pulmonary embolism. He had to be re-intubated and received dialysis for an acute kidney injury. This participant received a tracheostomy and was ventilated for a total time of 588hours and 40minutes.

A common denominating factor between both of these participants was diabetes. Diabetes and hyperglycaemia has been well described in literature with worse outcomes in hospitalised and surgical patients and is common in patients undergoing cardiac surgery. Duncan et al. (2010) found that both intraoperative and postoperative glucose measurements were important to predict outcomes after cardiac surgery and had an independent effect on morbidity and mortality postoperatively (Duncan et al. 2010). Hyperglycamia is common after a stressful event such as cardiac surgery and is associated with higher risk of complications that may include infections and increased mortality as mentioned previously.

Greco et al. (2016) confirmed that patients undergoing cardiac surgery that were diagnosed with diabetes were associated with higher costs and longer hospital LOS compared to patients with no diabetes. In patients with no diabetes hospital LOS, cost of hospitalisation and the incidence of infection all increased with increasing levels of glucose (Greco et al. 2016). Diabetes has been associated with alterations in the metabolism of muscle protein that causes decreased muscle mass that can lead to poor functionality.

Insulin-dependent diabetes has also been proven to be a direct risk factor for developing an acute kidney injury post-operatively ($p=0.012$) (Parolari et al. 2012). Acute kidney injuries following surgery has consequently also been linked in the short term to with increased hospital LOS, increased infection risk, increased cost and mortality (Parolari et al. 2012). Increasing creatinine levels following cardiac surgery also predispose patients presenting with chronic renal failure to progressing into worsening renal failure compared to preoperative values and may require more frequent dialysis interventions than previously required, increasing hospital LOS and costs (Ishani et al. 2011). Similarly to diabetes and other inflammatory conditions, acute and chronic renal failure involve the stimulation of the ubiquitin-proteasome system (UPS) and caspase-3, causing protein degradation on a cellular level (Thomas & Mitch, 2013). This leads to muscle wasting and atrophy, worsening the burden of disease and decreasing functional ability if muscles are severely affected.

A similar process occurs as a result of cardiac surgery, a state of catabolism is induced due to elevation of inflammatory cytokines in the postoperative period. This is directly associated with immediate postoperative muscle weakness caused by muscle proteolysis (Lida et al. 2014).

The aforementioned participant's functional abilities could have been caused by various different mechanics either owing to preoperative, intraoperative and postoperative complications. Comorbidities including diabetes predispose participants to risk factors that may affect their functional ability postoperatively and increase the length of their total hospital stay.

5.3.2 Height and Weight

The mean height for the included study population was 1.72metres and the mean weight was 81.99kg. For the purpose of this study, height and weight were used to calculate the predicted MIP for each patient. Usually, height and weight are used to calculate the BMI for patients. Using the mean height and weight values of the sample the BMI of the population was 27.79kg/m^2 indicating an overweight group of individuals. Obesity and high BMI's is a major risk factor in the development of cardiovascular disease and has been associated with increased mortality, major morbidity, increased LOS in ICU and hospital and incurred more costs (Ghanta et al. 2017). Higher BMI patients are also likely to have more comorbidities including diabetes, hypertension and congestive cardiac failure. Adding to increased morbidity, obese and morbidly obese patients had prolonged ventilation times, a greater incidence of pneumonia, deep sternal wound infections and renal failure (Ghanta et al. 2017). The risk for mortality is said to increase with a BMI ≥30, morbidly obese patients have a 1.57 increased odds for mortality when compared to normal weight patients (Ghanta et al. 2017).

Obesity is a noteworthy risk factor to evaluate to predict potential complications. Increased ventilation times and the potential for developing PPCs such as atelectasis and pneumonia may adversely affect ventilation kinematics postoperatively. Obesity causes altered chest wall mechanics, decreased lung volumes and increased resistance of the respiratory system. Obesity related chronic inflammation can impair and decrease the contractile properties of the respiratory muscles causing poor force generating capacities leading to decreased respiratory muscle strength and endurance. A combination of decreased respiratory muscle strength and increased respiratory demand postoperatively may predispose obese participant to develop pulmonary complications (Severin, 2019).

5.3.3 Surgery Type

Most patients (n=35, 57%) that participated in this study underwent CABG surgery, either for acute coronary syndrome or ischaemic heart disease. This co-insides with the mean age of 59 of the study population, as previously mentioned this population is most at risk for developing CVD.

Fifteen patients underwent valve surgery for various different conditions, these included either mitral valve regurgitation or prolapse, or aortic valve stenosis. Two patients underwent mixed valve and CABG surgery.

Five patients underwent PEA via median sternotomy, these patients all presented with chronic thromboembolic disease. Other surgeries included in this study was one mitral aneurysm repair, one secundum atrioseptal-defect (ASD) repair and two thymectomies for Myasthenia Gravis.

In Africa, there is currently only one cardiac centre per 33 million people, compared to 120 00 people in the United States (Zilla et al. 2018).

5.3.4 Post-Operative Drains

All patients had a mediastinal and pericardial drain inserted post-operatively. These drains are commonly placed retrosternal and retrocardiac positions to allow drainage of serosanguineous fluid from the mediastinum to prevent cardiac tamponade (Bansal et al. 2019). Chest drains are also critical in alerting ICU-staff to whether the patient has internal bleeding, air leaks or anastomic leaks, pericardial effusions or heamothorax (Shalli et al. 2009). Occlusion of drainage tubes are just as life threatening as they can lead to complications such as cardiac tamponade, sepsis and tension pneumothorax (Shalli et al. 2009). There is no clear consensus about the number of chest drains used post-operatively, this is guided by individual preference and institutional experience (Bansal et al. 2019).

Left and right sided pleural drains were also prevalent during this study, with 54.10% participants having left pleural drains inserted and 9.80% of patients having both left and right pleural drains inserted post-operatively. Pleural drains are predominantly inserted intercostally typically in the 6^{th} intercostal space and directed towards the apex of the lung, when left and/or internal mammary arteries are grafted and used as conduits for blocked coronary arteries (Abo Elnasr et al. 2017b).

Pleural drainage is often associated with higher post-operative pain, which may lead to pulmonary complications included hypoventilation and atelectasis (Abo Elnasr et al. 2017b). Pleural drains perforate the intercostal pleura as well as the intercostal muscles and cause great trauma to the chest wall. Insertion of intercostal drains have been directly associated with decreased pulmonary function in the immediate post-operative period (Abo Elnasr et al. 2017b). Due to constant irritation of the intercostal nerves and pleura due to friction produced by movement and breathing, patients usually limit themselves to shallow breathing and restricted immobilization and deep breathing efforts. This decreases the patient's functional residual capacity, functional vital capacity and FEV_1 immediately post-operatively (Guizilini

et al. 2004; Guizilini et al. 2007; Abo Elnasr et al. 2017b). This in return can cause decreased lung compliance, with increased work of breathing, decreased tidal volumes leading to alveolar collapse and consequent hypoxia (Guizilini et al. 2004).

Pleural intercostal drains are inserted when the left and/or right internal mammary arteries are dissected for grafts.

5.3.5 **Theatre Time**

The mean amount of time each participant spent in theatre was 5.85 hrs (±1.30hrs), with the minimum amount being 2.58 hrs and maximum 8.17 hrs. The median time spent on CPB was 2.01 hrs (1.14hrs) and on aortic cross-clamp was 1.36 hrs (0.85hrs).

Many studies have proven that CPB time and aortic cross-clamp times used during cardiac surgery are independent predictors for mortality and morbidity in the post-operative patient. Prolonged aortic cross-clamp times are associated with low cardiac output states, renal compromise and acute kidney injuries, prolonged ventilation as well as neurological deficits post-operatively (Hein et al. 2006; Shultz et al. 2016). Many studies suggest that the least adverse events occur within the ≤60 minutes of aortic-cross clamp, and that in-hospital mortality is significantly higher when a patient is cross-clamped for more than ≥ 90 minutes (Shultz et al. 2016).

Cardiopulmonary bypass has been associated with PPCs in conjunction with other contributing factors such as anaesthesia, temporary cardiac dysfunction, medication and altered thoracic cage mechanics. Cardiopulmonary bypass is said to cause a systemic inflammatory reaction that may lead to disturbances in lung mechanics leading to post-operative gaseous exchange abnormalities (Apostolakis et al. 2010). During CPB arterial flow to the bronchial arteries are maintained, however pulmonary arterial flow is markedly decreased (Stephens et al. 2013). Once reperfusion is restored, the lungs undergo an ischaemia-reperfusion cascade that leads to the production of reactive oxygen species, this predisposes the patient to pulmonary injury. During procedures such as pulmonary endarterectomies, longer periods of pulmonary ischaemia are required and these patients are at higher risk of developing ischaemic reperfusion injuries leading causing severe shunt physiology and hypoxaemia, leading to pulmonary oedema and acute respiratory distress syndrome. This commonly occurs within the first 72 hours post-operatively (Stephens et al. 2013).

The amount of time spent in theatre including CPB and aortic cross-clamp time include intraoperative factors that may predispose any participant undergoing cardiac surgery to postoperative complications.

5.3.6 Length of Time on Mechanical Ventilation

The median amount of time participants were ventilated post-operatively was 17.33 hrs (11.21hrs).

Due to the induction of general anaesthesia during cardiac surgery, most patients are mechanically ventilated post-operatively until normal temperatures and haemodynamic stability have been achieved (Flynn et al. 2019). The earliest possible extubation post-operatively has become the standard of care after cardiac surgery. “Early” extubation protocols are normally set into motion post-operatively to reduce the incidence of post-operative complications, these include pneumonia, sepsis, reintubation, decreased ICU and hospital length of stay as well as decreasing the cost associated with cardiac surgery (Flynn et al. 2019). Achieving extubation within six to eight hours post-operatively is seen as gold standard in low to moderate risk patients. Prolonged ventilation of patients are directly influenced by the age of the patient, previous cardiac surgery, peripheral artery disease, left ventricular hypertrophy, renal insufficiency and failure, emergency procedures, mixed cardiac surgical procedures and chronic obstructive pulmonary disease (Widyastuti et al. 2012).

5.3.7 Length of Stay in ICU and Hospital

The median amount of time participant spent in ICU was five days (2.75 days), with the minimum amount of days being one day and the maximum amount being 41 days. The median length of stay in hospital was nine days (7days) with the minimum number of days four and the maximum 85 days.

Most frequently patients were discharged from ICU once all their drains were removed, all inotropic support was weaned and patients were deemed haemodynamically stable, all rhythmic support i.e. external pacemakers were weaned off and the surgeon agreed the patient could be discharged. Factors that are most frequently associated with increased LOS in ICU include arrhythmias, atrial fibrillation, increased age, renal failure, emergency surgery and COPD (Almashrafi et al. 2016). Osnabrugge et al. (2014) found similarly that the average postoperative length of stay was a mean of 6.9 days. Pre-operative risk factors that included previous valve surgery, preoperative cardiogenic shock, emergency surgery and inotropic medications were said to be the highest risk for increase in the additional length of stay by two days when a regression analysis was done. When Osnabrugge et al. (2014) performed a combined model they found that predominantly post-operative event including reoperation for non-cardiac reasons, deep sternal wound infections and pneumonia were the highest cause for patients spending additional time in hospital (12.81, 11.77 and 7.61 extra hospitalised days) (Osnabrugge et al. 2014).

The current patients that were in hospital for the longest duration, i.e. 85 days, required mobility devices once discharged. Depending on the course of the participants hospital stay, factors that influence LOS in hospital such as prolonged mechanical ventilation, renal failure and infections, may affect the patient's physical ability. Intensive care unit-acquired weakness (ICUAW) affects patients whom are admitted to ICU for longer than one week (Fischer et al. 2016). The main risk factors include sepsis, hyperglycaemia and immobility (Fischer et al. 2016). ICUAW can affect patients undergoing cardiac surgery and may be rapidly progressed by aforementioned muscle proteolysis caused by hyper catabolism.

5.3.8 **Vital Signs**

When post-operative vital signs were compared to pre-operative values, oxygen saturation ($p<0.001$), temperature ($p<0.001$) and diastolic blood pressure ($p=0.004$) were significantly different. Various different mechanisms can cause the change in vital signs postoperatively.

Oxygen saturation was also lower at discharge than the suggested normal range for adult patients (normal range 97-100%). Oxygen saturation can be defined as "the ratio of oxyhaemoglobin to the total concentration of haemoglobin present in the blood". A few causes following cardiac surgery may lead to decreased oxygen saturation. One possible mechanism could be due to the occurrence of hypermetabolism following cardiac surgery causing a peak increase in oxygen metabolism. This can occur immediately after surgery up to some days postoperatively. One mechanism that can cause hypermetabolism is cardiopulmonary bypass itself as well as trauma to tissues, this can cause ischaemic injuries to the heart and lungs, tissue hypoperfusion and impair the ability of tissues to utilize oxygen. Changes in inflammatory levels postoperatively and the release of inflammatory cytokines may cause further oxygen deficits (Parolari et al. 2003). Others factors that may affect oxygen delivery to tissue can include hypothermia, fluid overload, blood loss, low haemoglobin levels, blood transfusion, anaemia, low cardiac output and myocardial dysfunction (Spoelstra-de Man et al. 2015).

Further mechanisms that can cause decreased oxygenation is the reduction of lung volumes and capacity that can contribute to the reduction in gaseous exchange to further cause hypoxaemia (Spoelstra-de Man et al. 2015). This finding can be associated with the significant decrease in other ventilation kinematics such as chest expansion and MIP found during this study. Multiple studies have concluded that a decrease in respiratory muscle strength may contribute to the reduction in functional vital capacity, tidal volumes and lung capacities (Stein et al. 2009). These changes may predispose any patient to atelectasis, especially in basal lung segments that increases the ventilation/perfusion mismatch (Stein et al. 2009). Altered ventilation kinematics may lead to lower oxygen saturation levels in circulating blood.

Westerdahl et al. (2016) confirmed that oxygen saturation levels were unchanged one year postoperatively (97±1% vs 97±2%, p=0.396) (Westerdahl et al. 2016). This finding suggests that once lung function, trauma due to surgery and a decrease in inflammation has recovered, vital signs return to normal.

5.3.9 Chest X-Ray Scores

During the current study, no patients presented with atelectasis pre-operatively, four patients had minor pleural effusions and two patients had a minor elevated left diaphragm. Post-operatively, 20 patients presented with minor atelectasis and eight participants presented with medium atelectasis; 26 participants presented with minor pleural effusions, 16 participants presented with minor diaphragm elevation and one presented with medium diaphragm elevation. Ragnarsdottir et al. (2004) used the same radiographic analysis scale pre-operatively and the 5th day post-operatively, this is slightly earlier than the 7th-8th day during the current study. Although their sample size was significantly smaller, 16 patients presented with signs of atelectasis (five minor, five medium and five major), all of the patients presented with a left sided pleural effusion and 12 patients had some signs of an elevated diaphragm (five moderate, three medium and four major) (Ragnarsdottir et al. 2004). The current study presents with significantly less radiographic evidence of pulmonary abnormality.

Kristjansdottir et al. (2004) performed an analysis with the same radiographic tool following a median sternotomy with internal mammary artery grafting, participants were evaluated pre-operatively, three months and 12 months post-operatively. At three months post-operatively, three participants still presented with atelectasis, two presented with left sided pleural effusions and five presented with elevated left diaphragms (severity of each not stated). At 12 months post-operatively the same study sample, two participants presented with atelectasis, one participant presented with a left sided pleural effusion and three participants presented with elevated left diaphragms. This study clearly states that pulmonary changes are still evident nearly a year post cardiac surgery (Kristjansdottir et al. 2004).

Atelectasis and pleural effusions are common complications after cardiac surgery. In a study performed by Elkolaly et al. (2018) 33.93%-81.81% of their patients presented with pleural effusions post-operatively, ranging from right sided, left sided and bilaterally (Elkolaly et al. 2018). Similarly atelectasis was also present between 64.29%-86.36% in patients that were diagnosed clinically and radiologically. This finding was supported by Badenes et al. (2015) that atelectasis was present in 16.6%-88% of post-operative cardiac patients (Badenes et al. 2015). Labidi et al. (2009) indicated the prevalence of pleural effusions over a two year period in their study after cardiac surgery and found that 6.6% of patients presented with pleural

effusions, with 59.4% classified as exudative fluid and 50% as haemorrhagic (Labidi et al. 2009). Pleural effusions may occur due to multiple factors post-operatively, most owing to internal mammary artery grafting, pleural injury, pulmonary oedema, post-operative bleeding, cardiac hypothermia during surgery and atelectasis (Labidi et al. 2009).

5.3.10 Pain Scores

On admission, most participants (95.1%) presented with VAS pain scores of 0/10, two (3.3%) participants had pain scores of 2/10 and only one participant presented with a pain score of 9/10. At discharge, 34.4% of participants presented with pain scores of 4/10, 13.1% of participants experienced scores of 3/10 and 11.5% experienced pain of 2/10. The median score on admission was 0/10 and for discharge the score was 4/10 indicating a statistical significant change (p=0.000).

Multiple structures can be the origin or cause pain. Pain usually occurs at the incision site, drain insertions site, conduit grafting sites, thoracic and back pain, pain following intubation, pain on invasive lines (central lines, radial lines, and urinary catheters (Mueller et al. 2000; Veal et al. 2016; Zubrzycki et al. 2018). Pain can originate from muscles, bones, tendons or ligaments due to the nature of surgery with incisions and sternal retraction. Higher pain levels have been recorded in patients that have had left internal mammary artery grafting, potentially due to intercostal nerve injury during grafting procedures (Gangwani & Akhtar, 2015). Pain levels may vary from study to study due to different pain management protocols at different institutions.

Gangwani & Akhtar (2015) performed a survey to assess pain management in cardiac surgery, they found that most patients (32.5%) experienced a cutting or a sharp pain. Pain was most experienced over the incision site (41.9%), the chest tube site (33.8%) and back pain (7.1%). Participants experienced deep breathing (39.8%) to be the most aggravating pain factor, followed by ambulation (27.9%), chest tube removal (20.1%) and turning or positioning (9.4%) (Gangwani & Akhtar 2015).

Baugmarten et al. (2009) also confirmed that the most common site of pain described by patients was the sternum and the spinal column at the level of T10. When describing pain from immediately post-op, the median level of pain on day 1 was 5/10, on the 2nd the median level of pain was 5/10, on the 3rd and 5th days the median scores were 3/10. There was a significant decrease in the level of pain from the 1st to the 5th post-operative day (Baugmarten et al. 2009). Pain was found to have a significant negative correlation with pulmonary function variables, including FEV1, EFP and Vimax (Baugmarten et al. 2009).

5.4 VENTILATION KINEMATICS

5.4.1 Chest Wall Expansion

Following the results of this study, there was a significant decrease between pre-operative chest expansion and chest expansion measured at discharge. The median (IQR) upper thoracic expansion for admission was 104.51cm (12.9) and showed a significant difference to the discharge measurement of 102.51cm (12) ($p<0.001$). For lower thoracic expansion, the difference between mean admission and mean discharge was 100.03cm (±12.04) vs. 98.70cm (±12.07) ($p=0.001$).

A loss of thoracic expansion can be caused by a multiple factors after a median sternotomy. Trauma to the ribs, costochondral joints and costovertebral joints with a decrease in respiratory muscle strength in the presence of pain all directly predispose the ribcage to function inadequately. Locket et al. (1990) first described uncoordinated breathing efforts after a median sternotomy. Similar to the current study, they found that there was significant reductions in lateral displacement of the chest wall at the level of the manubrium and xiphisternal levels, in an upright position it decreased from a mean of 4.20(95% CL 2.37-6.03) to 2.37 (95% CL 1.30-3.44) mm, $p=0.075$. During the study it was also found that majority of the patients had abnormalities of the timing of the onset of lateral chest wall motion at seven days post-operatively ($p=0.0008$). At three months post-operatively all measurements had started returning to baseline function.

Similarly, Ragnarsdottir et al. (2004a), measured chest and abdominal expansion with a Respiratory Movement Measuring Instrument, on the 7th post-operative day all chest movements were significantly diminished. Abdominal movement was 60% of the pre-operative values, lower thoracic movements were 72% of pre-operative values. In a similar study using the same measuring instrument, Krisjansdottir et al. (2004b) showed that abdominal respiratory movements were less in participants that underwent internal mammary artery grafting at three and twelve months post-operatively. They proved that abdominal respiratory movements were also significantly less on the left side than on the right ($p=0.003$) and were symmetrical in patients that had no internal mammary artery grafted (Kristjansdottir et al. 2004b).

Although none of the aforementioned studies used a tape measure to evaluate chest expansion, the results remained similar. Locke et al. (1990) stipulated that the changes could be due to trauma caused to the costovertebral joints that causes reflex inhibition of the intercostal muscles, making it impossible to resist inward contraction of the diaphragm (Locke et al. 1990). The bony configuration of the thorax may also change following a median sternotomy causing flattening of the ribs and increasing the curvature of the thoracic spine, directly altering the rib cage mechanics during breathing.

During the current study, there was also a fair negative correlation between upper thoracic expansion and length of time intubated (r=0.261, p=0.05). Thus meaning that an increase in the time of mechanical ventilation produces a decreased chest expansion measurement post-operatively. The influence of mechanical ventilation on respiratory muscle weakness is well-described. Diaphragm weakness occurs as a result of ventilator-induced diaphragm inactivity, the progression of weakness occurs as the duration of mechanical ventilation increases (Supinski & Callahan, 2013). Diaphragm weakness may present itself in cardiac surgery due to a phrenic nerve injury commonly described as a complication following cardiac surgery (Allam et al. 2019). Diaphragm weakness may predispose patients to respiratory failure, that prolongs mechanical ventilation time and the time needed to wean patients from mechanical ventilation (Supinski & Callahan, 2013).

5.4.2 Maximum Inspiratory Pressure and Peak Inspiratory Flow

There was a significant difference between the median MIP at admission of 55cmH_20 compared to discharge of 30.66cmH_20 ($p<0.001$), as well as a significant difference between the predicted MIP from admission to discharge (58.66cmH_20 vs. 33.26cmH_20, $p<0.001$). Peak Inspiratory flow14also showed a significant difference between admission and discharge (2.70l/s vs. 1.66l/s, $p<0.001$). The predicted MIP for the participants calculated at admission was 94.69cmH_20, the percentage of the predicted MIP achieved was calculated to be 58.66cmH_20. The achieved MIP of the participants were a lot lower than the predicted MIP. Evans & Whitelaw (2009) described a MIP of greater than 50cmH_20 to be normal (Evans & Whitelaw, 2009), however in the “Statement on Respiratory Muscle Testing”, a MIP of greater than 80cmH_20 excludes patients with respiratory pathology of clinical significance (American Thoracic Society/European Respiratory Society, 2002).

Urell et al. (2016) performed a study that evaluated MIP pre-operatively and at two months post-operatively. Their participants achieved a much higher percentage of predicted MIP of 78cmH_20 ± 24cmH_20 compared to the current study. They also found that at two months follow-up there was no significant difference when compared to pre-operative values (73cmH_20 ± 22cmH_20; $p=0.19$) (Urell et al. 2016). Morsch et al. (2009) founds similar results to the current study, there was also a significant decrease in MIP pre-operatively and on the 6th post-operative day (65.8 ± 28.6cmH_20 vs. 42.4 ± 19.9cmH_20; $p<0.001$).

A decrease in post-operative inspiratory muscle strength is caused by various different mechanisms. From a musculoskeletal perspective, two possibilities influence respiratory muscle strength. The first being the influence of the diaphragm, as the diaphragm being one of the main muscles responsible for respiratory muscle strength. The diaphragm may contribute to 30-60% of total minute ventilation and may cause a drop of between 20-30% of

vital capacity and 20% decreased oxygenation with a unilateral dysfunction (McCool & Tzelepis, 2012). It is well described following cardiac surgery for patients to experience diaphragm palsies or weakness, this is attributed to surgical technique and hypothermia (Mehta et al. 2008; Smetana, 2009). The phrenic nerve (which passes the internal mammary artery anteriorly in 54% of cases and posteriorly in 14% of cases), as the main innervation of the diaphragm may experience trauma or hypoxic cascades leading to decreased firing and function of more commonly unilateral diaphragm, leading to a significant decrease in respiratory muscle strength (McCool & Tzelepis, 2012; Allam et al. 2019). Another possible mechanism for diaphragm dysfunction, is the inability for the diaphragm to contract efficiently due to an unstable bony structure predisposed by the median sternotomy, owing to an active fracture, rib trauma and injury to the costovertebral joints (Kristjansdottiret et al. 2004). The diaphragm can therefore not perform at its optimal strength.

The second group of muscles affected are the intercostal muscles and nerves. The intercostal nerves may be damaged during internal mammary artery grafting and insertion of pleural drains via the intercostal space. The intercostal muscles are put at risk especially during internal mammary artery grafting, the added surgical trauma decreases blood flow to the intercostal muscles, thus decreasing the ventilator muscle force (Baugmarten et al. 2009)
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Roncada et al. (2015) related pulmonary function after CABG surgery to postoperative inflammation and hypercortisolemia. They postulated that respiratory muscles being part of a large group of skeletal muscles, are very sensitive to changes in circulation while undergoing cardiac surgery, affecting skeletal muscle mass and strength. They found a large increase in post-operative C-reaction protein (CRP) and cortisol concentration was directly associated with larger reductions in pulmonary function. Hypercortisolaemia has been directly linked to skeletal muscle wasting by increasing the amount of protein breakdown, in conjunction with elevated circulating CRP levels that impairs skeletal muscle protein synthesis (Roncada et al. 2015). This has a direct influence on the function of the respiratory muscles of the chest wall post-operatively.

Multiple studies have shown that post-operative spirometry values are significantly lower than those of pre-operative values, but have also shown that spirometry values gradually recover although a reduction of between 6-13% is still present several months after surgery.

During this study, there was a fair negative correlation between predicted MIP and age ($p=0.012$). Most studies have demonstrated that age and gender directly affect MIP in healthy subjects. There is no real consensus to when age-related decline in MIP starts occurring, but there has been a study to prove that MIP regresses in a linear fashion when describing age for both males and females (Pessoa et al. 2014).

Lastly, another correlation found during this study was a fair negative correlation between PIF and MIP with Chest X-ray Total scores at admission. This would be a clear explanation as changes in Chest x-ray scores would indicate any type of atelectasis, pleural effusion or diaphragm elevation pre-operatively that would directly affect the MIP and PIF. A direct correlation of any type of pathology would decrease the MIP and PIF as the lungs and/or chest wall would be compromised.

Chapter 6 will present the conclusions, limitations and recommendations of the research report.

CHAPTER 6

6. CONCLUSION, LIMITATIONS AND RECOMMENDATIONS

6.1 CONCLUSION

The aim of this study was to evaluate the effect of a median sternotomy on the ventilation kinematics of participants undergoing cardiac surgery.

The main findings of this study was that there was a significant difference between upper and lower thoracic expansion as well as MIP and PIF between admission and discharge. This is in accordance that the respiratory pump is altered post a median sternotomy incision, influencing the movement of the ribs as well as the strength needed to overcome resistance during inspiration. Changes in the chest wall are caused by trauma to the costovertebral joints, ribs, fracturing the sternum, trauma during internal mammary artery grafting and overstretching the intercostal muscles during retraction. Many studies describe a restrictive ventilatory change following cardiac surgery. Changes in the mechanics of the chest wall may be a possible cause adding to the changes in lower spirometry values described post-operatively.

This study showed that there was also changes that occur to the pulmonary system in conjunction with changes in chest wall mechanics including lower saturation levels and changes in chest x-ray scores at discharge. The prevalence of either atelectasis, pleural effusions, diaphragm weakness in conjunction with lower saturation levels is in accordance of developing PPCs. These complications may be caused or directly influenced by an altered respiratory pump. Post-operative pulmonary complications are frequently described in the literature as a consequence of cardiac surgery that include increased cost and LOS in hospital. Patients should therefor receive adequate information and home exercise programs to assist with optimal recovery once discharged. In addition, patients should be made aware of warning signs of potential complications post-operatively and should be taught to identify and monitor symptoms and to seek health care review if symptoms worsen.

It was also shown that there is a fair negative correlation between MIP and age at admission as well as a fair positive correlation between lower thoracic expansion and age at discharge. Further correlations found included a fair negative relationship between upper thoracic expansion and age as well as a fair negative correlation between MIP and PIF with chest x-ray total scores at admission. Patients in an older age categories should be identified as higher-risk patients for surgery, adequate evaluation and prehabilitation strategies should be implemented to ensure optimal surgical outcomes post-operatively.

Five participants (8,2%) during this study were discharged with the use of a mobility aid after no participant required any assistance to mobilise at admission. Early mobilisation routines and strengthening exercises can be recommended for patients that have longer ICU and hospital admissions. Identifying high risk patients that present with multiple co-morbidities and assessing mobility, muscle strength and frailty pre-operatively and conducting a prehabilitation program may also improve outcomes post-operatively. Attending a prehabilitation program has been proven to improve physical fitness when assessed by the 6MWT pre-operatively and the results are maintained post-operatively in patients undergoing elective cardiac surgery (Sawatzky et al. 2016). No adverse events were recorded during a prehabilitation program. In South Africa, very few prehabilitation programmes are run or are not very well attended due to medical costs and limited facilities. Such programmes could be beneficial to patients waiting to undergo elective cardiac surgery to improve mobility outcomes post-operatively.

Another potential way to improve physical function is to adhere to faster weaning and extubation regimes after surgery (Richey et al. 2018). The median amount of time each patient was ventilated was 17.33 (11.21) hours, gold standard recommends extubating patients within eight hours post-surgery. This would enable physiotherapists to engage in early mobilisation protocols.

All participants during this study received physiotherapy care including early mobilisation as soon as the participants were stable as well as chest physiotherapy including nebulisation, chest clearance techniques, coughing techniques, breathing exercises and spirometry. No physiotherapy interventions were rendered pre-operatively unless referred by a doctor.

6.2 LIMITATIONS

The study was conducted at a private hospital in Gauteng, all surgeries were performed by one surgeon, therefor most techniques and drains inserted were limited to the surgeon's preference, there was a limited variety of various surgical preferences. The timeframe of this study was a lot longer than expected, the centre used for this study also admits heart and lung transplants as well as ECMO patients, beds were often blocked by these patients as they generally have a much longer ICU stay and elective cardiac surgeries were put on hold if no bed were available.

Some patients were unable to be evaluated as the starting theatre time varied from day to day, the theatre list indicated that surgeries started at 07:30 but on occasions patients were taken to theatre much earlier. Patients that were not already admitted to hospital, only arrived at the hospital on the same day of their procedure and still had to undergo various procedures

like blood tests, admission vitals, anaesthesiology consult, bathing and chest x-rays, allowing very little to no time for further evaluations for this study.

There was a large age range included during this study as a full idea of the working population of this country wanted to be achieved.

Testing MIP is an effort based test, participants could vary from day to day, anxiety levels could have influenced MIP results at admission especially for patients whom were admitted on the same day for their surgery. The researcher however aimed to have a calming demeanour to lessen participant's anxiety level during assessments.

6.3 RECOMMENDATIONS

6.3.1 Clinical Recommendations

Physiotherapists could take note of this study as firstly an evaluation tool, especially for high risk patients undergoing cardiac surgery. All evaluation techniques including the POWERbreathe device used in this study are readily available at the bedside and inexpensive to use to clinically, which are important in a third world country. The evaluation techniques are not time consuming either and could be beneficial to take note of patients that may require more intervention post-operatively. Evaluating MIP using the POWERbreathe device could be beneficial to any pre-surgical patient to identify respiratory muscle weakness.

During this study, the participants achieved a much lower predicted MIP. In patients that will be undergoing elective surgery a prehabilitation programme consisting of respiratory muscle training could be implemented to optimise respiratory function prior to theatre and improve postoperative outcomes. Respiratory muscle training in the pre-operative period had a significant reduction in post-operative complications including pneumonia and atelectasis post-operatively and reduce the length of stay in hospital (Karanfil & Moller 2018; Kendall et al. 2017). Rehabilitation including respiratory training strategies were shown to be beneficial in all age groups and risk levels, patients that benefitted the most were older and high-risk patients as well as patients undergoing pulmonary surgery (Kendall et al. 2017). Respiratory muscle training should be included pre- and post-operatively.

Post-operative respiratory muscle training should be included in physiotherapy regimes in hospital and at discharge as a home programme to address the reduced MIP patients present with. Dos Santos et al. (2019) demonstrated that participants that completed a 12 week moderate to high intensity inspiratory muscle training program in conjunction with combine training (aerobic and resistance exercises) promoted increased exercise capacity, 6MWT distance, inspiratory muscle strength, quality of life and anti-oxidant profile. Recommended moderate to high intensity training on a POWERbreathe device included five sets of ten

repetitions, with one minute intervals for rest with rates of perceived exertion on a modified Borg Scale of between four to six out of ten. The program is incremented slowly, starting with 50% of MIP for the 1st two weeks, 55% of MIP in the 3rd week, 60% of MIP in the 4th week, 65% of MIP in the 5th week, 70% of MIP in the 6th week, 75% of MIP in the 7th week and 80% of MIP in the 8th week. During weeks 9 to 12 the load was adjusted to maintain a MIP of 80% (dos Santos et al. 2019).

The current research indicates the necessity of physiotherapy interventions that aim to prevent further PPCS. It is clear that cardiac surgery predisposes patients to pulmonary manifestations. Techniques to prevent further complications include coughing techniques, airway clearance techniques, breathing exercises, respiratory re-education, inspiratory muscle training, mobilization as well as aerobic and strengthening exercises. This study proves that physiotherapy should also continue post discharge, as participants were still compromised from a respiratory point of view. Cardiopulmonary rehabilitation in different phases is important to restore normal ventilation kinematics and full physical function.

6.3.2 Future Research

Future studies including the following would be of great benefit to the South African professions:

This study could aim to evaluate patients at different time periods after discharge during their recovery.

More outcomes measure including lung function values, thoracic range of motion, diaphragm excursion (on ultrasound), CT-scans, quality of life questionnaires as well as functional or physical outcome measures could be added and evaluated to gain a more complex description of how patients present post cardiac surgery.

Multiple cardiothoracic centres in the private sector as well as the government sector can be added to gain a more comprehensive distribution of patients undergoing cardiac surgery.

Randomised control trials can be conducted evaluating different techniques used to address post-operative cardiac patients and how they would influence outcomes measured.

A study identifying and evaluating high-risk patients could be beneficial to include pre-operative strategies to improve surgery outcomes.

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APPENDIX 1

- **DEMOGRAPHIC QUESTIONNAIRE**

Participant's study code:

Gender	Male 0/female 1	
Age		
Height		
Weight		
Admitting diagnosis		
Date admitted to hospital		
Social history	Alcohol use: Smoking history:	
Past medical history & co-morbidities	Categories HPT/DM/CH/Other	
Surgical history	Narrative review	
Mobility before surgery Numbering	Independently mobile Independently mobile with a mobility aid Wheelchair user Bedbound	O O O O
Theatre details		
	Surgery description: Grafts	
	Time in: Time out:	
	Time on pump: Off pump:	
	Time on aortic clamp: Time off:	
	Lowest temperature:	
	Complications:	

ICU details		
	Devices: 4 columns	Pacemaker IABP ECMO Ventilator
	Drains	Mediastinal Pleural L/R
	Wounds/incision:	
	Time extubated:	
	Length of time intubated:	
	Total length of stay in ICU:	
Ward details		
	General mobility:	Independently mobile O Independently mobile with a mobility aid O Minimal assistance with a walking aid O Wheelchair assistance O Bedbound O
	Total length of stay in hospital:	
	Date of discharge:	
Complications during hospital stay: Numbers	Pleural Effusions O Atrial Fibrillations O Pneumonia O Atelectasis O Other O	

APPENDIX 2

- **ASSESSMENT SHEET**

	Admission			Discharge		
Vitals	HR: RR: BP: Temp: SaO2: HGT:			HR: RR: BP: Temp: SaO2: HGT:		
Visual Analog Score for Pain (VAS)	Score: /10			Score: /10		
X-rays score (see figure 1 below)						
Outcome measures	Recording 1	Recording 2	Recording 3	Recording 1	Recording 2	Recording 3
Chest expansion						
• Upper expansion						
• Lower expansion						
Inspiratory muscle strength						
• Maximum inspiratory pressure (mmHg) Predicted values: female: 171 – 0.694 X age = 0.861 x weight (kg) x height (cm) male: 126 – 1.028 x age + 0.343 x weight (kg)						
• Peak inspiratory flow						

Radiographic Evaluation (X-rays)	Score
Atelectasis of the left lung 1= None 2= Minor. Little shadowing in the retrocardial area. No significant reduction in lung volume. 3= Medium. Significant shadowing in the retrocardial area and at the base of the lung. No major reduction of lung volume. 4= Major. Near total collapse of the inferior lobe. There is an opaque area in the basal/medial part of the lung with sharp lateral border. Significant reduction of the left hemi thorax.	
Pleural Fluid 1= Normal. 2= Minor. Some filling of the costophrenic angle. 3= Medium. Near total filling of the costophrenic angle. Fluid is seen running up the lateral chest wall and/or shadowing of the lower part of the left lung. 4= Major. Fluid fills the lower part of the left hemi thorax and/or shadowing of the whole left lung.	
The position of the diaphragm 1= Normal. 2= Minor. Left diaphragm is slightly higher than the right diaphragm. 3= Medium. Left diaphragm is elevated up to half the height of the left heart border. 4= Major. Left diaphragm is elevated above half the height of the left heart border.	
Total score	

VAS Scale:

Before surgery:



No pain Worst Imaginable Pain

Discharge:



No pain Worst Imaginable Pain

APPENDIX 3

- **RESEARCH APPROVAL**

RESEARCH OPERATIONS COMMITTEE FINAL APPROVAL OF RESEARCH

Approval number: UNIV-2017-0027

Ms Cary-Anne Gissing

E mail: cagissing@gmail.com

Dear Ms Gissing

RE: VENTILATION KINEMATICS OF ADULT PATIENTS WITH A MEDIAN STERNOTOMY INCISION FOLLOWING CARDIOTHORACIC SURGERY

The above-mentioned research was reviewed by the Research Operations Committee's delegated members and it is with pleasure that we inform you that your application to conduct this research at private Hospital, has been approved, subject to the following:

i) Research may now commence with this FINAL APPROVAL from the Committee.

ii) All information regarding the Company will be treated as legally privileged and confidential.

iii) The Company's name will not be mentioned without written consent from the Committee.

iv) All legal requirements regarding patient / participant's rights and confidentiality will be complied with.

v) The research will be conducted in compliance with the GUIDELINES FOR GOOD PRACTICE IN THE CONDUCT OF CLINICAL TRIALS IN HUMAN PARTICIPANTS IN SOUTH AFRICA (2006)

vi) The Company must be furnished with a STATUS REPORT on the progress of the study at least annually on 30th September irrespective of the date of approval from the Committee as well as a FINAL REPORT with reference to intention to publish and probable journals for publication, on completion of the study.

vii) A copy of the research report will be provided to the Committee once it is finally approved by the relevant primary party or tertiary institution, or once complete or if discontinued for any reason whatsoever prior to the expected completion date.

viii) The Company has the right to implement any recommendations from the research.



ix) The Company reserves the right to withdraw the approval for research at any time during the process, should the research prove to be detrimental to the subjects/ Company or should the researcher not comply with the conditions of approval.

x) APPROVAL IS VALID FOR A PERIOD OF 36 MONTHS FROM DATE OF THIS LETTER OR COMPLETION OR DISCONTINUATION OF THE TRIAL, WHICHEVER IS THE FIRST.

We wish you success in your research.

Yours faithfully

1/6/17

Prof Dion du Plessis
Full member: Research Operations Committee & Medical Practitioner evaluating research applications as per Management and Governance Policy

19/6/2017

Shannon Nell
Chairperson: Research Operations Committee
Date:

This letter has been anonymised to ensure confidentiality in the research report. The original letter is available with author of research

APPENDIX 4

- **ETHICAL CLEARANCE CERTIFICATE**

R14/49 Ms C-A Gissing

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)
CLEARANCE CERTIFICATE NO. M160957

NAME: (Principal Investigator)	Ms C-A Gissing
DEPARTMENT:	School of Therapeutic Sciences Physiotherapy Department Medical School
PROJECT TITLE:	Ventilation kinematics of adult patients with a median sternotomy incision, following cardiothoracic surgery
DATE CONSIDERED:	30/09/2016
DECISION:	Approved unconditionally
CONDITIONS:	
SUPERVISOR:	Dr R Roos
APPROVED BY:	Professor PE Cleaton-Jones, Chairperson, HREC (Medical)
DATE OF APPROVAL:	01/11/2017

This clearance certificate is valid for 5 years from date of approval. Extension may be applied for.

DECLARATION OF INVESTIGATORS

To be completed in duplicate and **ONE COPY** returned to the Research Office Secretary on 3rd floor, Phillip V Tobias Building, Parktown, University of the Witwatersrand, Johannesburg.
I/We fully understand the conditions under which I am/we are authorised to carry out the above-mentioned research and I/we undertake to ensure compliance with these conditions. Should any departure be contemplated from the research protocol as approved, I/we undertake to resubmit to the Committee. **I agree to submit a yearly progress report**. The date for annual re-certification will be one year after the date of convened meeting where the study was initially reviewed. In this case, the study was initially reviewed in **September** and will therefore be due in the month of **September** each year. Unreported changes to the application may invalidate the clearance given by the HREC (Medical).

Principal Investigator Signature _____ Date _____

PLEASE QUOTE THE PROTOCOL NUMBER IN ALL ENQUIRIES

APPENDIX 5

- **INFORMATION SHEET**

Study Title: Ventilation kinematics of adult patients with a median sternotomy incision following cardiothoracic surgery.

Dearest patient

I am a Physiotherapist currently conducting a study in the field of cardiothoracic surgery. The following document will give you information regarding the research I am currently conducting, please do not hesitate ask any questions. I am currently evaluating the effects a median sternotomy on ventilation kinematics, this is basically to determine the effects the surgery you are about to undergo has on your ability to expand your chest and breathe.

Purpose of the study

Cardiac surgery including valve repairs/replacements and bypass grafts are the most commonly performed surgical interventions in cardiac disease. A median sternotomy is the cut used to expose the heart in order to repair it. Physiotherapy is a crucial part of the recovery during this procedure, mobilization and chest clearing techniques being the most important. Therefor the aim of the current study is to evaluate your chest expansion and the strength of your muscles that control your breathing before surgery and at discharge. This study will enable us to improve and adapt current treatment techniques and prescribed exercise programs.

To evaluate the above mentioned parameters, I will be using the following: to determine your breathing strength we will use a hand held device in which you will take a deep breath, this will give us a digital reading of two different types of breathing strength. Chest expansion will be measured with a tape measure around your chest, this will test how well your chest and lungs are able to expand and the difference will be measured in centimetres. To complete the questionnaires and evaluations will take approximately 15 to 20 minutes in total.

Type of research

This research will be minimally invasive and will involve evaluation techniques before and after your surgery. The first test involves measuring chest expansion with a tape measure, this will involve exposing your chest area to ensure adequate readings. The second test will evaluate the strength of the muscles that help you take a deep breath in, this will be tested by a small handheld device through which you will take a deep breath in, and it will then give an electronic reading.

Participant selection and participation

I am currently inviting all adults under the age of 65 that are booked to undergo an elective cardiothoracic surgery at the Milpark Hospital to participate in this study. Your participation in this research is entirely voluntary, it is your choice whether to participate or not. Whether you choose to participate or not, all the services you receive and treatment at this hospital will continue as normal and nothing will change.

The information collected from this study will remain confidential. Information about you collected during this study will be confidential to only the researchers conducting the study. Only demographical data and evaluation results will be used in the purpose of the study. During any point of this study you have the right to withdraw your participation without any influence on the quality of treatment you will receive during your hospitalization.

The information collected during the study will be stored safely (locked away) for two years if the research is published or 6 years if there is no publication of this study.

In case you have any complaints or queries regarding the research process you can contact the Human Research Ethics Committee (Medical) at the following offices:
Prof P Cleaton Jones, Tel 0117172301, email peter.cleaton-jones1@wits.ac.za
Ms Zanele Ndlovu/ Mr Rhulani Mkansi/ Mr Lebo Moeng Administrative Officers, Tel 0117172700/2656/1234/1252, emails Zanele.ndlovu@wits.ac.za; rulani.mkansi@wits.ac.za; and lebo.moeng@wits.ac.za

Thank you for your help and willingness to participate,
Carry-Anne Gissing
Cell phone number: 0827140567

APPENDIX 6

- **CERTIFICATE OF CONSENT**

Study Title: Ventilation kinematics of adult patients with a median sternotomy incision following cardiothoracic surgery.

- I have read the foregoing information, or it has been read to me.
- I have had the opportunity to ask questions about it and any questions that I have asked have been answered to my satisfactions.
- I consent voluntarily to participate as a participant in this research.

Name of Participant :_____

Signature of Participant :_____

Date :_____
Day/month/year

If illiterate

A literate witness must sign (if possible, this person should be selected by the participant and should have no connection to the research team). Participants who are illiterate should include their thumb-print as well.

I have witnessed the accurate reading of the consent form to the potential participant, and the individual has had the opportunity to ask questions. I confirm that the individual has given consent freely.

Print name of witness_____ **AND** **Thumb print of participant**

Signature of witness _____

Date _____
Day/month/year

Statement by the researcher/person taking consent

- I have accurately read out the information sheet to the potential participant, and to the best of my ability made sure that the participant understands what will be expected during the study.
- I confirm that the participant was given an opportunity to ask questions about the study, and all the questions asked by the participant have been answered correctly and to the best of my ability. I confirm that the individual has not been coerced into giving consent, and the consent has been given freely and voluntarily.

Print Name of Researcher/person taking the consent_____

Signature of Researcher /person taking the consent_____

Date _____

Day/month/year

APPENDIX 7

- **CODING FORM**

Participant study code: _____

Name & Surname: _____

Date: _____

Hospital Number: _____

APPENDIX 8

- **TURN-IT IN REPORT**

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