

2012

7D Cardiac Flow MRI: Techniques & Automation of Reconstruction

Michael G. Ambrosia
Cleveland State University

Follow this and additional works at: <https://engagedscholarship.csuohio.edu/etdarchive>

 Part of the [Biomedical Engineering and Bioengineering Commons](#)

How does access to this work benefit you? Let us know!

Recommended Citation

Ambrosia, Michael G., "7D Cardiac Flow MRI: Techniques & Automation of Reconstruction" (2012). *ETD Archive*. 456.
<https://engagedscholarship.csuohio.edu/etdarchive/456>

This Thesis is brought to you for free and open access by EngagedScholarship@CSU. It has been accepted for inclusion in ETD Archive by an authorized administrator of EngagedScholarship@CSU. For more information, please contact library.es@csuohio.edu.

7D CARDIAC FLOW MRI – TECHNIQUES & AUTOMATION OF
RECONSTRUCTION

MICHAEL G. AMBROSIA

Bachelor of Science in Mechanical Engineering

Ohio University

June 2001

Master of Business Administration

Case Western Reserve University

January 2005

Submitted in partial fulfillment of requirement for the degree

MASTER OF SCIENCE IN BIOMEDICAL ENGINEERING

at the

CLEVELAND STATE UNIVERSITY

NOVEMBER 2012

This thesis has been approved

For the Department of CHEMICAL and BIOMEDICAL ENGINEERING

And the College of Graduate Studies by

Thesis Chairperson, Dr. Sandra Halliburton, Cleveland Clinic Foundation

Department & Date

Dr. George Chatzimavroudis, Cleveland State University

Department & Date

Dr. Melanie Traughber, Philips Healthcare

Department & Date

Dr. Michael Bolen, Cleveland Clinic Foundation

Department & Date

7D CARDIAC FLOW MRI – TECHNIQUES & AUTOMATION OF RECONSTRUCTION

MICHAEL G. AMBROSIA

ABSTRACT

Advances in magnetic resonance imaging to quantify the blood flow in the heart and major vessels stemming from the heart has recently allowed for advanced clinical applications for patients suffering from cardiac valve problems and aortic abnormalities. 7D cardiac flow quantification is relatively new, but has already shown potential in several clinical applications, including bicuspid valve and aortic coarctation characterization. In addition radiologists diagnosing valvular regurgitation may benefit from insight provided by the 7D cardiac flow quantification protocol.

7D cardiac flow quantification using magnetic resonance imaging will provide direction flow quantification in the anterior / posterior, head / foot, and left / right directions, in time, through the imaging volume. Providing MRI techniques that may lead to clinical applications to characterize the cardiac valves, the flow differentials during cardiac function, and the flow and pressure differentials of the aortic arch, as well as automation of the delayed reconstruction process for raw data, are the main focus of this study.

The study was approached in four stages. First, using the Philips ExamCard environment, a scan protocol was developed. The scan protocol provided the anatomical views for the 7D flow quantification in the heart. Execution of the ExamCard provides two anatomical areas of focus, the aortic arch and the valve plane of the heart. Raw data was saved to the scanner's database, for later reconstruction.

A second stage of the project was completed to verify the ExamCard and manual reconstruction had been properly developed. To do so, four volunteer studies were completed. Each volunteer was scanned on the same Philips 1.5T Achieva scanner, using the 7D flow ExamCard developed in stage one, and raw data reconstructed using the manual delayed reconstruction procedure. Flow quantification in a 3D volume in 3 directions over time was verified. Results were verified using existing studies as a gold standard.

Because manual delayed reconstruction is time consuming, and may lead to errors, automation of the delayed reconstruction is desired. A third stage of the project was aimed at automation of the delayed reconstruction process.

The third stage of the project involved writing a batch file to automate the reconstruction of the raw data saved from the previously described scan protocol. The batch file is an executable script file that will automate the manual work of the Philips delayed reconstruction procedures. The batch file, when executed, will select, change reconstruction parameters for each of the 2 anatomical areas, in three different directions, for a total of 6 scan reconstructions, run the reconstruction, and name the scans appropriately. Using raw data of the four volunteer studies in stage 2, the batch file was tested.

The focus then shifted to a fourth stage of the project. The focus was verifying the results of the automation versus the manual delayed reconstruction process.

Using standard Philips Achieva analysis software, reports for all manual, automated, and “subtraction” data sets were generated. These reports were compared. In

all cases, both the manual and automated data sets produced analysis exactly the same for the given parameters. The “subtraction” data set further proved the manual and automated data sets were the same by analysis where all measured parameters were zero, proving the hypothesis and demonstrating the automated batch file did indeed reconstruct the raw data equivalent to reconstruction produced using the standard manual delayed reconstruction package from Philips.

Finally, the data sets from the automated reconstruction were used to plot velocity profiles across regions of interest and compare results between operators as well as patients.

The project was completed at the Philips Healthcare facility located at 595 Miner Rd, Highland Heights, OH, in conjunction with the Cleveland Clinic Foundation of Cleveland, Ohio.

TABLE OF CONTENTS

ABSTRACT.....	iii
LIST OF FIGURES	viii
LIST OF TABLES.....	x
 CHAPTER	
I. INTRODUCTION	1
a. Stage 1.....	7
b. Stage 2.....	7
c. Stage 3.....	7
d. Stage 4.....	7
 II. EXPERIMENTAL FACILITY.....	 12
a. Experimental Facility.....	12
b. Philips XR Achieva 1.5T MRI.....	12
c. Surface Coils.....	12
d. Wireless Gating.....	13
e. Exam Card Environment.....	14
 III. DESCRIPTION OF EXPERIMENT – IN 4 STAGES.....	 16
a. Stage 1.....	17
i. Introduction / Purpose	17
ii. Description of Experiment.....	17
1. Exam Card Development – Scan Selection, Modification, and Planning.....	21
2. Balanced TFE Survey Scan (SURVEY).....	22
3. Reference Scan for XL Torso Coil (Ref XL Torso)	22
4. Single Shot Dual Inversion Black Blood Breath-Hold Scan (BB SSh BH).....	24
5. AORTA SENSE TFE Flow quantification (sQFLOW BH SENSE TFE)	25
6. SENSE Balanced TFE Cine Scan (VLA sBTfE BH)	26
7. SENSE Balanced TFE Cine Scan (PSA sBTfE BH)	28
8. SENSE Balanced TFE Cine Scan (4CH sBTfE BH)	29
9. VALVES SENSE TFE Flow quantification (sQFLOW BH SENSE TFE)	30
iii. Results and Discussion	31

1. Next Steps – Stage 2	31
b. Stage 2.....	32
i. Introduction / Purpose.....	32
ii. Description of Experiment.....	32
1. Manual Reconstruction	33
iii. Results and Discussion	36
1. Next Steps – Stage 3	39
c. Stage 3.....	40
i. Introduction / Purpose.....	40
ii. Description of Experiment.....	40
1. Automated Delayed Reconstruction	
Batch File	40
iii. Results and Discussion	43
1. Next Steps – Stage 4	47
d. Stage 4.....	48
i. Introduction / Purpose.....	48
ii. Description of Experiment.....	48
iii. Results and Discussion	50
IV. CONCLUDING REMARKS.....	69
BIBLIOGRAPHY.....	71
APPENDICES	73
A. Automated Delayed Reconstruction Batch File Code	74
B. Manual Delayed Reconstruction Workflow	77
C. Volunteer Scans not previously referenced	94

LIST OF FIGURES

Figure	Page
1. 7D Flow Overview (Ebbers, 3).....	3
2. Cardiac Valve Plane (Bax, 3).....	5
3. 3D Visualization Package (Ebbers, 6)	11
4. Wireless Gating Set Up.....	14
5. ExamCard Environment.....	15
6. Valve Plane of the Heart	18
7. Placement of the Slice Plane	18
8. Aortic Arch	19
9. 7D Flow ExamCard	21
10. Survey Scan	22
11. XL Torso Coil.....	22
12. Single Shot Dual Inversion.....	24
13. Aortic Flow Quantification Planning.....	25
14. SENSE Cine Planning 1.....	26
15. SENSE Cine Planning 2.....	28
16. SENSE Cine Planning 3.....	29
17. Valve Flow Quantification Planning	30
18. Manual Delayed Reconstruction.....	34
19. Manual Delayed Reconstruction Work Flow	35
20. Manual Delayed Reconstruction Data Set 1	36
21. Manual Delayed Reconstruction Data Set 1 – Phase Mapping	37
22. Manual Delayed Reconstruction Data Set 2	38
23. Manual Delayed Reconstruction Data Set 2 – Phase Mapping	38
24. Automatic Delayed Reconstruction Work Flow.....	42
25. Automatic Delayed Reconstruction Data Set 1	44
26. Automatic Delayed Reconstruction Data Set 1 – Phase Mapping.....	45
27. Automatic Delayed Reconstruction Data Set 2	46
28. Automatic Delayed Reconstruction Data Set 2 – Phase Mapping.....	46
29. Manual Delayed Reconstruction Data Set 3	51
30. Manual Delayed Reconstruction Data Set 3 – Phase Mapping	52
31. Automatic Delayed Reconstruction Data Set 3 – Phase Mapping.....	52
32. Subtraction Data Set 4	53
33. Manual Delayed Reconstruction Data Set 4	54
34. Manual Delayed Reconstruction Data Set 4 – Phase Mapping	55
35. Automatic Delayed Reconstruction Data Set 4 – Phase Mapping.....	55
36. Subtraction Data Set 4	56
37. Boxplot of AP Manual, AP Automatic	57

38. Boxplot of FH Manual, FH Automatic	58
39. Boxplot of RL Manual, RL Automatic	58
40. Test for Equal Variances for AP Manual, AP Automatic.....	59
41. Test for Equal Variances for FH Manual, FH Automatic.....	59
42. Test for Equal Variances for RL Manual, RL Automatic.....	50
43. Flow Velocity Profiles, Right / Left, Valves, Volunteer 4	62
44. Mean Flow (cm/s) Boxplot, Right / Left, Valves, Volunteer 4	62
45. Flow Velocity Profiles, Foot / Head, Valves, Volunteer 4	63
46. Mean Flow (cm/s) Boxplot, Foot / Head, Valves, Volunteer 4	63
47. Flow Velocity Profiles, Anterior / Posterior, Valves, Volunteer 4.....	64
48. Mean Flow (cm/s) Boxplot, Anterior / Posterior, Valves, Volunteer 4.....	64
49. Flow Velocity Profiles, Right / Left, Aorta, Volunteer 4	65
50. Mean Flow (cm/s) Boxplot, Right / Left, Aorta, Volunteer 4	65
51. Flow Velocity Profiles, Foot / Head, Aorta, Volunteer 4	66
52. Mean Flow (cm/s) Boxplot, Foot / Head, Aorta, Volunteer 4	66
53. Flow Velocity Profiles, Anterior / Posterior, Aorta, Volunteer 4.....	67
54. Mean Flow (cm/s) Boxplot, Anterior / Posterior, Aorta, Volunteer 4.....	67
55. Mean Flow (cm/s) Boxplot, Anterior / Posterior, Valves, Volunteer 2, 4.	68
56. Mean Flow (cm/s) Boxplot, Anterior / Posterior, Aorta, Volunteer 1, 2, 3, 4.....	68

LIST OF TABLES

Table	Page
1. Subtraction Data Sets	50

CHAPTER I

INTRODUCTION

Cardiac magnetic resonance imaging is a tool used by diagnostic radiology staff in a variety of cases. While identifying new areas of potential clinical validation for cardiac imaging, 7D cardiac flow quantification was chosen as an area of interest. Research at the time indicated full flow quantification of the heart and great vessels was possible, in 3 different flow directions, throughout the scan volume, applied over time. (Beerbaum, 1)

Currently, cardiac MR is an important imaging modality for diagnosis and management of heart disease. It has been identified as an appropriate test for an increasing number of clinical indications, such as complex congenital heart disease, ARVD and cardiac tumors, and even as a triage for managing revascularization procedures. (Philips Healthcare, 1)

Flow quantification using magnetic resonance has been achievable since the mid 1980s. Early studies proved flow quantification was possible (Branyt, 1), and quickly turned to such areas as the heart and great vessels (Firmin, 1), but also the brain (Murase, 81) and cerebral column. (Lee, 81)

Early studies focused on capturing the flow characteristics in a single slice of anatomy, at a single point in time. Particularly, studies dating back to 2003 used flow quantification to create velocity maps in single slice acquisitions in the brain and cerebral column.

A team at Ulsan University was able use this technique repeatedly at three different anatomical levels, to study the cerebral aqueduct. (Lee, 82) Similarly, a cerebral blood flow model was tested using MRI flow quantification by a team at the University of Osaka. Using flow quantification MRI, the cerebral flow model was completed. (Murase, 85)

Newer cardiac MR techniques, including Flow Sensitive 7 dimensional tissue phase mapping (7D Flow) has opened up the possibility of quantifying blood flow in the entire heart, over a period of time. (Beerbaum, 1) Such techniques can be used to characterize valve function, stresses within the heart tissue, and great vessels, including the aorta. While the techniques are relatively new, there are already a number of studies that have demonstrated their potential.

A review of the existing studies suggested phase contrast cardiovascular magnetic resonance is able to measure all three directional components of the velocities of flow relative to the three spatial dimensions and the time course of the heart cycle. (Ebbers, 1)

Physicians have traditionally turned to Doppler ultrasound to assess regional blood flow velocities. The ease of use, non-invasiveness, and proven applications of ultrasound make it a widely used tool for diagnosis. However, Doppler ultrasound is limited to user variability, because the velocity detected is relative to the direction of the

A team at the University of California has used the technique to evaluate the bicuspid aortic valve and aortic coarctation. The study characterized the abnormal blood flow of a juvenile boy. In addition to the expected flow disturbance in the region of the juxtaductal coarctation, the study showed an unusual flow feature in the ascending aorta that had not been previously reported in the clinical setting. The study indicated that this may be unique to Bicuspid Aortic valve defects, which occurs in 1 to 2% of the population and may account for more morbidity and mortality than all other congenital cardiac malformations combined. (Alley, 1)

In addition to studying aortic valve function and shear stress in the aorta, studies have demonstrated the potential of 7D flow to characterize heart valve function. Flow assessment through 4 heart valves simultaneously has been demonstrated by a team at Leiden University. The study demonstrated flow assessment using 7D flow techniques with retrospective valve tracking during off-line analysis can provide accurate quantification of net flow volumes through 4 heart valves within a single acquisition in healthy volunteers and in patients with valvular regurgitation. (Bax, 1) (See Figure 2)

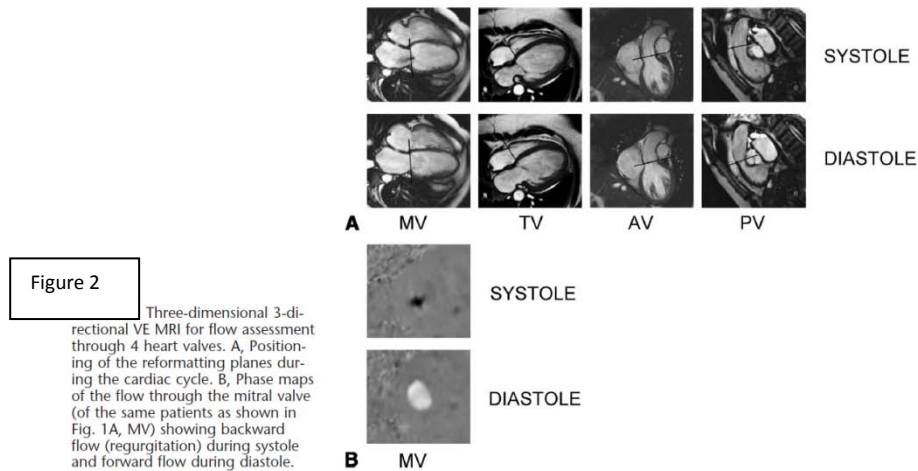


Figure 2 – Cardiac Valve Plane (Bax, 2)

The existing studies show 7D flow is a technique that can be used for specific heart conditions in existing patients. However, the acquisitions require appropriate placement of the velocity mapping plane and require a more rapid and user friendly strategies for acquisition and analysis.

While possible, many questions remained and a volume of work presented itself.

First, the target anatomy of the heart would have to be chosen. Second, a pre-packed exam protocol would need to be developed that targeted the chosen anatomy through easily planned scans. The protocol was required to be as short as possible to limit restriction on workflow, while capturing all the necessary data to provide the 7D flow quantification across the target anatomy. The protocol would need to be validated through a series of volunteer scans, and reconstructions. Validation would occur through the successful observation of DICOM data sets of the target anatomy showing flow in three different directions.

Furthermore, because DICOM data sets showing flow in three different directions currently require a delayed reconstruction only available under research agreement, and because that delayed reconstruction required an extended process of manual selection and input, automation was seen as advantageous.

By automating the delayed reconstruction process, it was assumed console time would be saved, throughput limitations reduced, and reconstruction errors eliminated. After validation, a research agreement would no longer be required, and next steps regarding clinical studies of 7D cardiac patients could be performed.

The automation of the delayed reconstruction process would need to be statistically validated and determined to be entirely equivalent to the research agreement manual delayed reconstruction process.

Finally, the data sets from the automated reconstruction would be used to plot velocity profiles across regions of interest and compare results between operators as well as patients.

To this end, a Master's thesis to satisfy graduation requirements at the Cleveland State University was proposed. The thesis committee would consist of subject matter experts at the Cleveland Clinic, Philips Healthcare, and Cleveland State University, and would be carried out over the course of 1 year. The project would consist of four distinct and stand alone stages, and presented in a way that each could be submitted for review independently. When taken as a whole, the 4 stages would represent the comprehensive satisfaction of the unmet needs of the Cleveland Clinic Foundation, would provide Philips Healthcare with a commercial advantage to its hardware / software platform, and

would satisfy the research and practical needs of a Master's thesis for the Cleveland State University, while providing a platform for advanced 7D cardiac flow quantification to occur.

The four stages of the project are as follows:

a. Stage 1

Learn to operate the Philips XR Achieva 1.5T MRI scanner and develop a standalone 7D Flow Cardiac scan protocol (ExamCard) that covered the desired anatomy.

b. Stage 2

Validate the ExamCard with volunteer studies, enable raw data to be saved and later reconstructed manually. Verify flow quantification in three different directions, in 2 anatomical areas of the heart, over time.

c. Stage 3

Optimize workflow – create a batch file script to automate 7D reconstruction. Apply the batch file script to volunteer raw data created in stage 2 and verify flow quantification in three different directions, in 2 anatomical areas of the heart, over time.

d. Stage 4

Validate the automated reconstruction batch file by comparing manual to automatic reconstruction data sets. Complete statistical analysis of said data sets and test hypothesis that the automated reconstruction was identical in make up to the manually reconstructed data sets, in all cases. Finally, use data sets from the automated

reconstruction to plot velocity profiles across regions of interest and compare results between operators as well as patients.

Each is presented in summary here, and detail in later chapters.

Stage 1 - Learn to operate the Philips XR Achieva 1.5T MRI scanner and develop a standalone 7D Flow Cardiac scan protocol (ExamCard) that covered the desired anatomy.

In this stage, we developed and demonstrated an MR protocol that accurately places the mapping plane for a 4 chamber valvular flow study and a cross section of the aortic arch packaged into one exam.

Stage 2 - Validate the ExamCard with volunteer studies, enable raw data to be saved and later reconstructed manually. Verify flow quantification in three different directions, in 2 anatomical areas of the heart, over time.

In this stage, we verified the ExamCard and manual reconstruction had been properly developed. To do so, four volunteer studies were completed. Each volunteer was scanned on the same Philips 1.5T Achieva scanner, using the 7D flow ExamCard developed in stage one, and raw data reconstructed using the manual delayed reconstruction procedure. Flow quantification in a 3D volume in 3 directions over time was verified. Results were verified using existing studies as a baseline.

The manual process involves users to input certain parameters and reconstruct the collected raw data one set at a time.

For our study, the reconstruction would need to be repeated 6 times, 3 for the 4 chamber valvular data set and 3 for the aortic arch data set. This is a complicated and time-consuming process that is not sufficient for routine clinical use.

Stage 3 - Optimize workflow – create a batch file script to automate 7D reconstruction. Apply the batch file script to volunteer raw data created in stage 2 and verify flow quantification in three different directions, in 2 anatomical areas of the heart, over time.

In this stage, we aimed to validate a batch file script to automate the reconstruction of the raw data acquired during the exam. We demonstrate and validate a method to 1) automatically find the raw data after the exam is completed, 2) reconstruct both data sets in each of three flow directions, and 3) name the scans accordingly. The method results in quantitative DICOM data sets for flow in 3 directions and in both the 4-chamber valve and aortic arch profiles.

Stage 4 - Validate the automated reconstruction batch file by comparing manual to automatic reconstruction data sets. Complete statistical analysis of said data sets and test hypothesis that the automated reconstruction was identical in make up to the manually reconstructed data sets, in all cases. Finally, use data sets from the automated reconstruction to plot velocity profiles across regions of interest and compare results between operators as well as patients.

Finally, in stage 4, we verify the automated delayed construction data sets were quantifiably equivalent to the manually delayed reconstruction data sets, through comparison and statistical analysis.

In stage 2, raw data from each 7D flow study (Aorta and Valves), was reconstructed manually, and using the automated batch file, in 3 directions. In stage 3, the same raw data was reconstructed automatically, using the batch file script. In this stage, each data set was compared to its counterpart by first subtracting the manual data set from the automated data set, and creating a third “subtraction” data set. This “subtraction” data set would show only differences between the 2 reconstructions, and was hypothesized to be zero in all measurements. In all 3 directions in both sets of anatomy, these “subtraction” data sets were saved for later analysis. (See Table 1)

Data sets from the automated reconstruction were then used to plot velocity profiles across regions of interest and compare results between operators as well as patients.

Automation of 7D flow reconstruction allows for the next steps towards clinical validation. In particular, quantification of the flow characteristics should be confirmed. By using the validated exam card and delayed reconstruction batch file, users can achieve clinical validation by calculating the forward flow of the aorta and comparing it to the left ventricle stroke volume. Users can employ such methods along other areas of the anatomy to quantify flow.

Secondly, by analyzing the reconstructed flow data sets with a third party visualization package, flow lines and patterns can be studied. Such packages are available and have been validated in other studies. (See Figure 3)

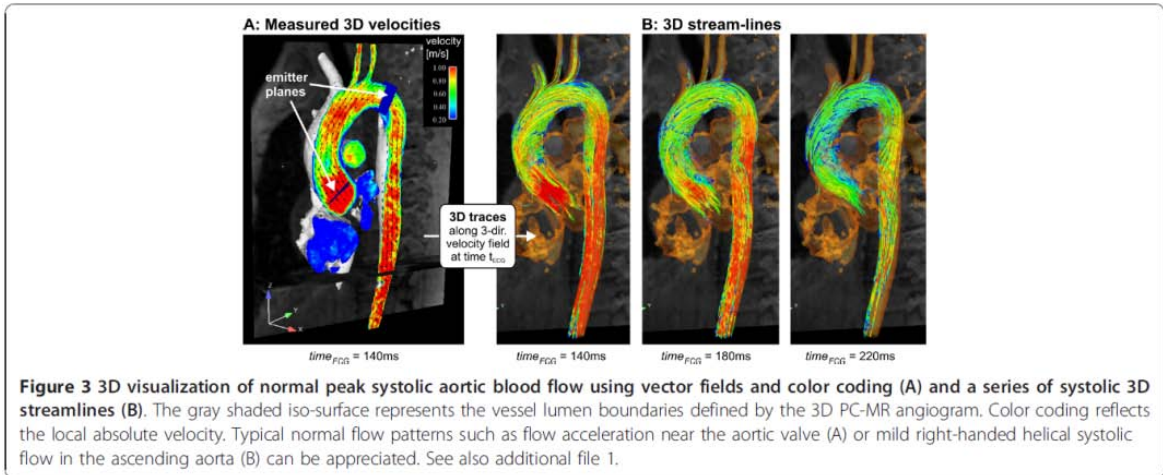


Figure 3 – 3D Visualization Package (Ebbers, 6)

CHAPTER II

EXPERIMENTAL FACILITY

a. Experimental Facility

Philips Medical Systems, (Philips Healthcare), as part of Royal Philips Electronics, located at 595 Miner Rd., Cleveland, OH, 44143, was the primary site where the research was developed, tested, and validated. Further validation occurred at the Cleveland Clinic Main Campus, located at 9500 Euclid Ave., Cleveland, OH, 44195.

b. Philips XR Achieva 1.5T MRI

The MRI platform used throughout the study was the Philips XR Achieva 1.5T MRI scanner, software release 3.2.6. The Philips XR Achieva 1.5T MRI scanner is a powerful system featuring high intrinsic homogeneity. FreeWave digital data acquisition platform is the data acquisition used on the Philips Achieva XR 1.5T MRI scanner.

c. Surface Coils

Scan protocols and exam card development employed the Philips SENSE XL Torso Coil. The 16 channel SENSE XL Torso Coil is a flexible, multi-application coil which provides high quality images with adequate anatomical coverage. The coil has a

soft, thin foam design that contours to patients. The SENSE XL Torso Coil is designed for proton imaging and is intended for imaging applications of the organs of the abdomen, pelvis and chest. The XL Torso Coil is made of 2 flexible halves, each positioned on the posterior and anterior of the patient, and each consisting of 8 channels.

d. Wireless Gating

In cardiac exams, the patients' ECG-signal is measured to trigger scans and collect data during a particular phase of the cardiac cycle of the patient. A four-lead VCG signal is measured to reduce the effects of the static magnetic field on the ECG-signal by measuring the cardiac conductivity in two dimensions.

The studies conducted here employed the wireless gating unit and triggering software provided by Philips. Set up was completed according to the supplier's recommendations, summarized here.

Recommended lead positioning for the wireless triggering module is displayed in the image below and is set-up according to these guidelines:

- white electrode at first intercostal space, just left of the sternum
- green electrode at the level of the xyphoid, just left of the sternum
- red electrode on the patient's left side, horizontally aligned with the green electrode
- black electrode close to the left armpit
- white, red and green electrode make 90-degree angle
- black electrode completes the "square"

- distance white / green ~ 15 cm
- distance red / green ~ 15 cm

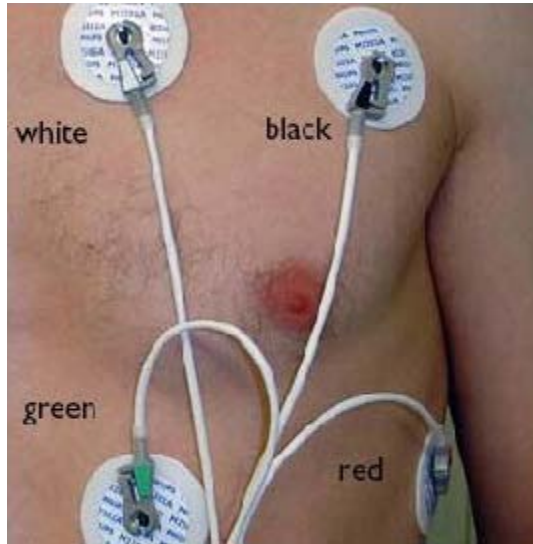


Figure 4 – Wireless Gating Set Up

e. ExamCard Environment

The exam protocol was built using the Philips ExamCard environment. An ExamCard contains all the scans required for a complete MR examination in a single file that can be uploaded directly into a Philips MRI scanner. ExamCards contain examples of clinical images, as well as tips and notes on the scan being performed. New exams can be built using a library of designated scans, and the order of those scans can be easily changed to fit workflow needs. (See Figure 5)

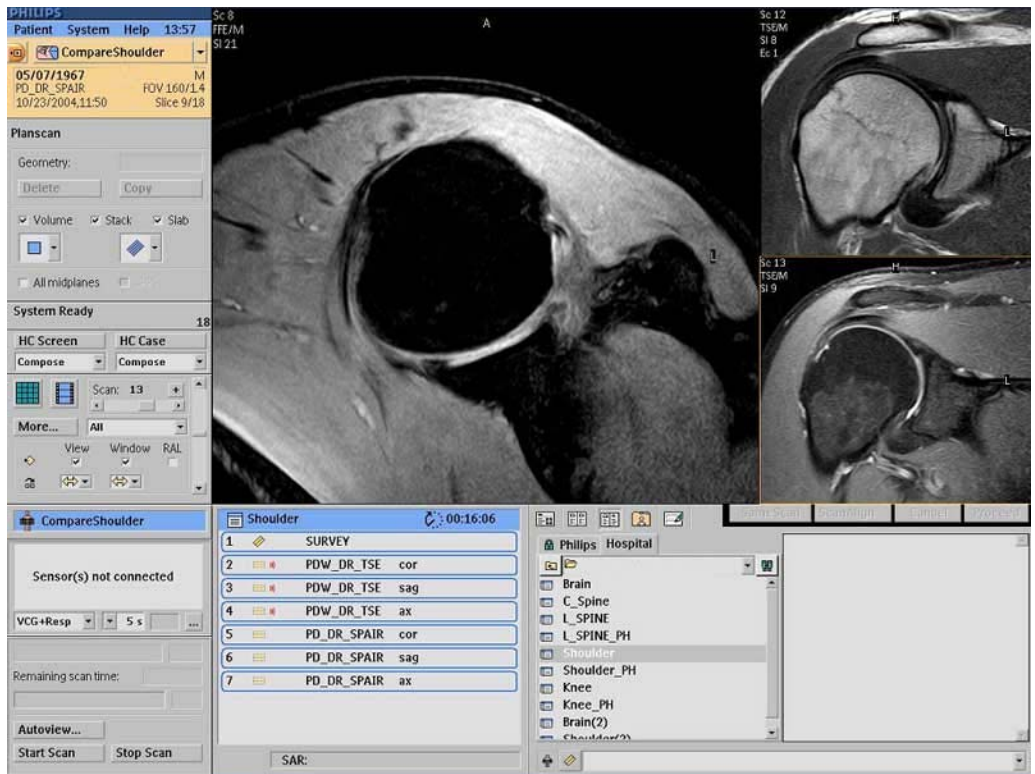


Figure 5 – ExamCard Environment

CHAPTER III

DESCRIPTION OF EXPERIMENT – IN 4 STAGES

7D cardiac flow quantification using magnetic resonance imaging will provide flow quantification in the anterior / posterior, head / foot, and left / right directions, in real time, in a 3D imaging volume. The work presented here provides MRI techniques that may lead to clinical applications for the cardiac valves and the flow differentials during cardiac function, as well as the flow and pressure differentials of the aortic arch.

The study was carried out in stages.

-
- a. Stage 1** - Learn to operate the Philips XR Achieva 1.5T MRI scanner and develop a standalone 7D Flow Cardiac scan protocol (ExamCard) that covered the desired anatomy.

i. Introduction / Purpose

The purpose of this study was to develop and demonstrate an MR protocol that accurately places the mapping plane for a 4 chamber valvular flow study and a cross section of the aortic arch packaged into one exam, taking into account set up and scan time parameters as well as all pertinent acquisition information, in a simple to execute, pre-packaged scan protocol.

The result is a complete scan protocol that captures the desired anatomy and allows for delayed reconstruction of raw data that provides three dimensional, phase encoded flow quantification images of the desired anatomy.

First, the target anatomy of the heart was chosen. Second, a pre-packed exam protocol was developed that targeted the chosen anatomy through easily planned scans. The protocol needed to be as short as possible to limit restriction on workflow, while capturing all the necessary data to provide the 7D flow quantification across the target anatomy.

ii. Description of Experiment

Two physiological areas of heart anatomy were targeted for the study.

Fist, a slice plane that intersected the cardiac valves was chosen. The quantitative flow scans were to show both the aortic valve and the mitral valve in their planning. (See Figures 6 and 7)

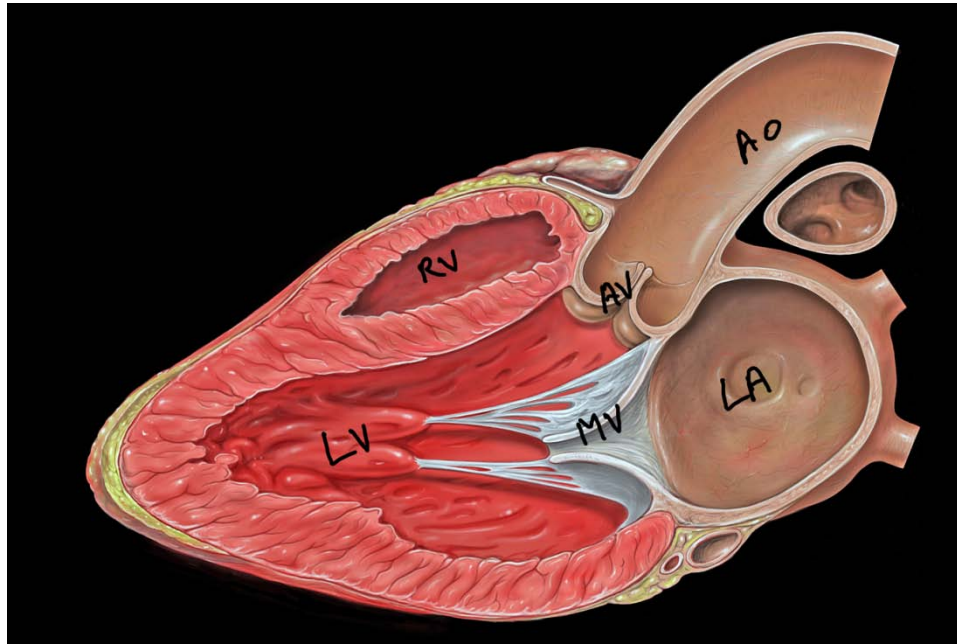


Figure 6 – Valve Plane of the Heart

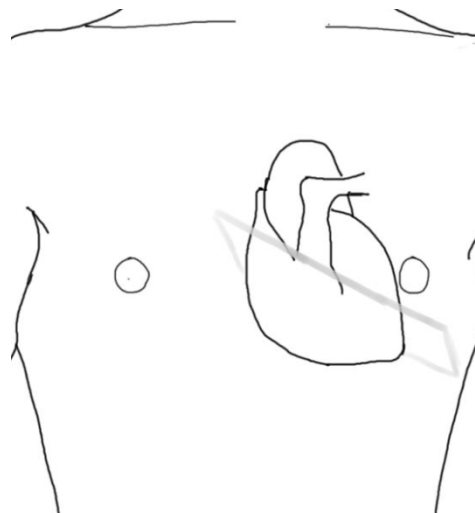


Figure 7 – Placement of the Slice Plane

Second, the scan protocol was expected to locate and collect data of the aortic arch. In this scan, the descending thoracic aorta, aortic arch, and ascending thoracic arch were to be covered. (See Figure 8)

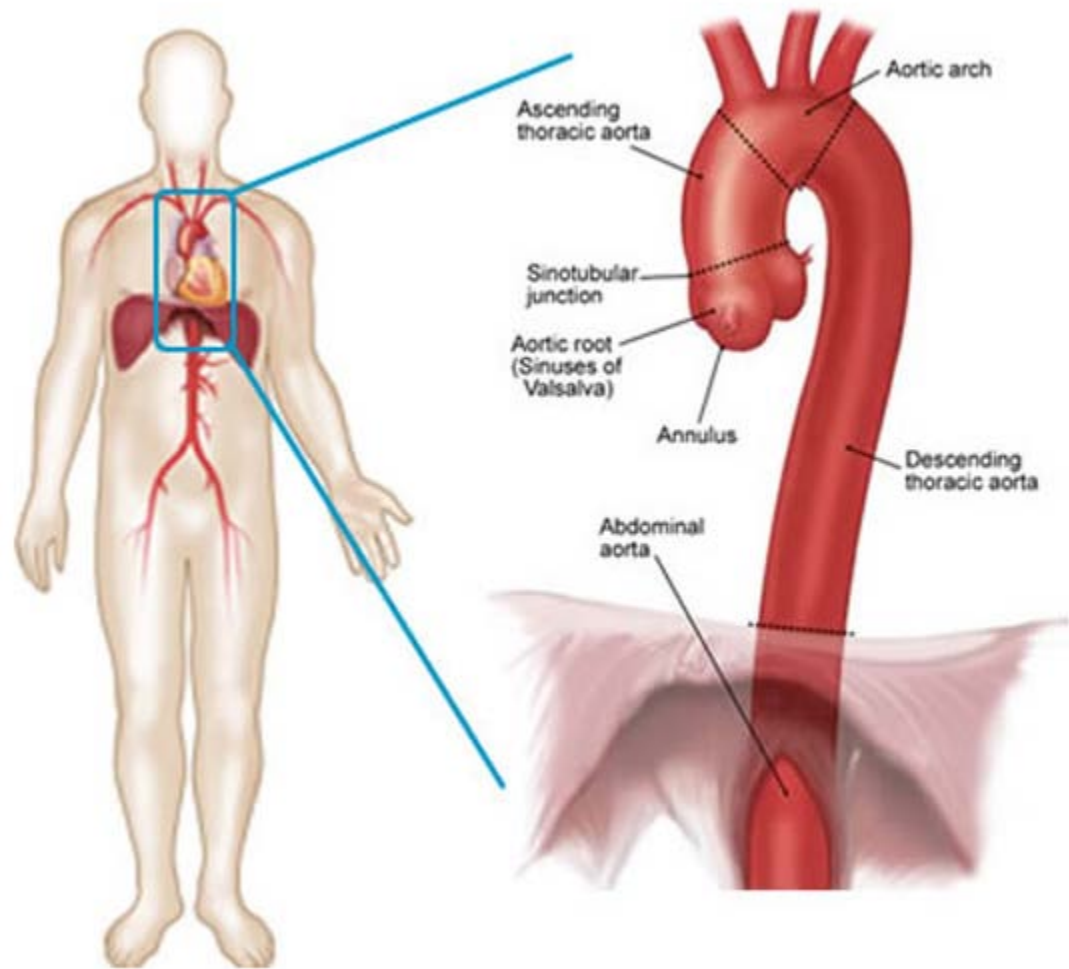


Figure 8 – Aortic Arch

After the target anatomy had been chosen, a scan protocol, or ExamCard, was developed.

To complete the development of the ExamCard, first a functional understanding of the Philips Achieva 1.5T MRI scanner platform use and function was gained. Through the instruction of Philips personnel and hands on practical use of the scanner, a working knowledge of the hardware was achieved. This was the basis for the development of the ExamCard, and served as a platform for the subsequent stages of the project.

This stage addresses the exam and the scan / plan sequence itself and reasoning behind the sequence development.

The ExamCard consists of individually run successive scans. Each scan is described here. (See Figure 9)

1. Exam Card Development – Scan Selection, Modification, and Planning

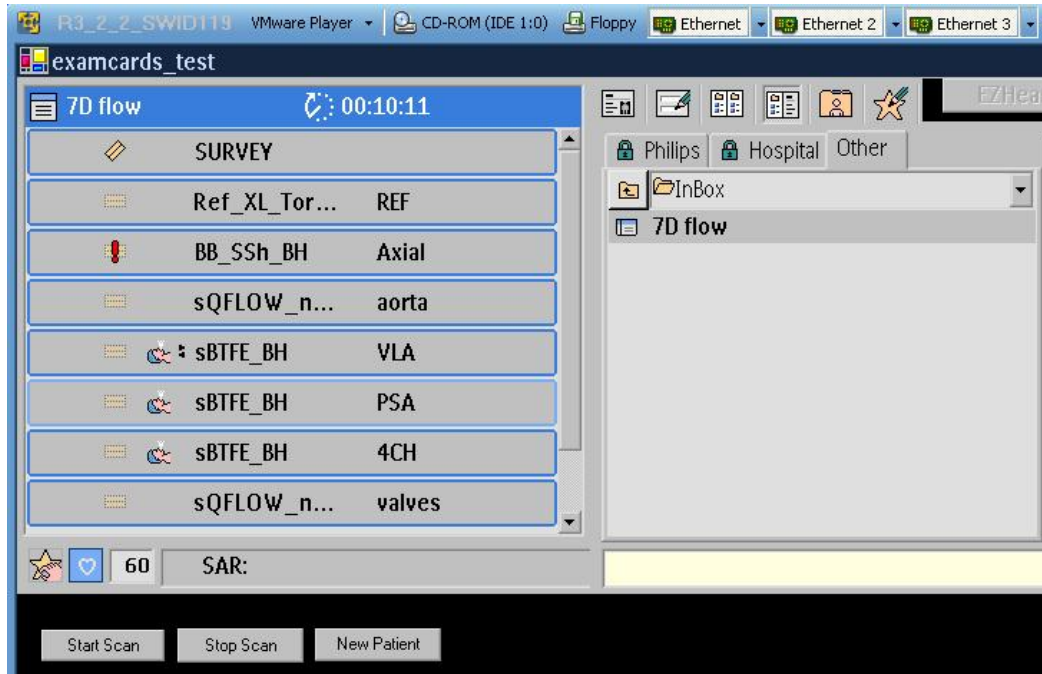


Figure 9 – 7D Flow ExamCard

2. Balanced TFE Survey Scan (SURVEY)

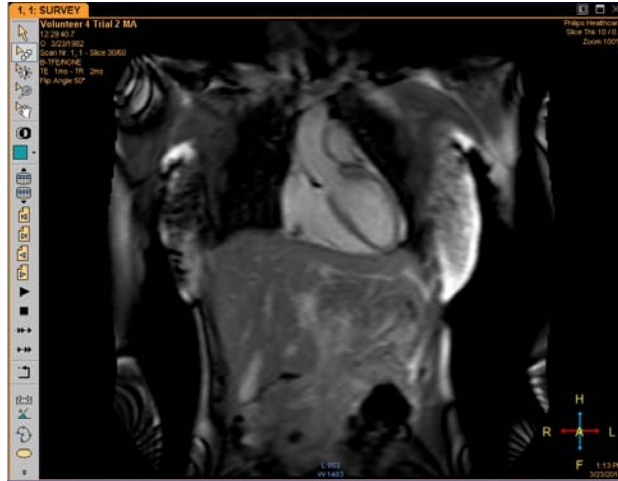


Figure 10 – Survey Scan

As is typical with MR scanning, the exam sequence began with a survey scan that covered the mid torso and heart region of the scan subject. The standard cardiac survey scan was chosen. The standard cardiac survey scan acquired 60 slices (20 in each orthogonal direction) within a few seconds using balanced TFE (Turbo Field Echo). The survey was not cardiac triggered.

3. Reference Scan for XL Torso Coil (Ref XL Torso)



Figure 11 – XL Torso Coil

Because the 16 element 1.5 T XL torso coil was used, the next scan in the exam card sequence was the reference scan for this coil. The scan was used to acquire sensitivity information from each coil element that was used for all CLEAR and SENSE reconstructions during the entire examination.

SENSE is a Philips specific scan technique used for optimal coil performance. The SENSE principle relies on the multiple coil elements in the XL Torso Coil simultaneously receiving a reduced field of view image. SENSE reconstruction combines and unfolds the individual coil images. The SENSE information acquired during the reference scan is used throughout the remainder of the ExamCard, and is specific to each time the ExamCard is run, dependant on the specific coil, and it's placement on the scan subject.

CLEAR is likewise a Philips specific scan technique used for optimal coil performance. CLEAR data is used to correct for coil sensitivity and coil placement. It is a calibration technique based in the location of the coil, and the coil elements in relation to each other. The CLEAR information acquired during the reference scan is used throughout the remainder of the ExamCard, and is specific to each scan, dependant on the specific coil, and it's placement on the scan subject.

4. Single Shot Dual Inversion Black Blood Breath-Hold Scan (BB SSh BH)

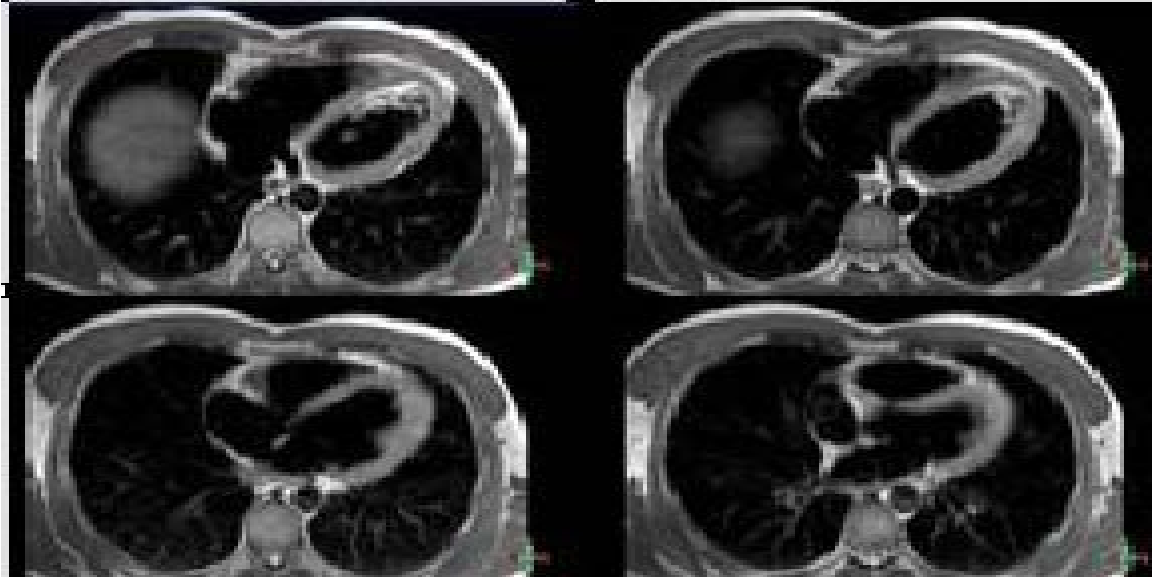


Figure 12 – Single Shot Dual Inversion

Next, a single shot, dual inversion black blood breath hold scan was used to acquire a stack of axial slices in the heart. Every slice of this scan was acquired in a heart-beat and required triggering. A trigger delay was facilitated by the wireless gating unit described in Chapter 2. The trigger delay was set to avoid timing conflicts while allowing acquisition at the same cardiac phase in each cardiac cycle. Phase oversampling was enabled in cases of double-oblique scan angulation to avoid phase wrap.

5. AORTA SENSE TFE Flow quantification (sQFLOW BH SENSE TFE)

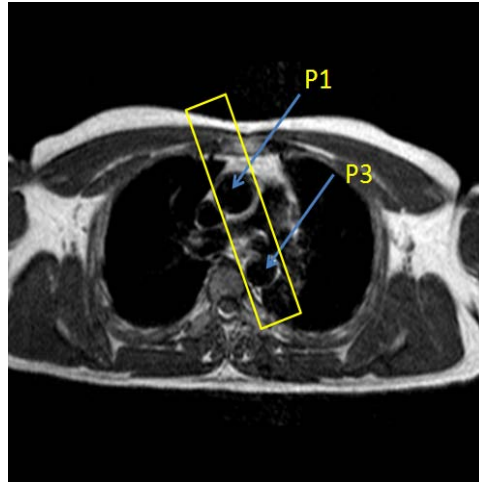


Figure 13 – Aortic Flow Quantification Planning

Using the single shot dual inversion scan described above for planning, a SENSE QFLOW triggered scan was used. During this scan, the directional flow information was collected and saved as raw data.

The anatomy targeted during this scan was the aortic arch, and the scan was planned using three point plane generation. The first point was set in the center of the ascending aorta, mid torso. Using the same axial plane, the third point was defined in the center of the descending aorta. Moving towards the head axially, the second point was defined at the peak of the aorta. When all three points were defined, a scan plane was generated that covered a cross section of the aortic arch.

After the scan plane was defined, the scan was run. The scan consisted of a through plane flow quantification using navigator gating to accommodate for respiratory motion. SENSE parallel imaging was used to improve both spatial and temporal

resolution. Retrospective triggering was used to cover the entire cardiac cycle with the maximum number of cardiac phases. A reduced phase percentage was used to reconstruct more cardiac phases, and a data sharing strategy was applied during reconstruction. TFE (Turbo Field Echo) shot mode was set to default, which means that the TFE turbo factor was automatically calculated from the requested number of cardiac phases and the heart rate. As a result, changing the heart rate did not influence the scan time or the number of cardiac phases.

The velocity encoding (Venc) was set at 200 cm/s to avoid aliasing.

Finally, in order to facilitate flow quantification in 3 different directions, raw data was saved for later reconstruction.

6. SENSE Balanced TFE Cine Scan (VLA sBTfE BH)



Figure 14 – SENSE Cine Planning 1

The exam then shifted to focus on the valve plane. In order to achieve a 4 chamber valve plane, several sequential cine scans were planned and completed. The

first was planned using the survey scan. Mid torso slices were viewed and a scan plane defined that split the apex of the heart and the top of the heart. (See Figure 14) The scan was then run.

The SENSE balanced cine scan captured the motion of the beating heart in a single breath-hold using SENSE. Retrospective triggering was used to cover the entire cardiac cycle with the maximum number of cardiac phases. Phase percentage was set to less than 100% and, as in previous scans, a data sharing strategy was applied during reconstruction to reconstruct more phases.

TFE shot mode was set to default. The TFE turbo factor was automatically calculated from the requested number of cardiac phases and the heart rate. As a result, changing the heart rate did not influence the acquisition time or the number of cardiac phases. A volume shim was enabled and the volume was placed in-line with the scan plane to minimize inhomogeneity in the image.

SENSE was used to shorten the breath-hold duration. Phase oversampling was enabled to avoid SENSE back folding. Spatial resolution and temporal resolution were chosen to give a short breath hold while still achieving the data characteristics necessary. In future studies, the number of slices per breath-hold can be changed to fit the breath-holding capabilities of the patient.

7. SENSE Balanced TFE Cine Scan (PSA sBTFE BH)

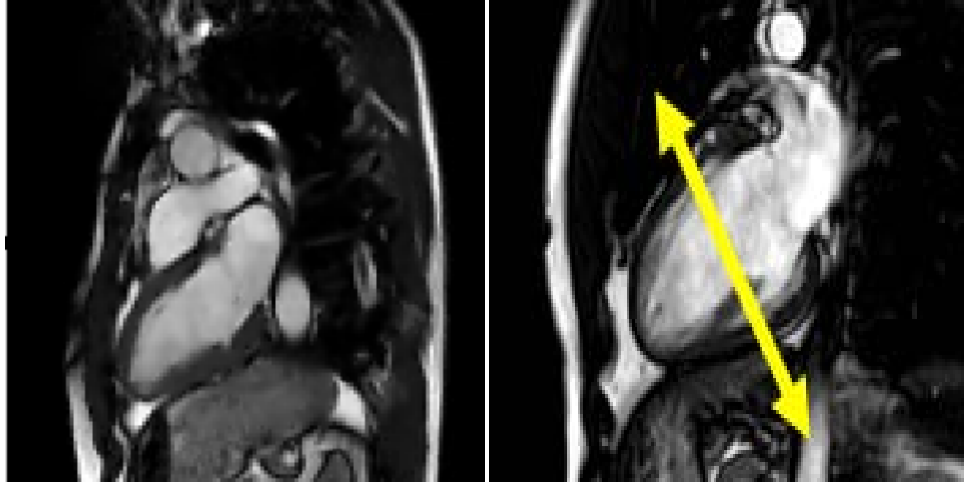


Figure 15 – SENSE Cine Planning 2

Using the previous Cine scan, a second cine scan was planned. This scan split the valve plane. (See Figure 15) Scan parameters remained unchanged from the previous scan. The scan was then run.

8. SENSE Balanced TFE Cine Scan (4CH sBTfE BH)

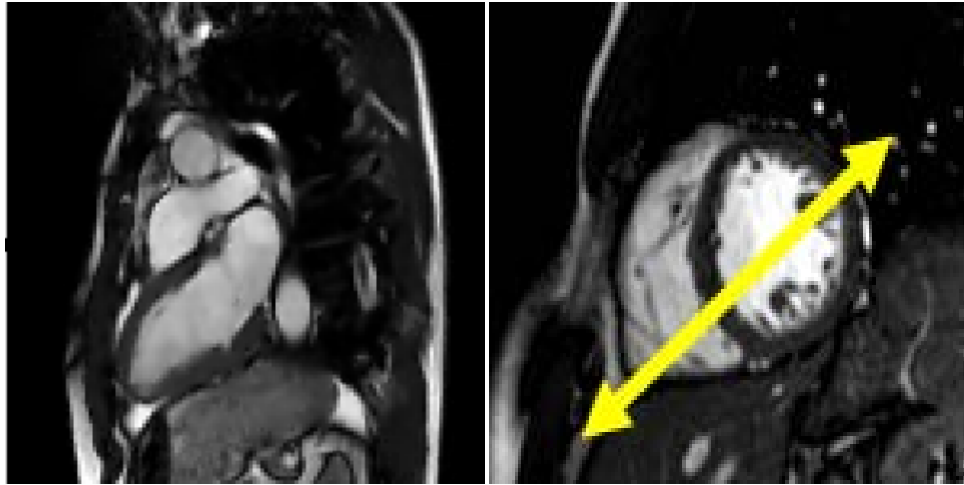


Figure 16 – SENSE Cine Planning 3

Using the second Cine scan, a third scan and final cine scan was planned. This provides a four chamber view of the heart, allowing for the planning of a flow quantification scan in the valve plane. (See Figure 16) Scan parameters remained unchanged from the previous scan. The scan was then run.

9. VALVES SENSE TFE Flow quantification (sQFLOW BH SENSE TFE)

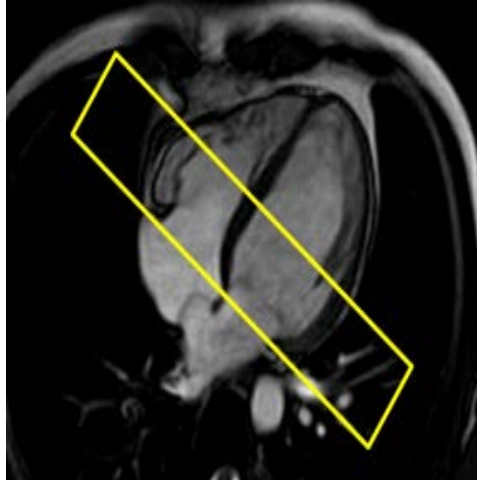


Figure 17 – Valve Flow Quantification Planning

The resulting images of the previous scan provide a 4 chamber view of the heart. From this, the valve plane was planned to facilitate the flow quantification scan through the valves. As shown in Figure 17, a scan area was chosen that targeted the valve plane of the heart.

As in the previous aortic scan, the valve plane flow quantification scan used navigator gating to accommodate respiratory motion. SENSE was used to improve both spatial and temporal resolution. Retrospective triggering was again used to cover the entire cardiac cycle with the maximum number of cardiac phases. A reduced phase percentage was used to reconstruct more cardiac phases, and a data sharing strategy was applied during reconstruction. The TFE shot mode was set to default, which means that the TFE turbo factor was automatically calculated from the requested number of cardiac

phases and the heart rate. As a result changing the heart rate did not influence the scan time or the number of cardiac phases.

The velocity encoding (Venc) was set at 200 cm/s to avoid aliasing.

Finally, in order to facilitate flow quantification in 3 different directions, raw data was saved for later reconstruction.

iii. Results and Discussion

Using the Philips ExamCard environment, a scan protocol was developed. The scan protocol provided the anatomical views for the 7D flow quantification of the valvular plane and the aortic arch. Raw data was saved to the scanner database for later reconstruction.

The exam card sequence was developed over a period of trial runs and modified through a process of trial and error to obtain the optimal anatomical / DICOM data.

Preliminary images acquired throughout the development of the ExamCard were presented and discussed with Cleveland Clinic staff and served as proof that the ExamCard had been developed to a point where a volunteer study could be completed.

1. Next Steps – Stage 2

Given the success of Stage 1, a second stage of the project was planned. Stage 2 would include volunteer scans, and a more in-depth and verification of resulting scans. It would also focus on the delayed reconstruction process needed to reconstruct the quantitative flow images, in 3 directions, over two anatomical areas of the heart.

b. Stage 2 - Validate the ExamCard with volunteer studies, enable raw data to be saved and later reconstructed manually. Verify flow quantification in three different directions, in 2 anatomical areas of the heart, over time.

i. Introduction / Purpose

Following the development of the ExamCard, the protocol would need to be validated through a series of volunteer scans, and reconstructions. Validation would occur through the successful observation of DICOM data sets of the target anatomy showing flow in three different directions.

ii. Description of Experiment

This stage of the experiment consisted of scanning 4 patients using a pre-developed ExamCard (see stage 1) that focused on the aortic arch and the 4 chamber valve plane of the heart. Equipment used was described in previous chapters.

After development of the ExamCard, the scan subject population was selected and over the course of 1 week, the subjects were scanned (using the described set up / equipment in Chapter 2). Four volunteers were scanned on the same Philips Achieva scanner at Philips Healthcare in Highland Heights, Ohio.

The experimental model chosen for the work described here is aimed to validate the MR scan sequence (ExamCard), through the visual examination of acquired images, and the verification of the collection of raw data used in later delayed reconstructions. Delayed reconstruction of the raw data collected from the quantification flow scans in three different flow and spatial directions in time, of two different anatomical areas of the heart were needed to validate the ExamCard.

1. Manual Delayed Reconstruction

The Philips 1.5T XR Achieva MRI scanner allows for delayed reconstruction of raw data saved during exams.

In this stage, raw data was saved for both the aortic arch study and the valve plane study during the flow quantification scans for each anatomy. In order to reconstruct images that show phase contrast and flow quantification in 3 different directions, each set of raw data was reconstructed 3 times, for a total of 6 directionally unique 3D data sets.

For each, a user typically must complete several steps to select, rename, change parameters, and reconstruct the data. (See Figure 18) The process is somewhat tedious, and for clinical applications, can limit throughput of the machine (delayed reconstruction must take place on the scanner console itself, and there is no good way to reconstruct raw data offline).

For base lining future stages of the project, and for validation of the ExamCard created in stage 1, the manual delayed reconstruction was used. Each set of raw data was selected and renamed according to the anatomy and flow direction of interest. In the “settings” tab, the phase / magnitude selection was set to phase, and the direction of flow was indicated.

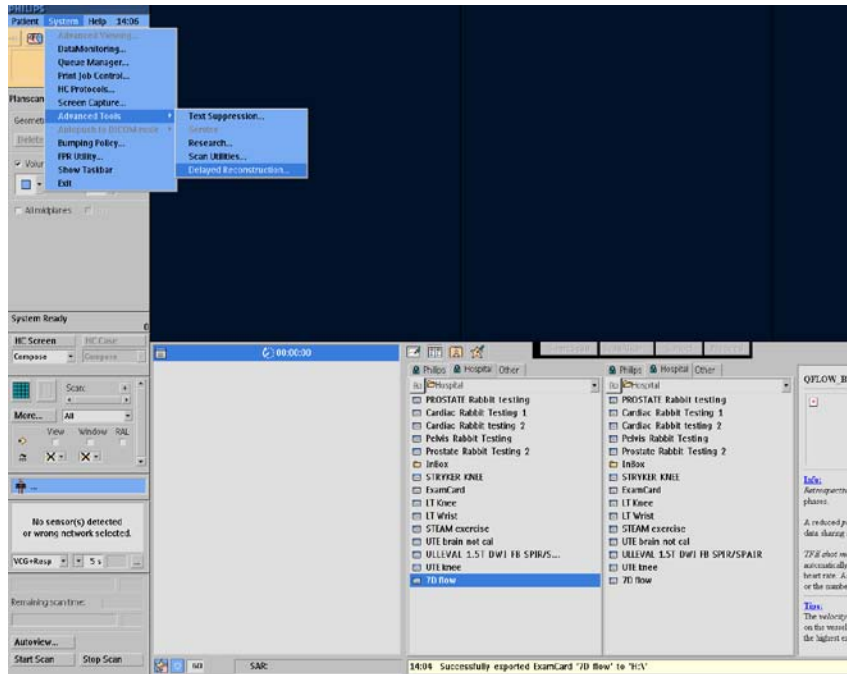


Figure 18 – Manual Delayed Reconstruction

Workflow for manual delayed reconstruction is visually described in the following block diagram. (See Figure 19) The flow involves changing 2 reconstruction parameters in each set of raw data, followed by renaming and reconstructing the data, 6 times in total.

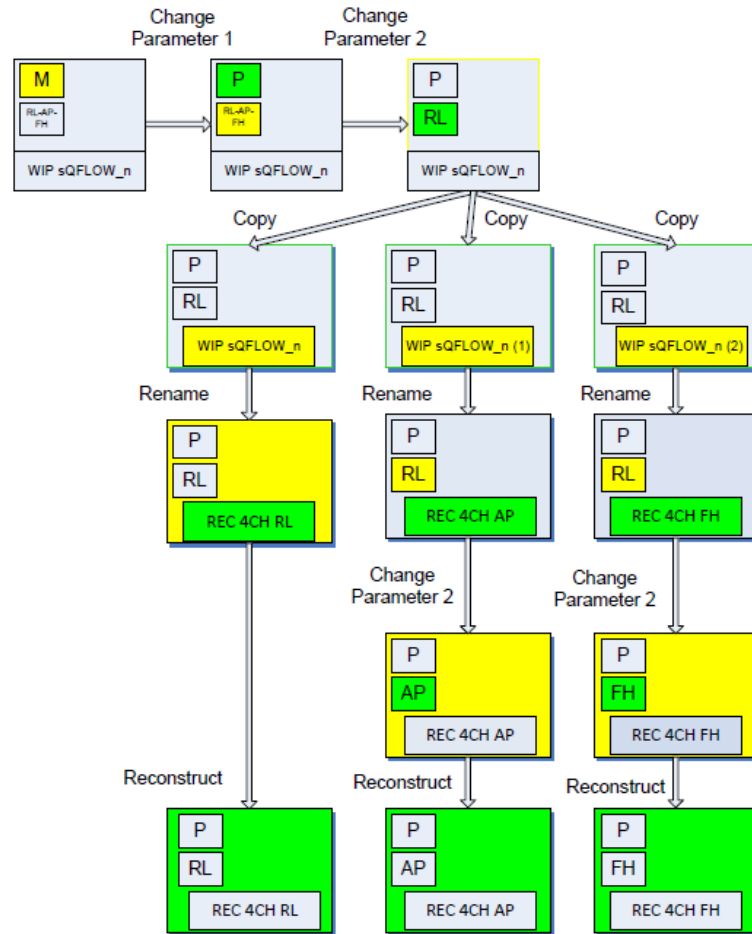


Figure 19 – Manual Delayed Reconstruction Work Flow

iii. Results and Discussion

Resulting reconstructed scans were verified to show flow in 3 different directions using the same raw data. (See Figures 20 – 23)

Aorta – Manual Delayed Reconstruction

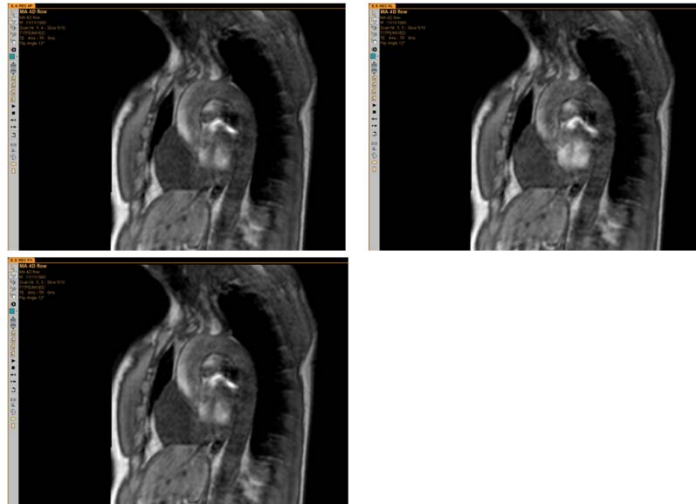


Figure 20 – Manual Delayed Reconstruction Data Set 1

For each reconstruction completed, a magnitude image was generated for each slice, corresponding to the phase contrast, velocity encoded image. Figure 20 shows the magnitude image for a specific slice of the aortic arch scan, in each of the three flow directions, anterior / posterior, head / foot, and right / left. The three images in Figure 20 are equivalent in magnitude.

Magnitude images are used to show anatomy, and are later used in this study to identify a region of interest to validate flow results between manual and automatic delayed reconstruction procedures. For the images shown, the lighter areas represent denser anatomy than the dark areas.

Aorta – Manual Delayed Reconstruction

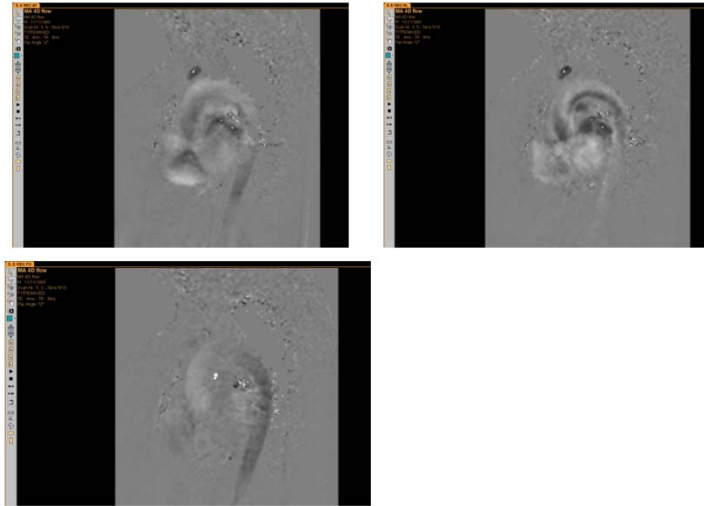


Figure 21 – Manual Delayed Reconstruction Data Set 1 – Phase Mapping

Likewise, phase contrast, velocity encoded flow images were generated for each slice. Figure 21 shows the phase contrast, velocity encoded images for a specific slice of the aortic arch scan, in each of the three flow directions, anterior / posterior, head / foot, and right / left.

Phase encoded flow images are used to quantify flow. Each indicates the value of flow in a specific direction. For the images shown, the lighter areas represent a greater flow value than the dark areas. By comparing the differences in flow values between flow direction images and noting differences in appearance, the manual reconstruction process was confirmed.

Magnitude and phase encoded flow images were also generated for the valve plane of the heart, and are shown below. Again, by comparing the differences in flow values between flow direction images and noting differences in appearance, the manual reconstruction process was confirmed.

Valves – Manual Delayed Reconstruction

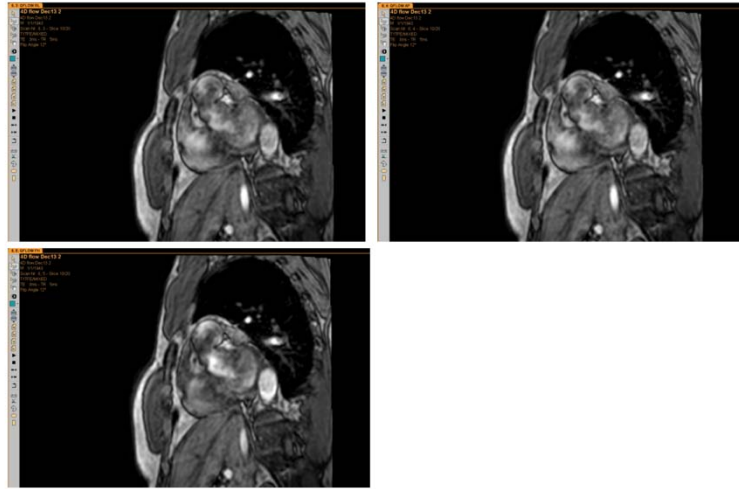


Figure 22 – Manual Delayed Reconstruction Data Set 2

Valves – Manual Delayed Reconstruction

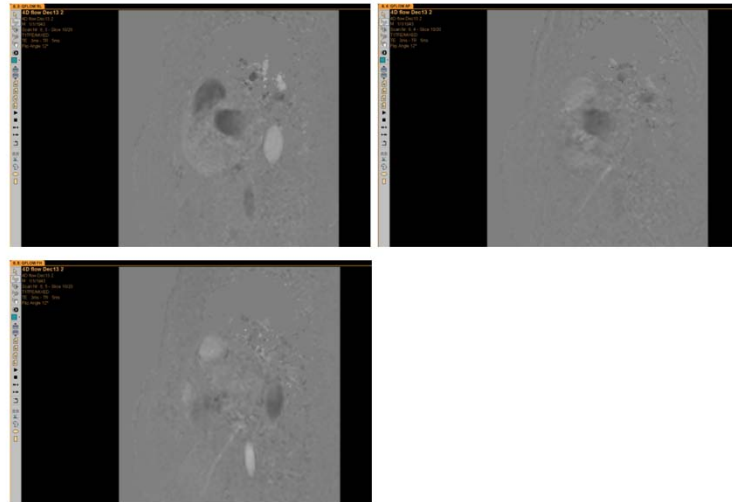


Figure 23 - Manual Delayed Reconstruction Data Set 2 – Phase Mapping

Further analysis to quantify the flow characteristics were not covered in this study, but it is recommended as an area of further study to do so.

1. Next Steps – Stage 3

With the phase encoded flow quantification scans completed and verified, the focus of the study then shifted to taking time and effort out of the reconstruction process. Again, working within the Philips Achieva 1.5T infrastructure was a prerequisite, so further research into coding the commands was needed.

The next stage of the project describes the effort to create and test a batch file, or script, which would automate the delayed reconstruction process, taking time and effort out of the process.

-
- c. Stage 3 - Optimize workflow – create a batch file script to automate 7D reconstruction.** Apply the batch file script to volunteer raw data created in stage 2 and verify flow quantification in three different directions, in 2 anatomical areas of the heart, over time.

i. Introduction / Purpose

Added workflow time and specific clinician expertise on delayed reconstruction procedures are required to complete the manual delayed reconstruction process described in stage 2 of this project. The need for an automated way to complete the delayed reconstruction of the flow data sets stemmed from those requirements. Furthermore, DICOM data sets showing flow in three different directions currently required a delayed reconstruction process only available under research agreement, and because that delayed reconstruction required an extended process of manual selection and input, and we sought to automate the process.

By automating the delayed reconstruction process, console time would be saved, throughput limitations reduced, and reconstruction errors reduced. After validation, a research agreement would no longer be required, and next steps regarding clinical studies of 7D cardiac patients could be performed.

ii. Description of Experiment

1. Automated Delayed Reconstruction Batch File

The primary goal of the third phase of this study was to automate the delayed reconstruction of the raw data collected during the volunteer studies of stage 2.

A batch file was written, tested, and validated, that, when executed, completed all of the steps of the manual delayed reconstruction with minimal user input. See Appendix A for the code of the batch file.

The batch file completes the same steps of the manual delayed reconstruction, but does not require the user to input parameter changes or name or rename the delayed reconstruction scans. In order for the batch file to run, naming of scans should be done using a specific nomenclature, which can be changed in the code, or facilitated through a second batch file run prior to the actual patient scanning (included in Appendix A).

A block diagram describing the steps the batch file completes is presented below. (See Figure 24) The batch file simplifies the steps to complete delayed reconstruction by selecting the appropriate raw data, changing the parameters needed, and automatically saving the scan using the appropriate naming convention.

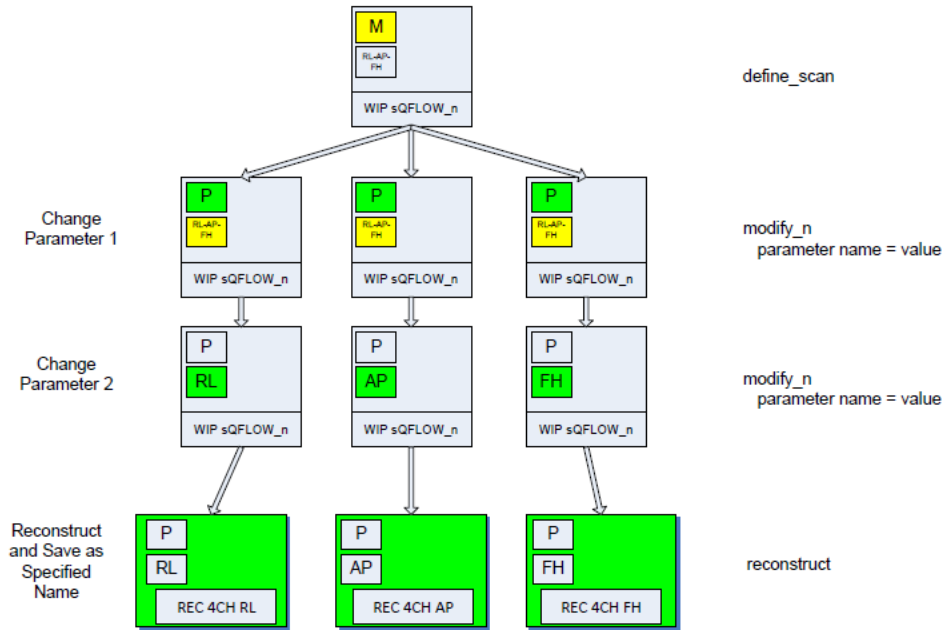


Figure 24 – Automatic Delayed Reconstruction Work Flow

To run the batch file, users employ the batch interpreter (part of the standard software installation for the Philips 1.5T XR Achieva).

The Batch Interpreter is invoked by selecting the corresponding menu entry in the Service mode menu. But also by supplying a Batch File on the command line of the Acquisition Simulator.

Batch Files are written in ASCII format and given the extension ACQ. To enable selection within the Service menu, the files have to be located in one of the directories linked within the logical GYRO_TESTBATCH. The file is only processed if it also contains Batch Commands.

iii. Results and Discussion

The third phase of the project involved writing a batch file to automate the reconstruction of the raw data saved from the previously described scan protocol. The batch file is an executable script file that will automate the manual work of the Philips delayed reconstruction procedures. The batch file, when executed, will select, change reconstruction parameters for each of 6 scan reconstructions, run the reconstruction, and name the scans appropriately.

The delayed reconstruction batch file was developed during the same period of time as the volunteer studies, through a process of trial and error, and tested on existing raw data available on the system.

In the 4 cases used to validate the batch file, the user was asked to select the raw data for each anatomy. When selected, the batch file generated the desired 3 scans, and named them accordingly. The scans were saved in the study with all other scans for later interpretation. (See Figures 25 – 28)

Volunteer 1, Trial 2, Aorta

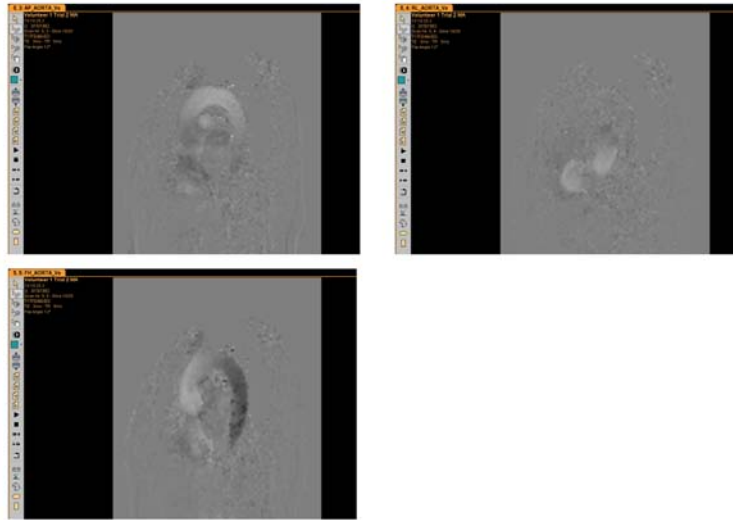


Figure 26 – Automatic Delayed Reconstruction Data Set 1 – Phase Mapping

Likewise, phase encoded flow images were generated for each slice. Figure 26 shows the phase encoded images for a specific slice of the aortic arch scan, in each of the three flow directions, anterior / posterior, head / foot, and right / left.

Phase encoded flow images are used to quantify flow. Each indicates the value of flow in a specific direction. For the images shown, the lighter areas represent a greater flow value than the dark areas. By comparing the differences in flow values between flow direction images and noting differences in appearance, the automatic reconstruction process was confirmed.

Magnitude and phase encoded flow images were also generated for the valve plane of the heart, and are shown below. Again, by comparing the differences in flow values between flow direction images and noting differences in appearance, the automatic reconstruction process was confirmed.

Volunteer 2, Trial 2, Valves

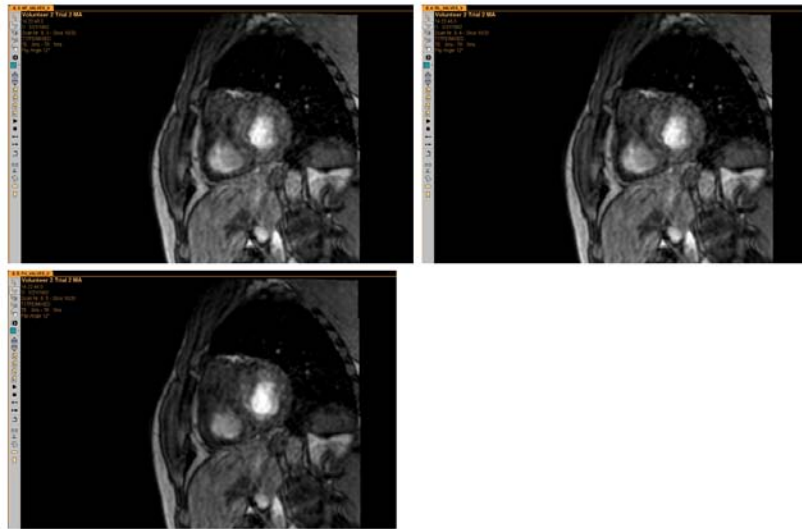


Figure 27 – Automatic Delayed Reconstruction Data Set 2

Volunteer 2, Trial 2, Valves

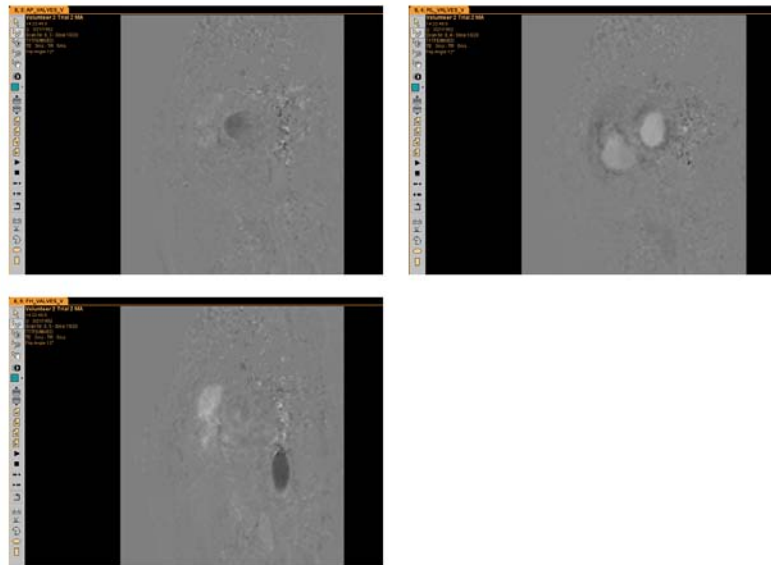


Figure 28 – Automatic Delayed Reconstruction Data Set 2 – Phase Mapping

Further analysis to quantify the flow characteristics were not covered in this study, but it is recommended as an area of further study to do so.

1. Next Steps – Stage 4

Results from stage 3 appeared to be identical to those obtained in stage 2.

However, quantifiable analysis of the two data sets would need to be completed in order to prove the batch file achieved the desired results and proved the hypothesis that the results were equal.

Stage 4 of the study analytically compares both data sets, runs statistical analysis on the differences, and proves the hypothesis the delayed reconstruction batch file produces equal results as those from the manual delayed reconstruction process.

d. Stage 4 - Validate the automated reconstruction batch file by comparing manual to automatic reconstruction data sets. Complete statistical analysis of said data sets and test hypothesis that the automated reconstruction was identical in make up to the manually reconstructed data sets, in all cases. Finally, use data sets from the automated reconstruction to plot velocity profiles across regions of interest and compare results between operators as well as patients.

i. Introduction / Purpose

The automation of the delayed reconstruction process would need to be statistically validated and determined to be entirely equivalent to the research agreement manual delayed reconstruction process. Finally, use data sets from the automated reconstruction to plot velocity profiles across regions of interest and compare results between operators as well as patients.

ii. Description of Experiment

The raw data that was saved during the second stage of the project, and reconstructed in the second and third stages, by the manual and then automated delayed reconstruction process was used in stage 4. Resulting data sets of the reconstructions were compared by algebraic subtraction and the batch file was to be validated.

First, raw data from each QFlow study (Aorta and Valves), was reconstructed both manually, and using the automated batch file, in 3 directions. Each data set was compared to its counterpart by first subtracting the manual data set from the automated data set, and creating a third “subtraction” data set. This “subtraction” data set would show only differences between the 2 reconstructions, and was hypothesized to be zero in

all measurements. In all 3 directions in both sets of anatomy, these “subtraction” data sets were saved for later analysis. (See Table 1)

Next, a region of interest was specified using the magnitude encoded portion of each of the 3 directional and 2 anatomical scans, from the manually reconstructed data sets. This ROI was copied and transferred to its corresponding “subtraction” data set, and saved. (See Figures 29, 32)

Using standard Philips Achieva analysis software, reports for all manual, automated, and “subtraction” data sets was generated. These reports were compared. In all cases, both the manual and automated data sets produced analysis exactly the same for the given parameters. The “subtraction” data set further proved the manual and automated data sets were the same by analysis where all measured parameters were zero, proving the hypothesis and demonstrating the automated batch file did indeed reconstruct the raw data equivalent to reconstruction produced using the standard manual delayed reconstruction package from Philips. (See Table 1)

Finally, data sets from the automated reconstruction were used to plot velocity profiles across regions of interest and compare results between operators as well as patients.

iii. Results and Discussion

	Velocity (cm/s)	Flux (ml/s)	Velocity Standard Deviation	Minimum Velocity Value	Maximum Velocity Value
AP Aorta Manual	3.95	507.79	21.47	-104.57	108.08
RL Aorta Manual	-5.05	-659.69	19.54	-123.52	186.23
FH Aorta Manual	0.70	86.84	23.43	-97.53	114.82
AP Aorta Automated	3.95	507.79	21.47	-104.57	108.08
RL Aorta Automated	-5.05	-659.69	19.54	-123.52	186.23
FH Aorta Automated	0.70	86.84	23.43	-97.53	114.82
AP Aorta "Subtraction"	0.00	0.00	0.00	0.00	0.00
RL Aorta "Subtraction"	0.00	0.00	0.00	0.00	0.00
FH Aorta "Subtraction"	0.00	0.00	0.00	0.00	0.00
AP Valves Manual	0.07	10.61	15.56	-132.50	111.31
RL Valves Manual	3.30	538.89	14.36	-80.15	89.72
FH Valves Manual	3.56	631.01	15.64	-134.16	124.49
AP Valves Automated	0.07	10.61	15.56	-132.50	111.31
RL Valves Automated	3.30	538.89	14.36	-80.15	89.72
FH Valves Automated	3.56	631.01	15.64	-134.16	124.49
AP Valves "Subtraction"	0.00	0.00	0.00	0.00	0.00
RL Valves "Subtraction"	0.00	0.00	0.00	0.00	0.00
FH Valves "Subtraction"	0.00	0.00	0.00	0.00	0.00

Table 1 – Subtraction Data Sets

After standard Philips analysis was run on both the manual and automatic delayed reconstruction phase encoded flow images, data was compiled. Flow velocity, flux, minimums, and maximums for each flow direction were recorded. By comparing the same slice and same flow direction for each of the manual and automatic reconstructions, the hypothesis that the two reconstructions were equivalent was proven. Data was identical in all cases for corresponding reconstructions.

Aorta – Manual Delayed Reconstruction

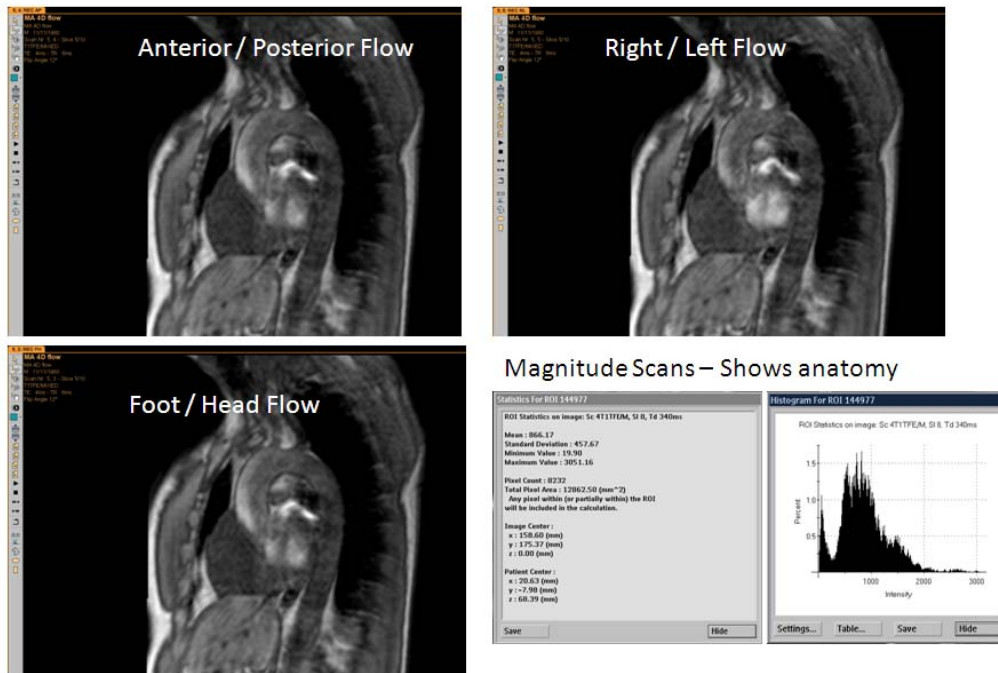


Figure 29 – Manual Delayed Reconstruction Data Set 3

As described in previous stages, magnitude images are generated for each corresponding phase encoded flow slice. To identify a region of interest for comparison of the phase encoded images, the magnitude images were used. The region of interest was then copied to the subtraction images. (See Figure 29)

Aorta – Manual Delayed Reconstruction

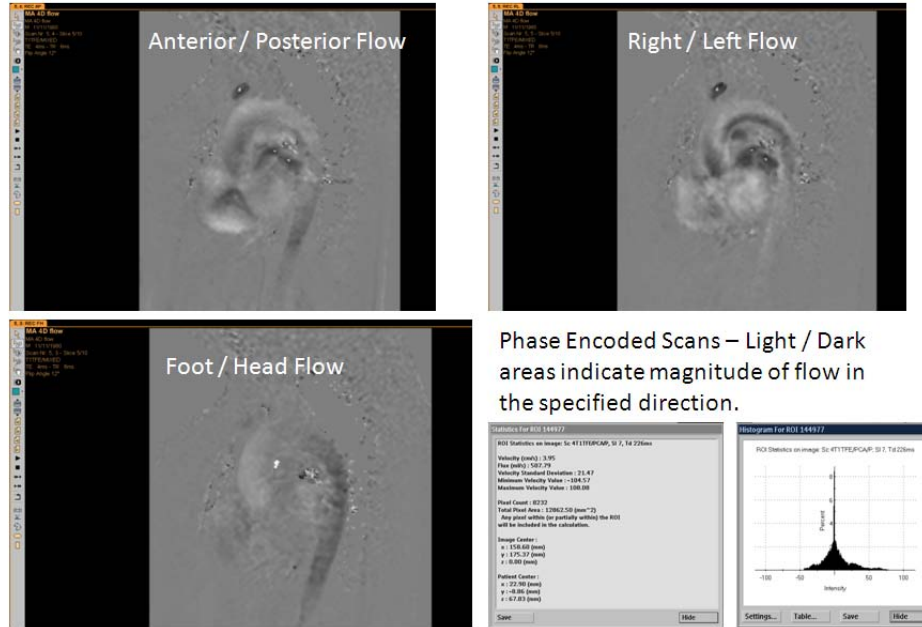


Figure 30 – Manual Delayed Reconstruction Data Set 3 – Phase Mapping

Aorta – Automated Delayed Reconstruction

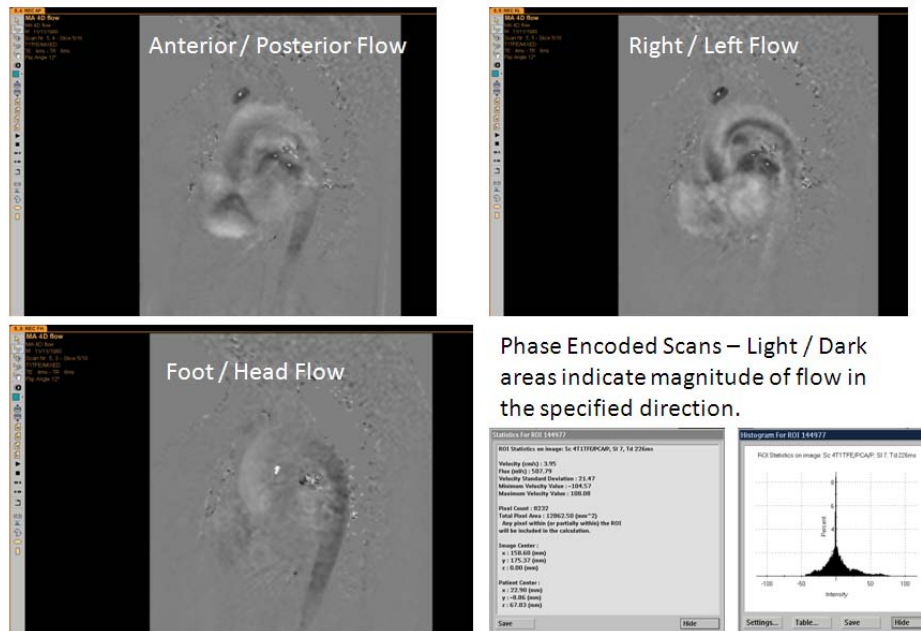


Figure 31 – Automatic Delayed Reconstruction Data Set 3 – Phase Mapping

Figures 30 and 31 show the phase encoded flow images for 3 flow directions for both the manual and automatic reconstruction. Data used in comparison is shown in the bottom right of Figures 30 and 31. Raw data and histograms are shown. A subtraction image was created that compared this data from each of the manual and automatic reconstruction images, and generated a third image, showing only the differences. (See Figure 32)

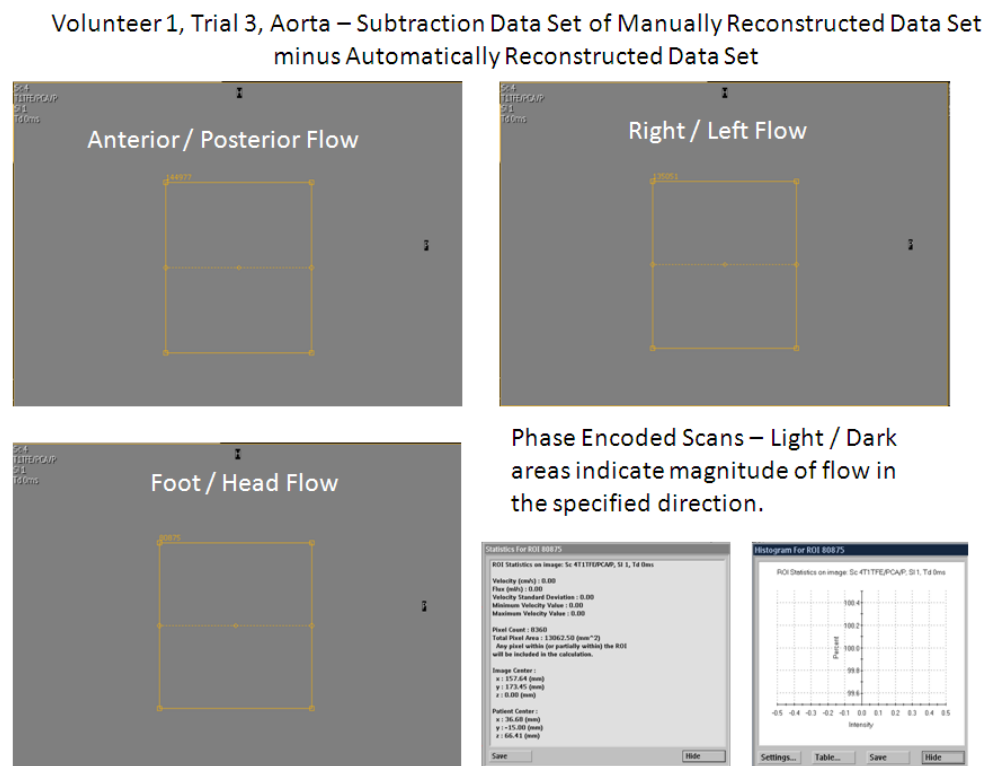


Figure 32 – Subtraction Data Set 3

Figure 32 shows the subtraction images for each flow direction. The orange box is the region of interest copied from the magnitude image described above. Inspection of the data and histogram of the subtraction image is shown in the bottom right, and

inspection of said data indicated zero values in all cases. The hypothesis that the automated reconstruction was equivalent to the manual reconstruction was confirmed.

The subtraction images and analysis was repeated for the valve plane anatomy, and is shown below. (See Figures 33 – 36)

Valves – Manual Delayed Reconstruction

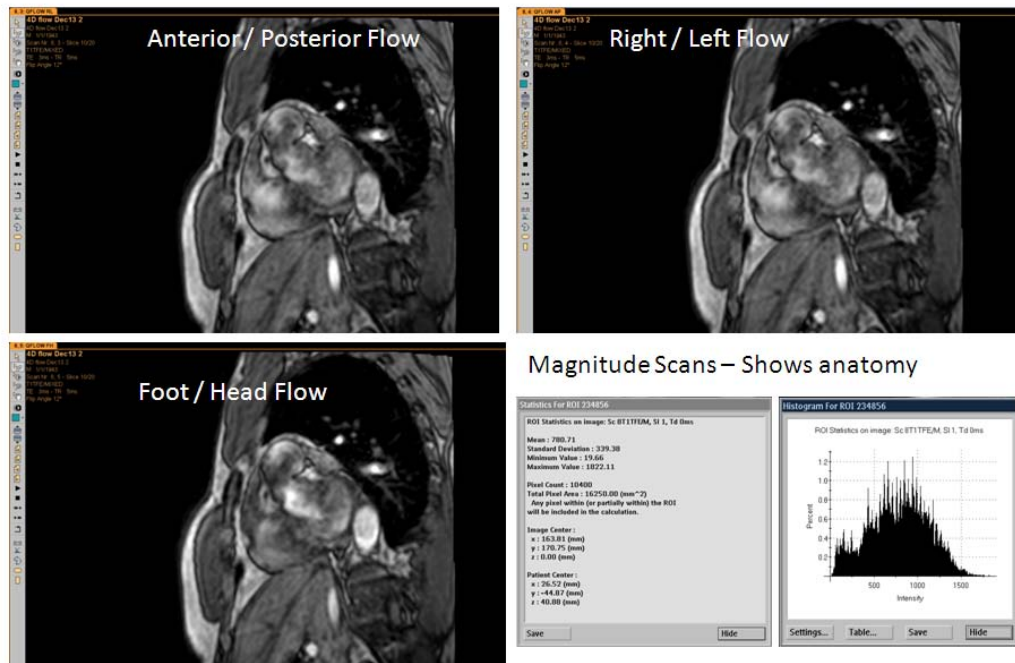


Figure 33 – Manual Delayed Reconstruction Data Set 4

Valves – Manual Delayed Reconstruction



Figure 34 – Manual Delayed Reconstruction Data Set 4 – Phase Mapping

Valves – Automated Delayed Reconstruction



Figure 35 – Automatic Delayed Reconstruction Data Set 4 – Phase Mapping

Volunteer 1, Trial 3, Valves – Subtraction Data Set of Manually Reconstructed Data Set
minus Automatically Reconstructed Data Set

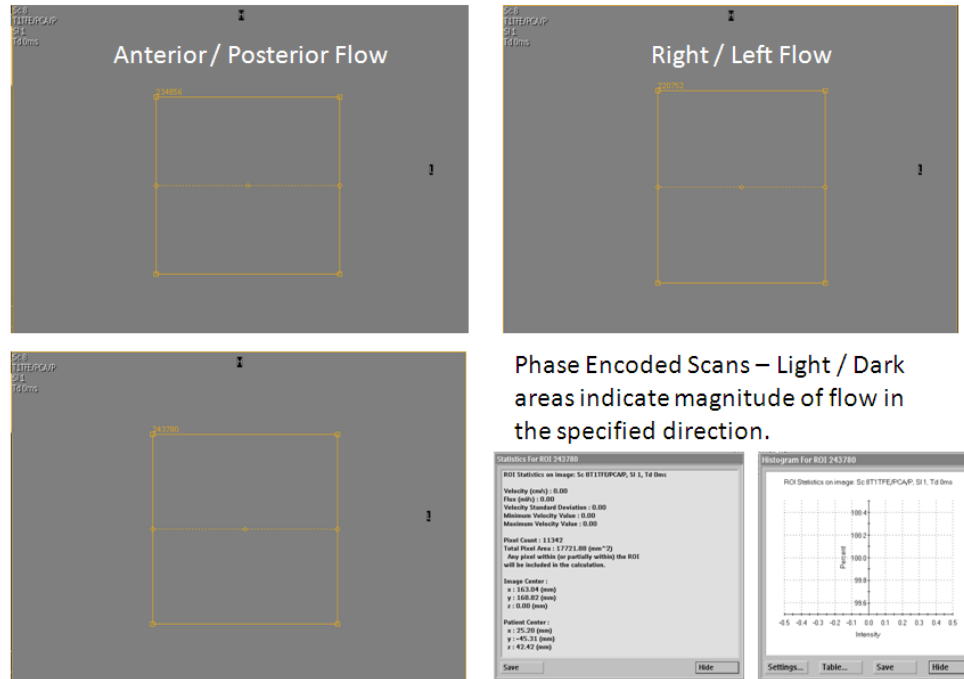


Figure 36 – Subtraction Data Set 4

Again, Figure 36 shows the subtraction images for each flow direction. The orange box is the region of interest copied from the magnitude image described above. Inspection of the data and histogram of the subtraction image is shown in the bottom right, and inspection of said data indicated zero values in all cases. The hypothesis that the automated reconstruction was equivalent to the manual reconstruction was confirmed.

Further statistical analysis was then completed on the data sets. Box plots were generated for both the manual and automatic delayed reconstructions, in all three directions. All data sets were equal and identical. (See Figures 37 – 39)

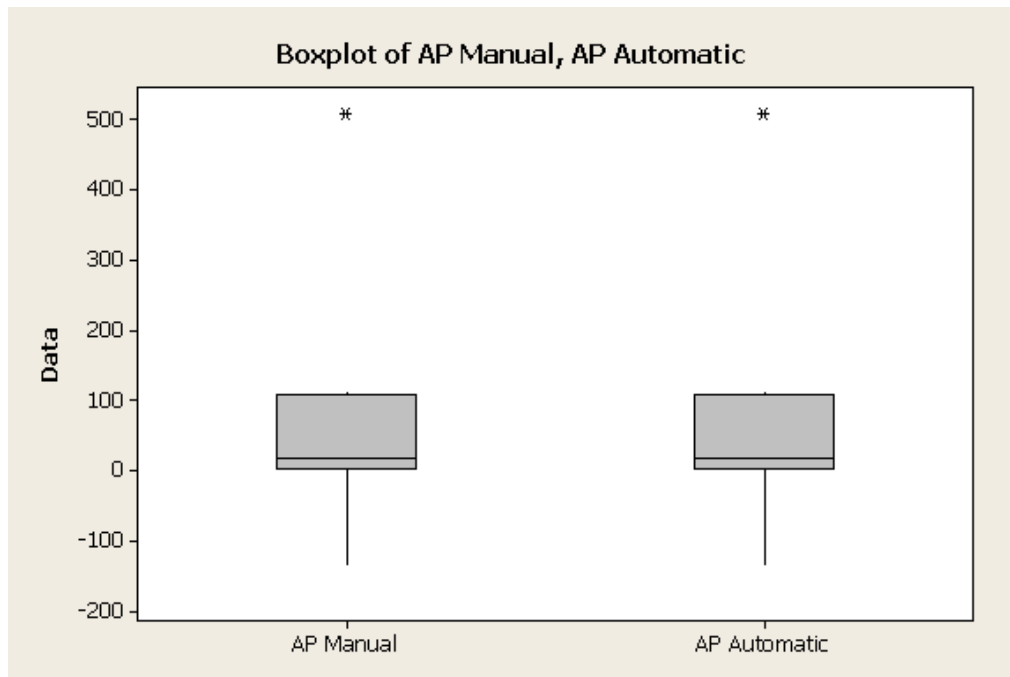


Figure 37 – Boxplot of AP Manual, AP Automatic

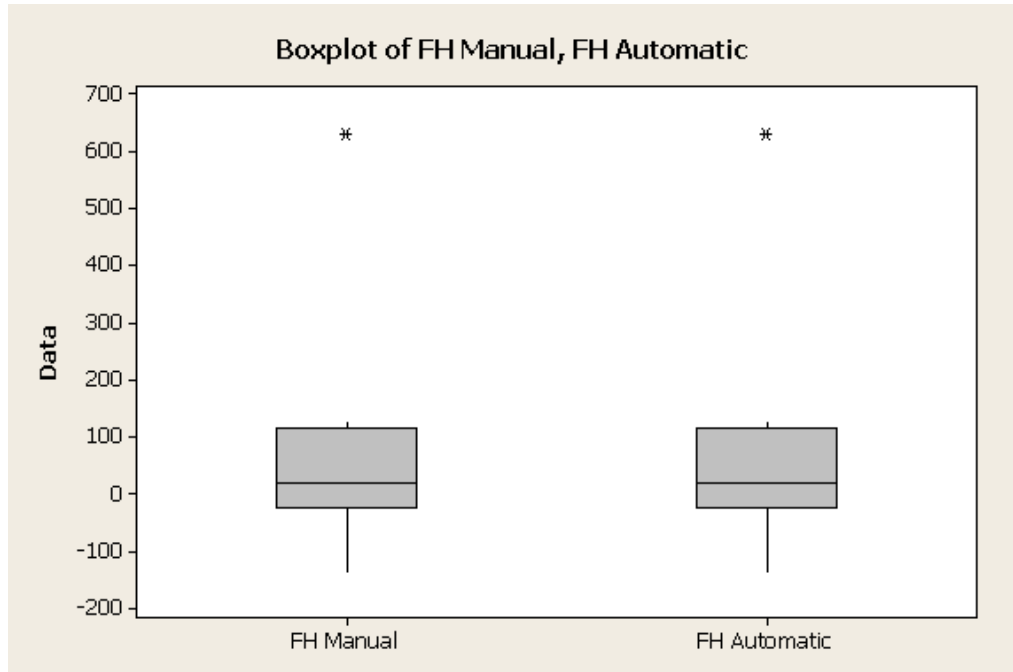


Figure 38 – Boxplot of FH Manual, FH Automatic

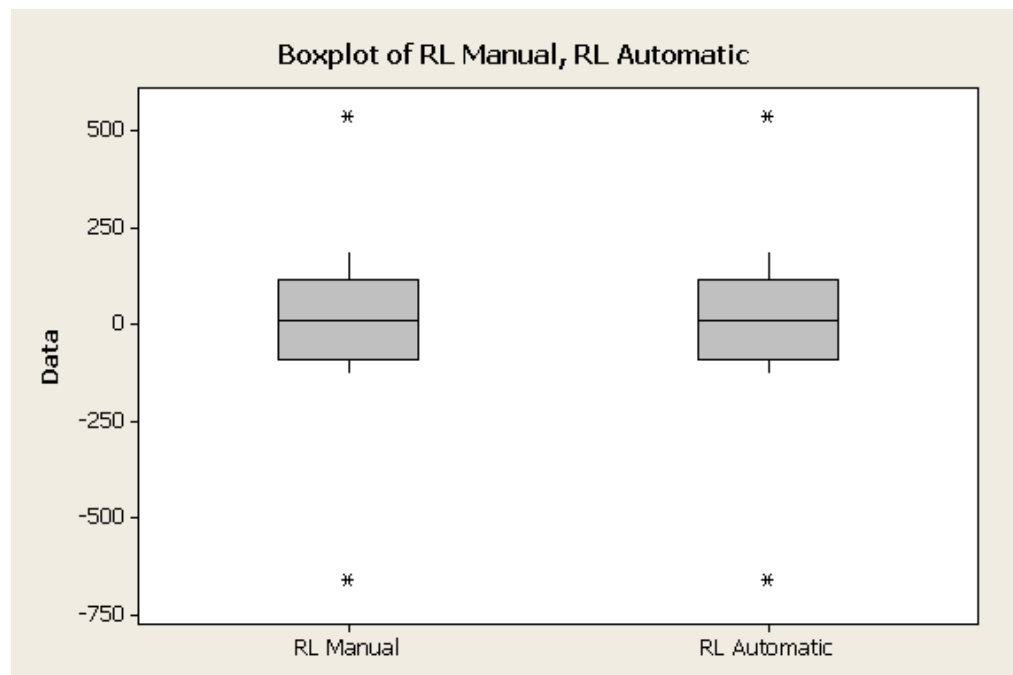


Figure 39 – Boxplot of RL Manual, RL Automatic

The three data sets were statistically analyzed in a test for equal variances. Again, the three data sets were proved equal, with P values of 1 in every case. (See Figures 40 – 42)

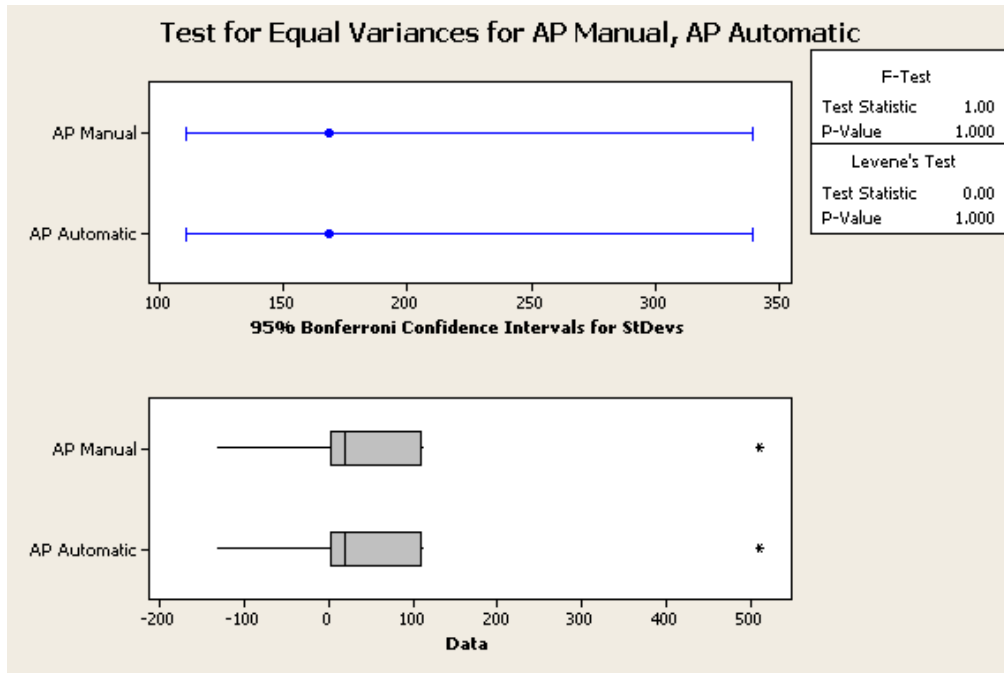


Figure 40 – Test for Equal Variances for AP Manual, AP Automatic

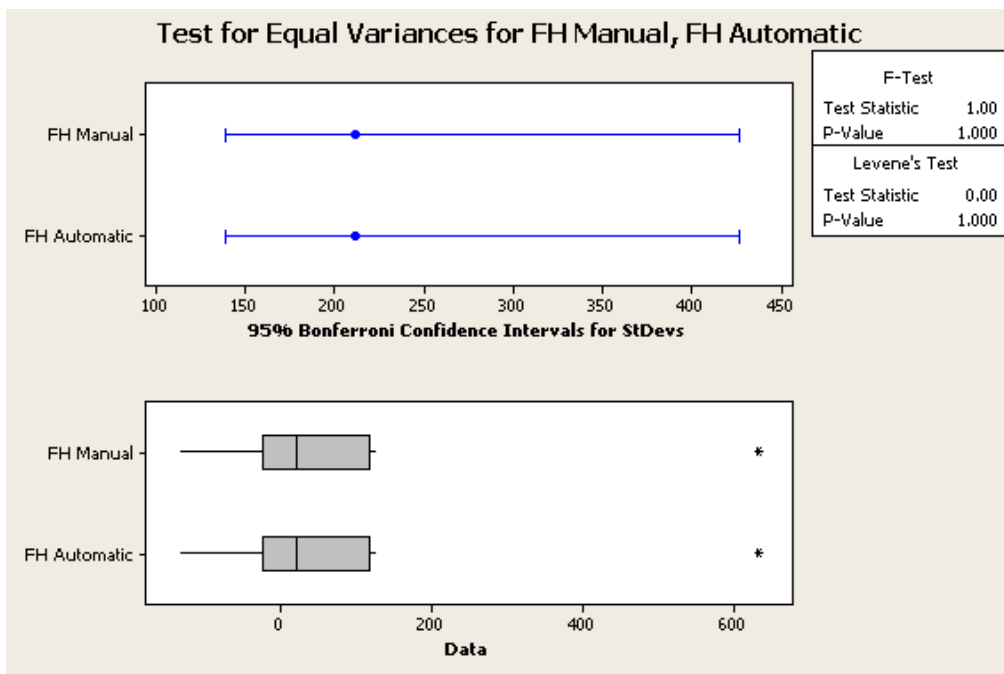


Figure 41 – Test for Equal Variances for FH Manual, FH Automatic

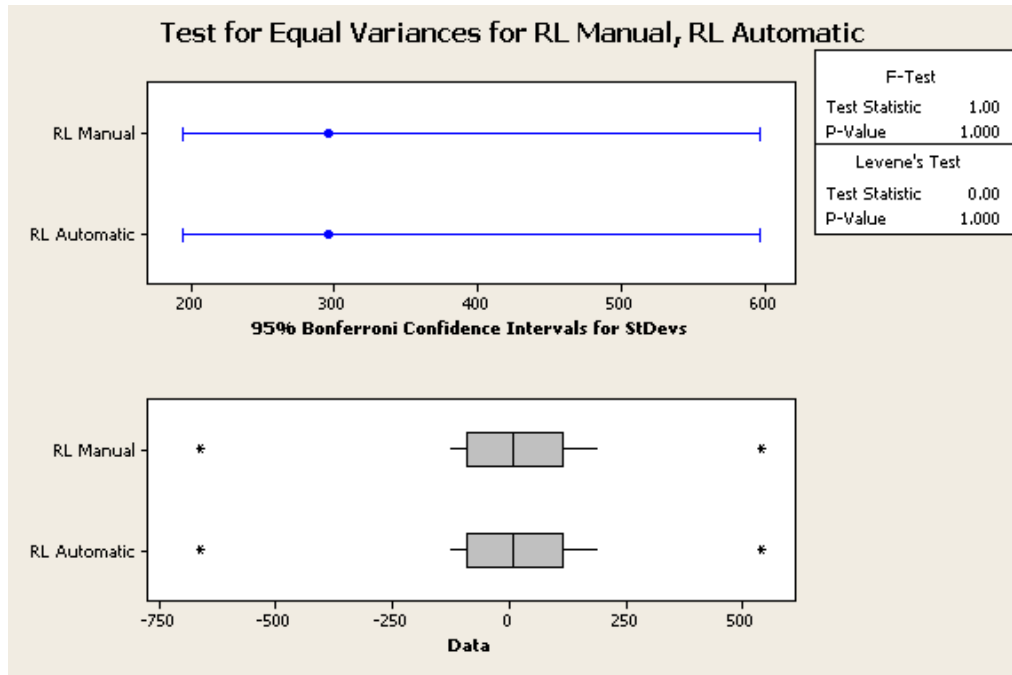


Figure 42 – Test for Equal Variances for RL Manual, RL Automatic

Finally, data sets from the automated reconstruction were used to plot velocity profiles across regions of interest and compare results between operators as well as patients.

Regions of interest in selected slices of the automated delayed reconstruction data sets for the valves and aorta were chosen. Those regions of interest were propagated over the entire cardiac cycle, and velocity plots were generated.

To illustrate the variability introduced by operator interpretation, the region of interest was created 4 times for each direction, in each of the valves and aorta automated delayed reconstruction data sets. For each direction, box plots were generated to illustrate the differences introduced by different operators. (See Figures 43-54)

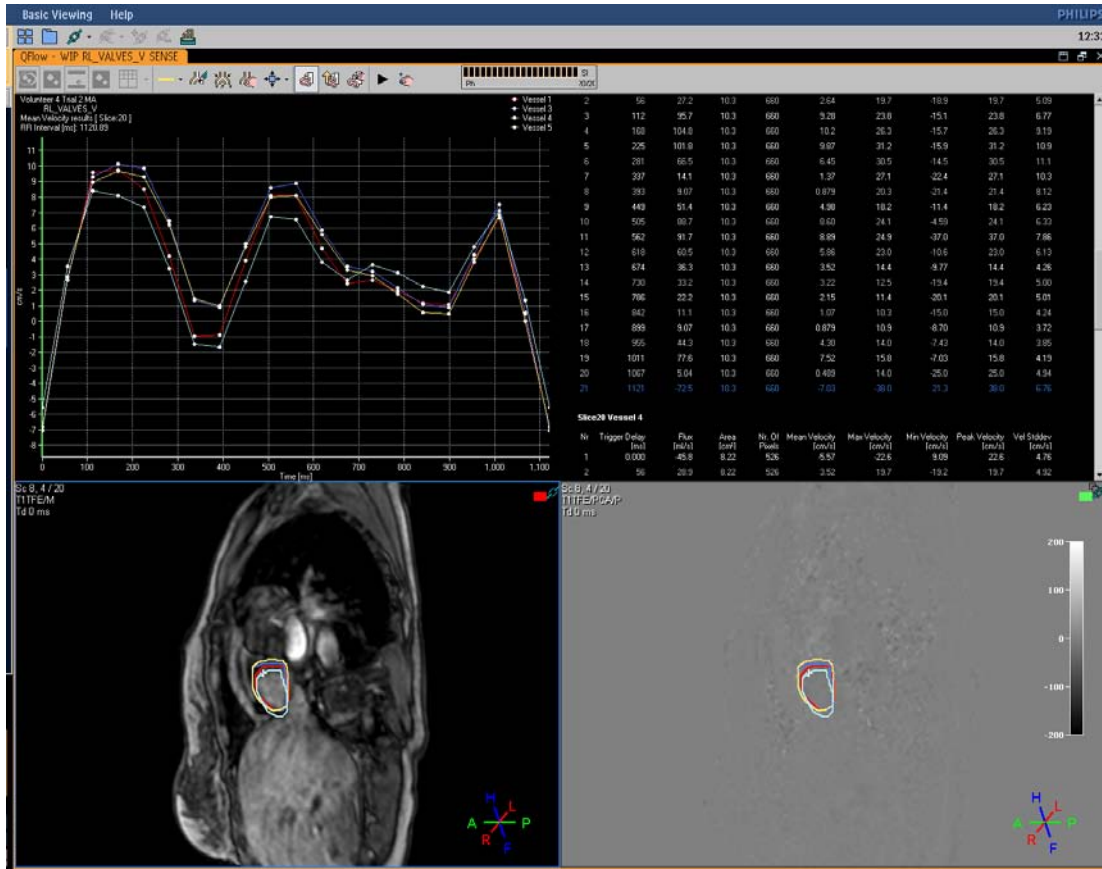


Figure 43 – Flow Velocity Profiles, Right / Left, Valves, Volunteer 4

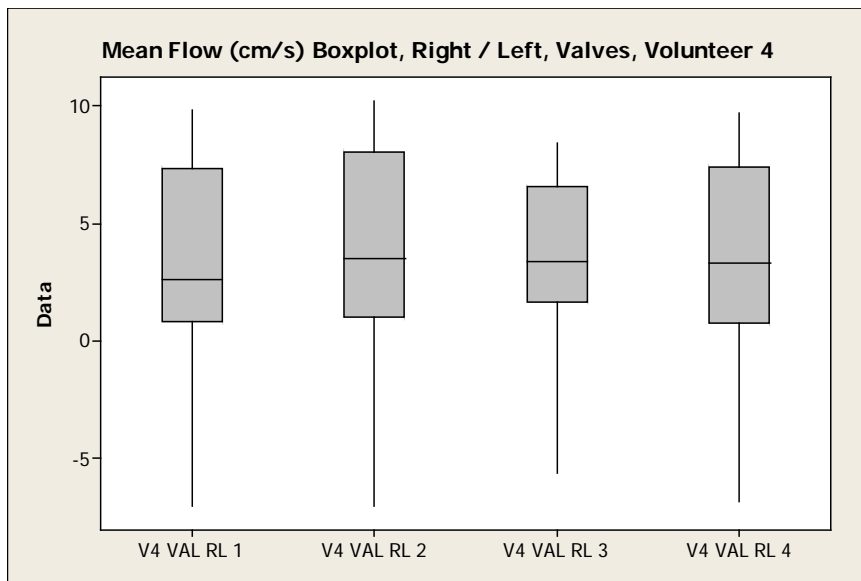


Figure 44 – Mean Flow (cm/s) Boxplot, Right / Left, Valves, Volunteer 4

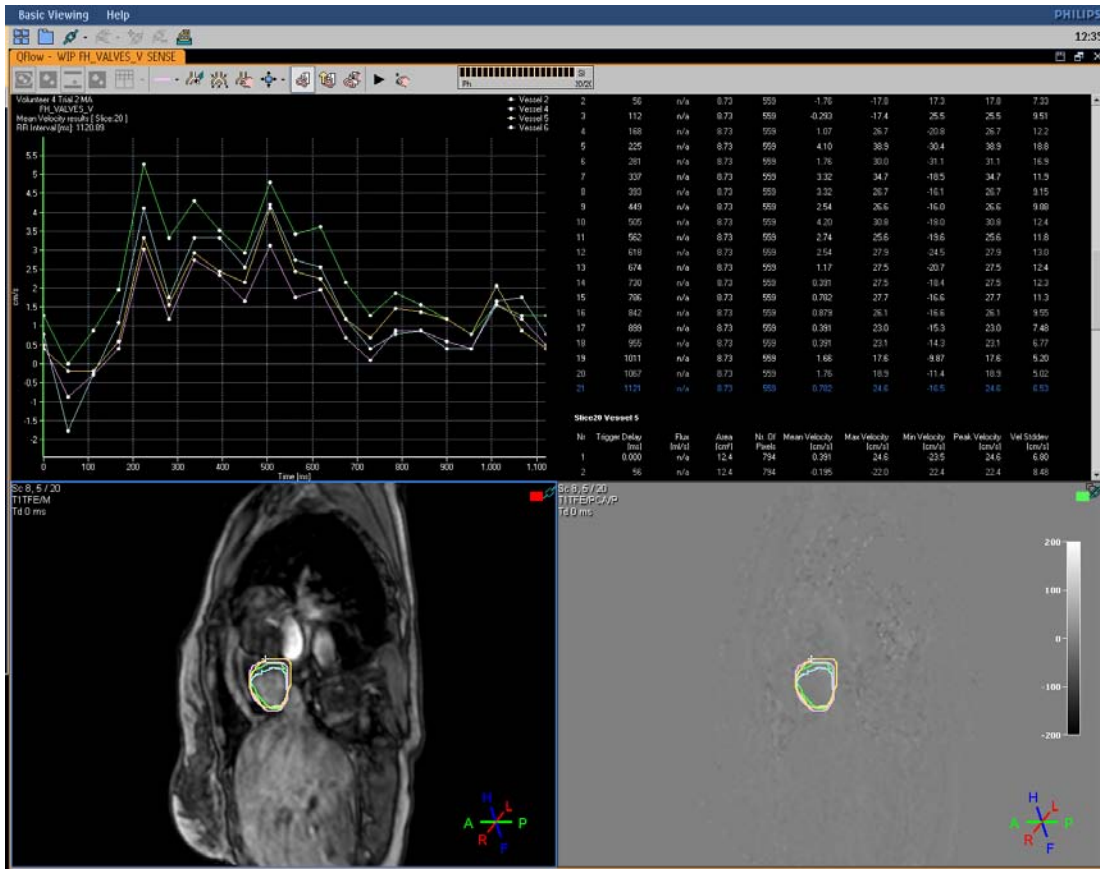


Figure 45 – Flow Velocity Profiles, Foot / Head, Valves, Volunteer 4

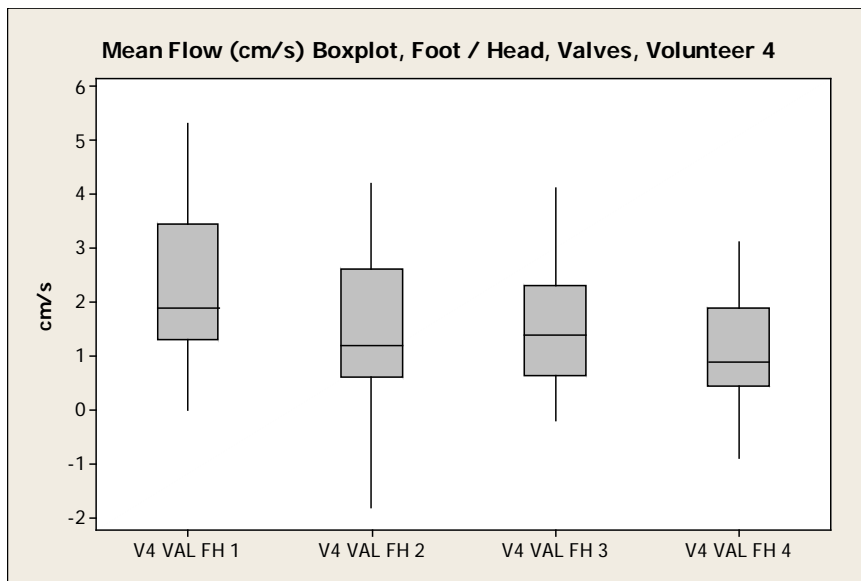


Figure 46 – Mean Flow (cm/s) Boxplot, Foot / Head, Valves, Volunteer 4

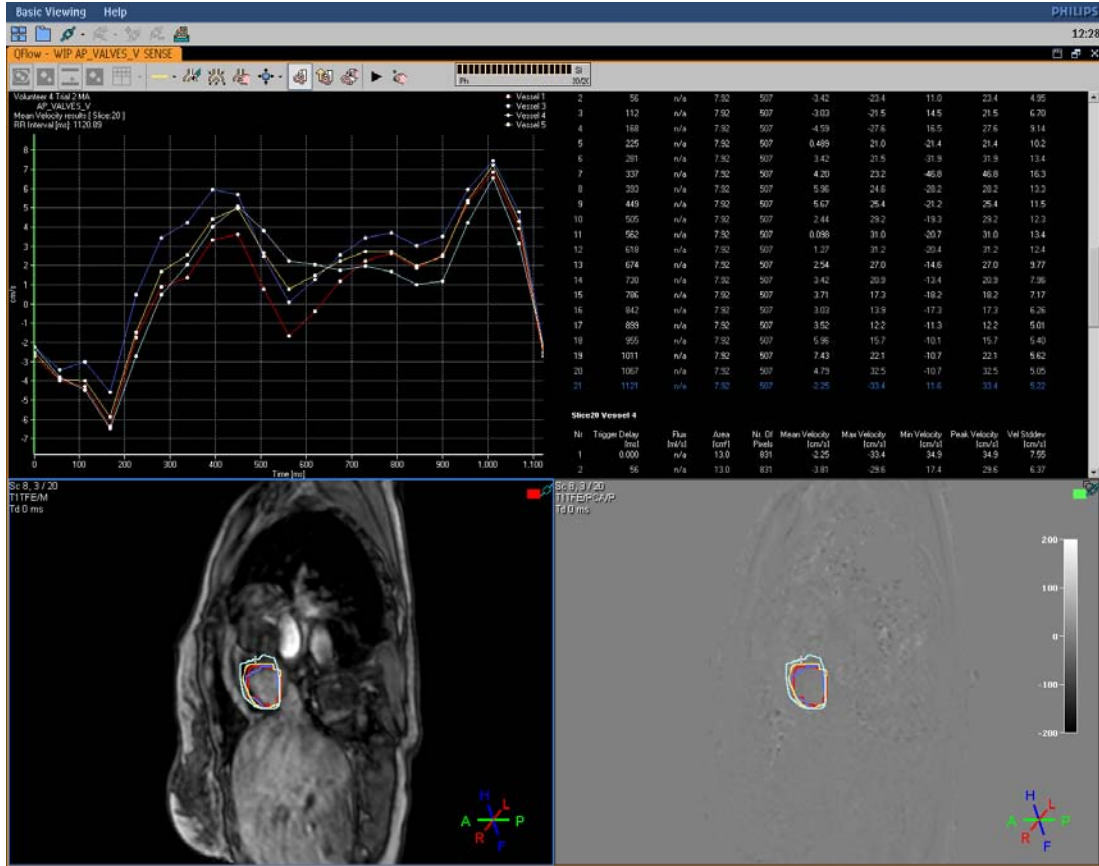


Figure 47 – Flow Velocity Profiles, Anterior / Posterior, Valves, Volunteer 4

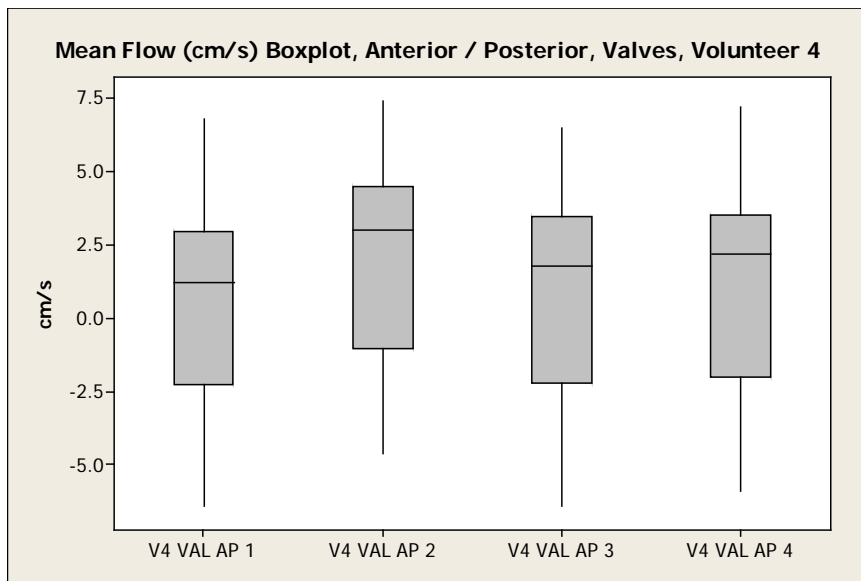


Figure 48 – Mean Flow (cm/s) Boxplot, Anterior / Posterior, Valves, Volunteer 4

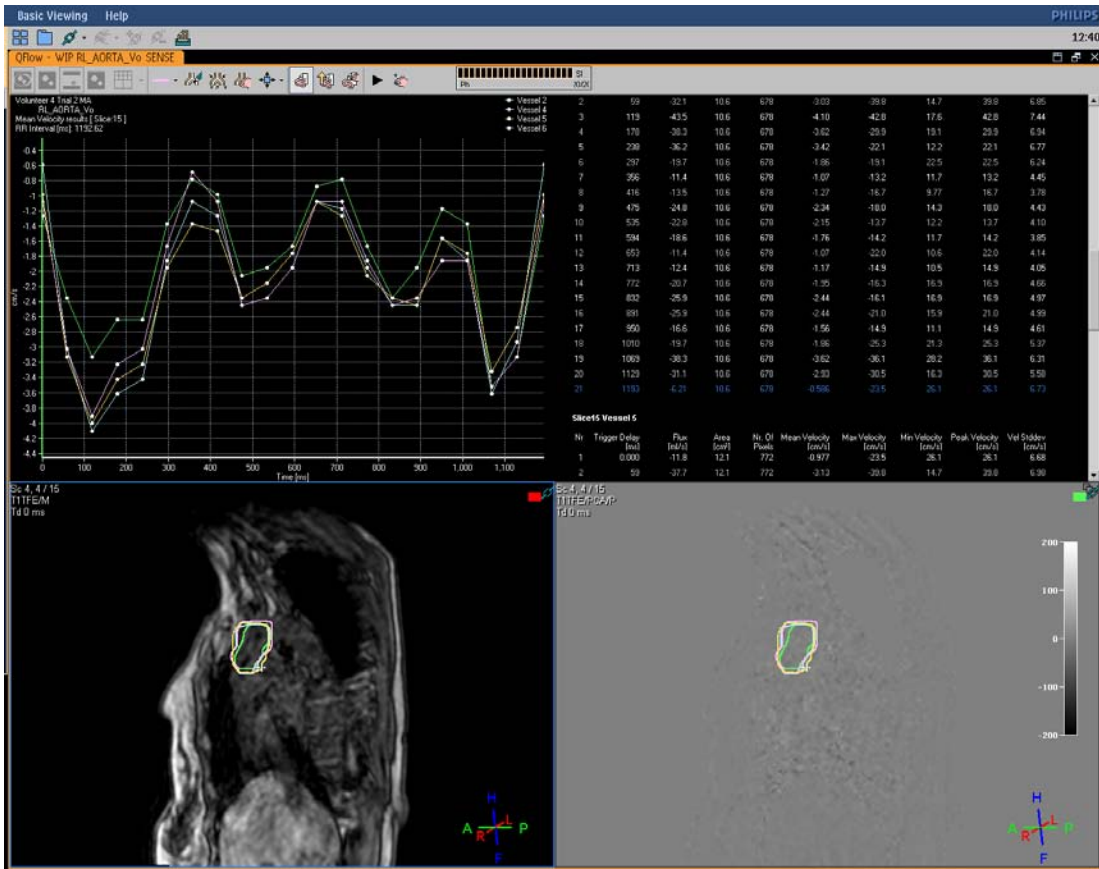


Figure 49 – Flow Velocity Profiles, Right / Left, Aorta, Volunteer 4

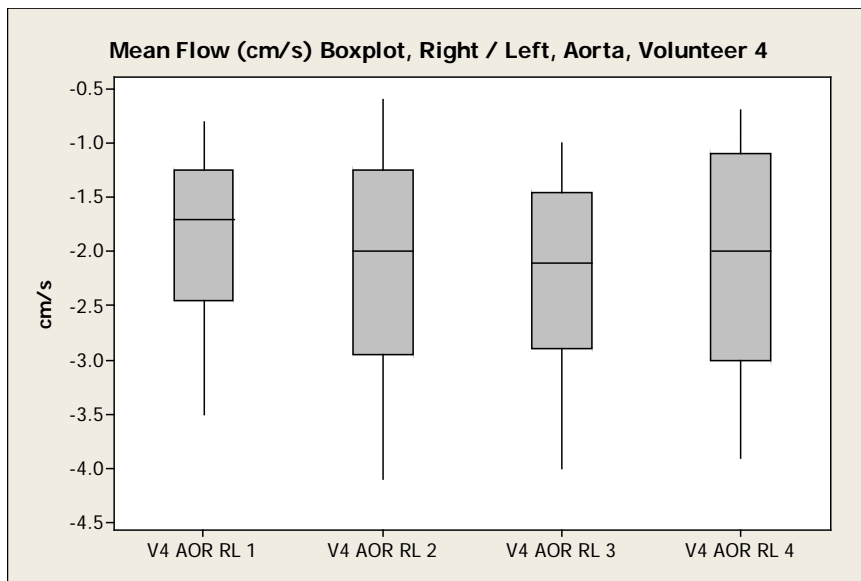


Figure 50 – Mean Flow (cm/s) Boxplot, Right / Left, Aorta, Volunteer 4

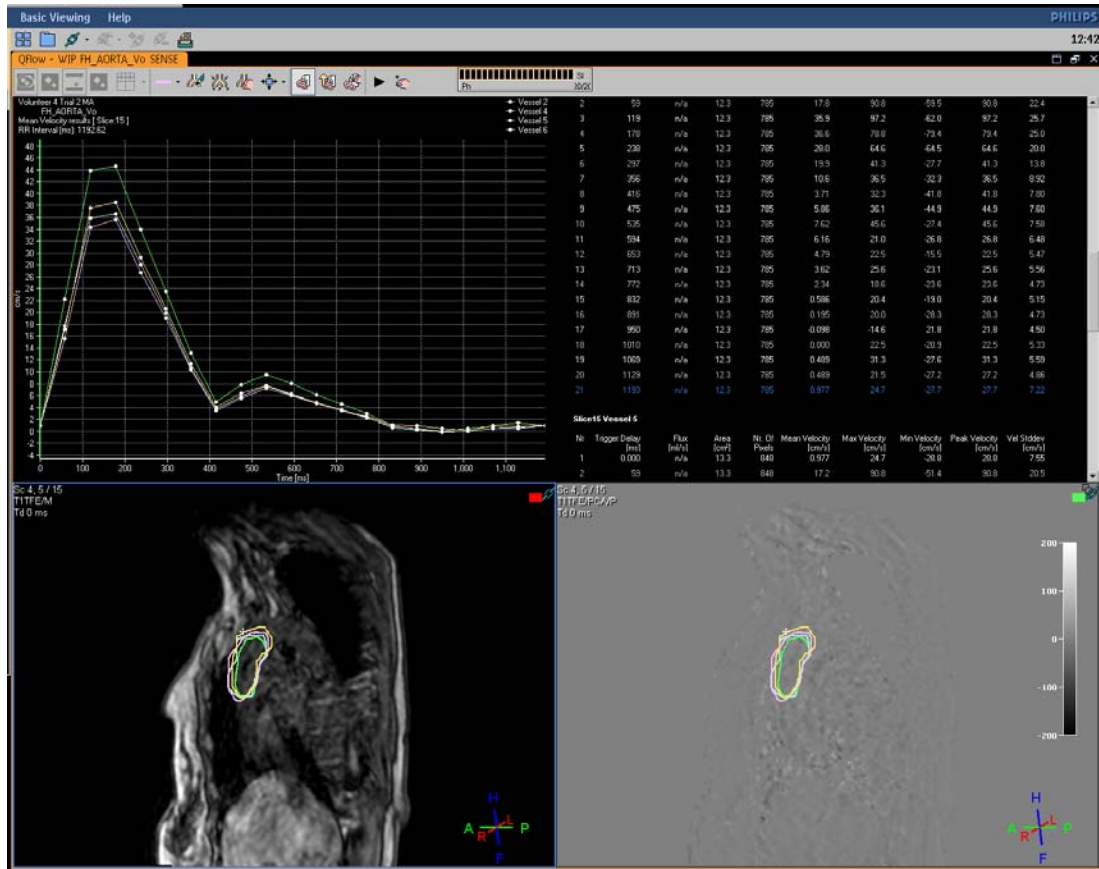


Figure 51 – Flow Velocity Profiles, Foot / Head, Aorta, Volunteer 4

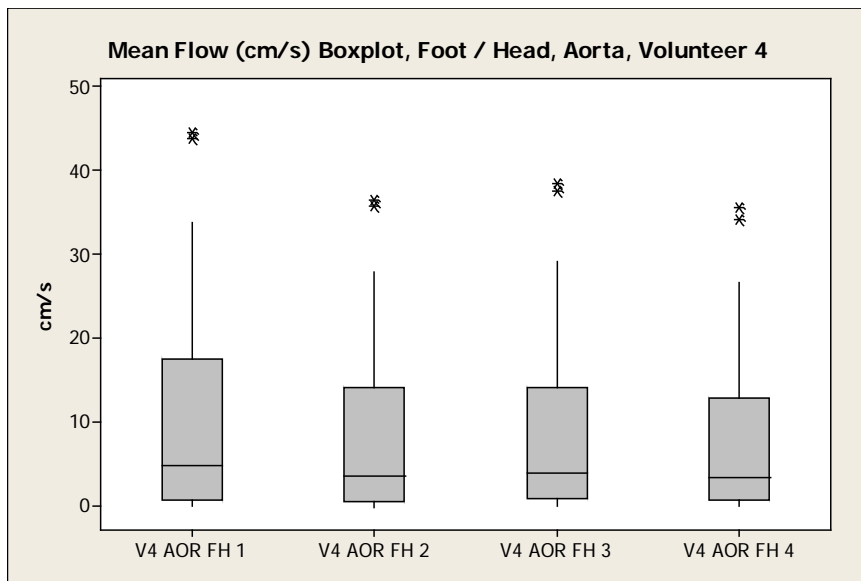


Figure 52 – Mean Flow (cm/s) Boxplot, Foot / Head, Aorta, Volunteer 4

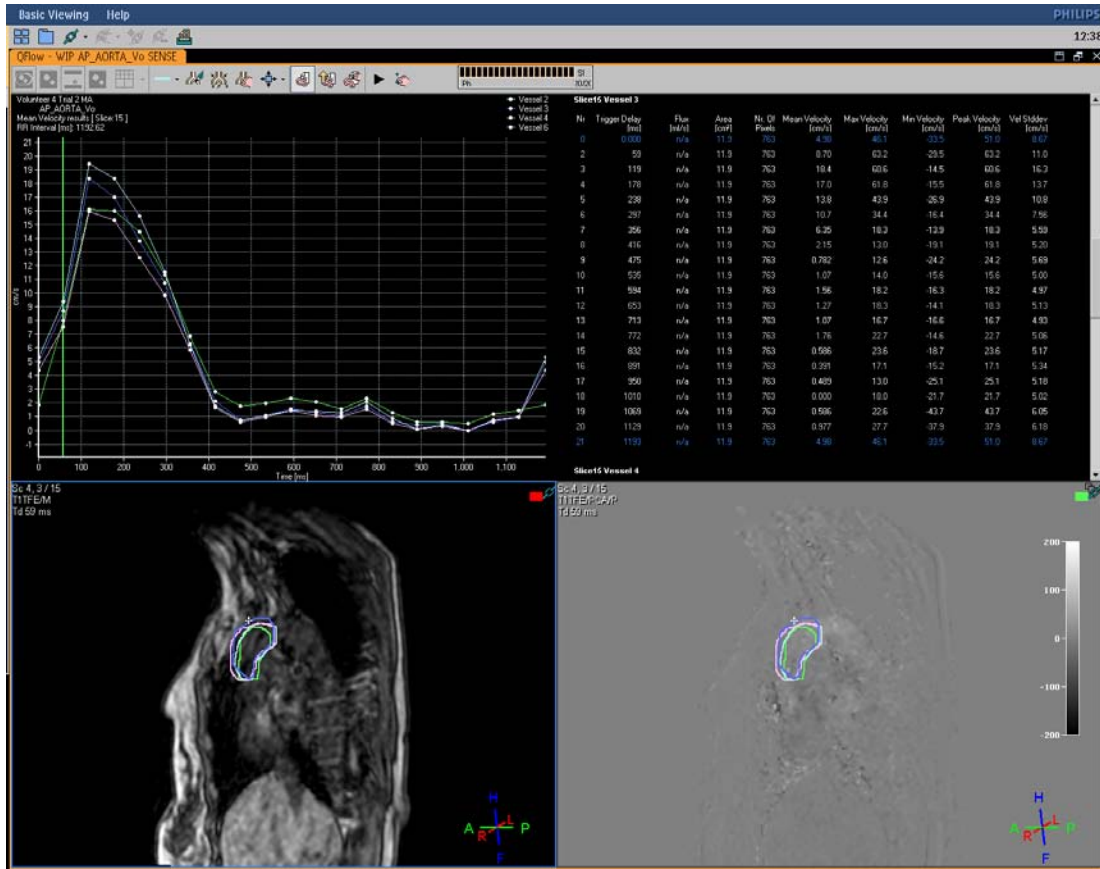


Figure 53 – Flow Velocity Profiles, Anterior / Posterior, Aorta, Volunteer 4

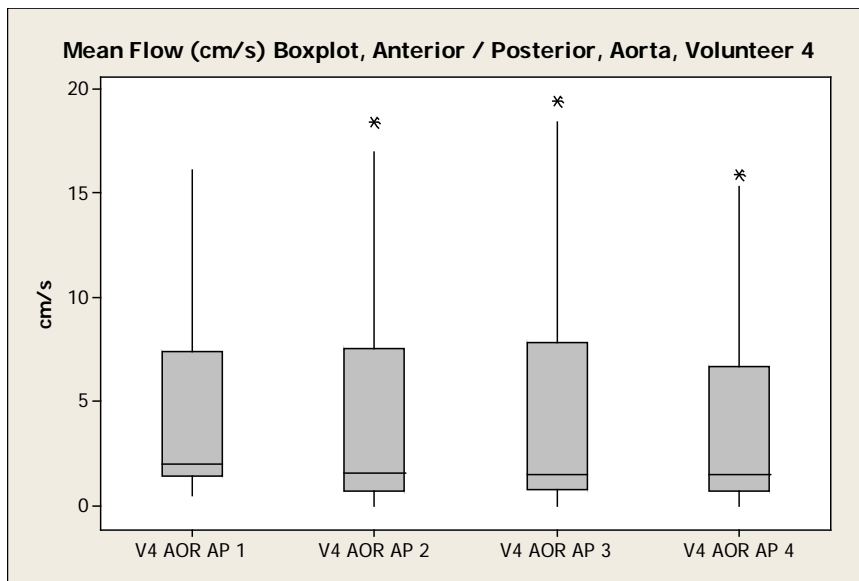


Figure 54 – Mean Flow (cm/s) Boxplot, Anterior / Posterior, Aorta, Volunteer 4

Flow velocity plots were then compared between patients.

The anterior / posterior directional region of interest was applied to the same slice, in the same anatomy, and propagated through the entire cardiac cycle, for 2 or 4 different patients. (See Figures 55-56)

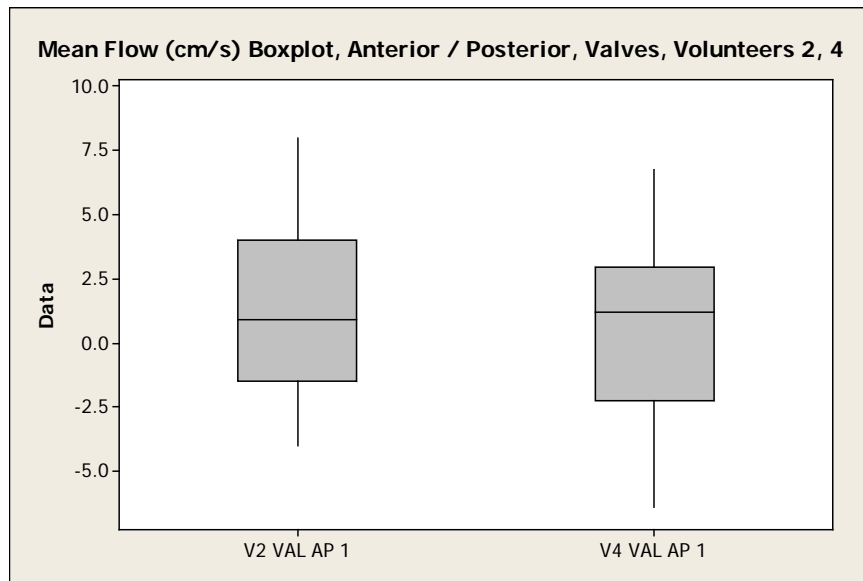


Figure 55 – Mean Flow (cm/s) Boxplot, Anterior / Posterior, Valves, Volunteer 2, 4

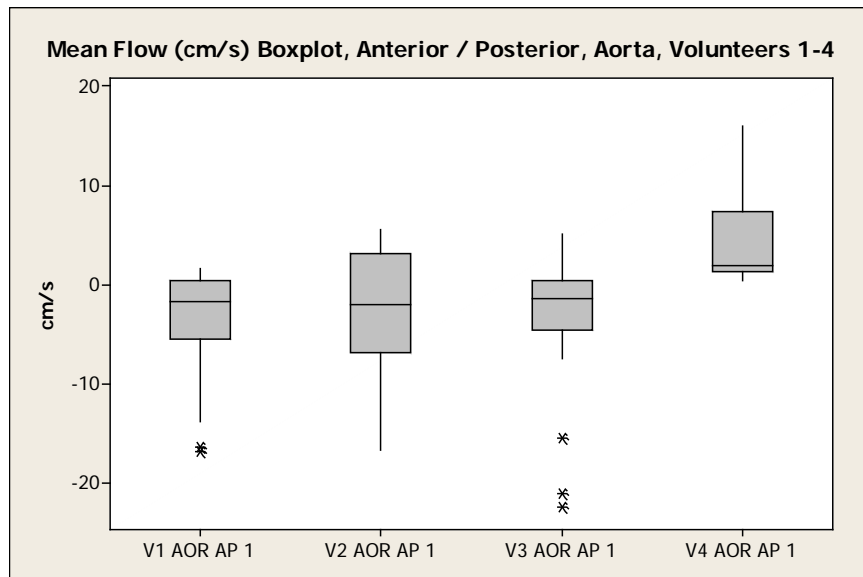


Figure 56 – Mean Flow (cm/s) Boxplot, Anterior / Posterior, Aorta, Volunteer 1, 2, 3, 4

CHAPTER IV

CONCLUDING REMARKS

This study set out to create a defined protocol that contained all the necessary scans and settings to collect 7D flow quantification of the aortic arch and valve plane of the heart. The complete protocol was tested and validated in 4 subjects.

Following validation of the exam card, the study shifted focus to the delayed reconstruction of the raw data collected during the exam. A batch file script was written and tested to complete the reconstruction automatically. When used in a clinical setting, this batch file will save user and console time, eliminating the complicated user input needed in manual delayed reconstruction.

In the future, quantification of the flow characteristics should be examined. By using the validated ExamCard and delayed reconstruction batch file, users can achieve clinical validation by calculating the forward flow of the aorta and comparing it to the left ventricle stroke volume. Users can employ such methods along other areas of the anatomy to quantify flow. Studies in this area are currently ongoing.

Secondly, by analyzing the reconstructed flow data sets with a third party visualization package, flow lines and patterns can be studied. Such packages are available and have been validated in other studies. (See Figure 3)

Finally, the clinical value of our study holds tremendous promise. However, testing in a clinical setting should take place, and with the guidance of a cardiologist and/or radiologist, a clinical case can be made for diagnosis of heart pathology using this method.

Finally, when creating velocity profiles, special care should be taken when drawing regions of interest, as there is variability between operators.

BIBLIOGRAPHY

10. Beerbaum, P; Rasmusson, A; Razavi, R; Schaeffter, T; Sorensen, TS; Uribe, S. "Four-dimensional (4D) flow of the whole heart and great vessels using real-time respiratory self-gating." Magnetic Resonance Medical, 2009 October, 62 (4):984-92
11. Simplifying Cardiac MRI. (n.d.) *Philips Healthcare*. Retrieved from http://www.healthcare.philips.com/us_en/products/mri/clinical_specialties/cardiology/cardiac_mri.wpd
12. Bryant, DJ; Firmin, DN; Longmore, DB; Payne, JA. "Measurement of flow with NMR imaging using a gradient pulse and phase difference technique." Journal of Computed Assisted Tomography, 1984 August, 8 (4):588-93
13. Firmin, DN; Longmore, DB; Nayler, GL. "Blood flow imaging by cine magnetic resonance." Journal of Computed Assisted Tomography, 1986 September - October, 10 (5):715-22
14. Murase, Kenya; Shinohara, Masaaki; Yamazaki, Youichi. "Autoregressive Moving Average (ARMA) Model Applied to Quantification of Cerebral Blood Flow Using Dynamic Susceptibility Contrast-enhanced Magnetic Resonance Imaging." Magnetic Resonance in Medical Science, Vol. 2, No. 2, p. 85-95, 2003
15. Choi, Choong Gon MD; Kim, Hyun Jeong MD; Kim, Jae Kyun MD; Lee, Ho Kyu MD; Lee, Jeong Hyun MD; Park, Ji Kang MD. "CSF Flow Quantification of the Cerebral Aqueduct in Normal Volunteers Using Phase Contrast Cine MR Imaging." Korean Journal of Radiology, 2004; 5 : 81-86
16. Ebbers, Tino; Kilner, Philip J; Markl, Michael. "Comprehensive 4D velocity mapping of the heart and great vessels by cardiovascular magnetic resonance." Journal of Cardiovascular Resonance 2011 13:7
17. Alley, Marcus T.; Higgins, Charles B.; Hope, Michael D.; Hope, Thomas A.; Meadows, Alison K.; Ordovas, Karen G.; Reddy, Gautham P. "Evaluation of Bicuspid Aortic Valve and Aortic Coarctation With 4D Magnetic Resonance Imaging Flow" Circulation, Journal of the American Heart Association 2008

18. Bax, Jeroen J. PhD, MD; De Roos, Albert PhD, MD; Hammer, Sebastiaan PhD, MD; Lamb, Hildo J. PhD, MD; Marsan, Nina Ajmone MD; Reiber, Johan H. C. PhD; Roes, Stijntje D. MD; Van der Geest, Rob J. MSc; Westenberg, Jos J. M. PhD. "Flow Assessment Through Four Heart Valves Simultaneously Using 3-Dimensional 3-Directional Velocity-Encoded Magnetic Resonance Imaging With Retrospective Valve Tracking in Healthy Volunteers and Patients With Valvular Regurgitation." Investigative Radiology Volume 44, Number 10, October 2009
19. Philips 1.5T XR Achieva Users Manual

APPENDICES

(A) AUTOMATED DELAYED RECONSTRUCTION BATCH FILE CODE

```
$ startup_init
```

```
$ restore_site_values
```

```
$ disable_read_class
```

```
$ select_exam "Volunteer 3 Trial 2 MA"
```

```
$ wait_proceed "Check 1"
```

```
$ restore_site_values
```

```
-----  
$ startup_init
```

```
$ restore_site_values
```

```
$ disable_read_class
```

```
$!
```

```
$ select_exam "Volunteer 3 Trial 2 MA"
```

```
$!
```

```
$ modify ,IEX_PC_delrec_pars
```

```
    EX_PC_image_types = "MGU_ITYP_PHASE";
```

```
    EX_PC_recon_flow_dirs    = "MPUPC_DIR_AP";
```

```
$!
```

```
$ wait_proceed "CHOOSE AORTA SCAN!"
```

```
$ reconstruct AP_AORTA_Volunteer_3_Trial_2_MA, select
```

```
$ modify ,IEX_PC_delrec_pars
```

```
    EX_PC_image_types = "MGU_ITYP_PHASE";
```

```
    EX_PC_recon_flow_dirs    = "MPUPC_DIR_RL";
```

```

$!
$ wait_proceed "CHOOSE AORTA SCAN!"
$ reconstruct RL_AORTA_Volunteer_3_Trial_2_MA, select
$!
$ modify ,IEX_PC_delrec_pars
    EX_PC_image_types = "MGU_ITYP_PHASE";
    EX_PC_recon_flow_dirs = "MPUPC_DIR_FH";
$!
$ wait_proceed "CHOOSE AORTA SCAN!"
$ reconstruct FH_AORTA_Volunteer_3_Trial_2_MA, select
$!
$ modify ,IEX_PC_delrec_pars
    EX_PC_image_types = "MGU_ITYP_PHASE";
    EX_PC_recon_flow_dirs = "MPUPC_DIR_AP";
$!
$ wait_proceed "CHOOSE VALVES SCAN!"
$ reconstruct AP_VALVES_Volunteer_3_Trial_2_MA, select

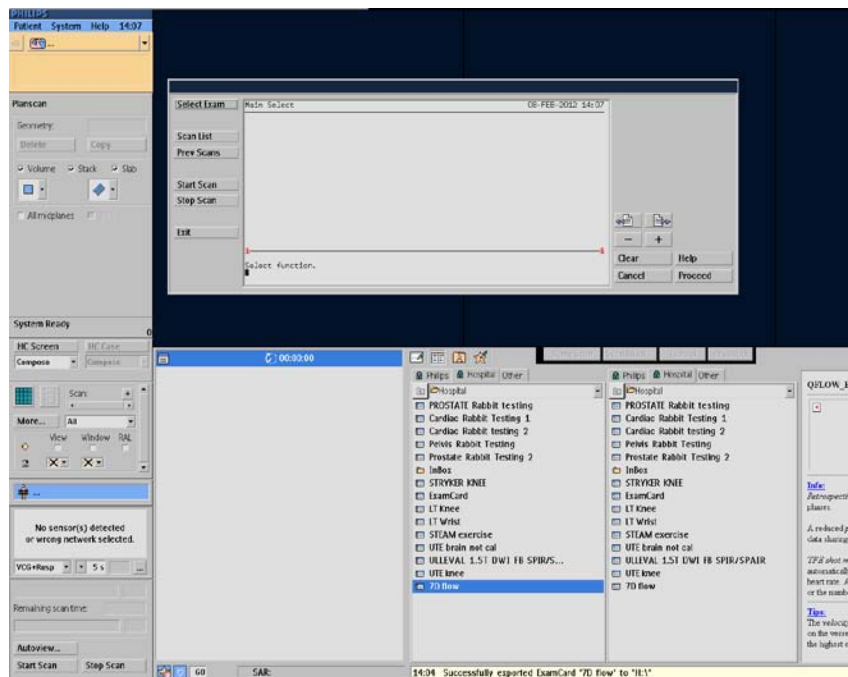
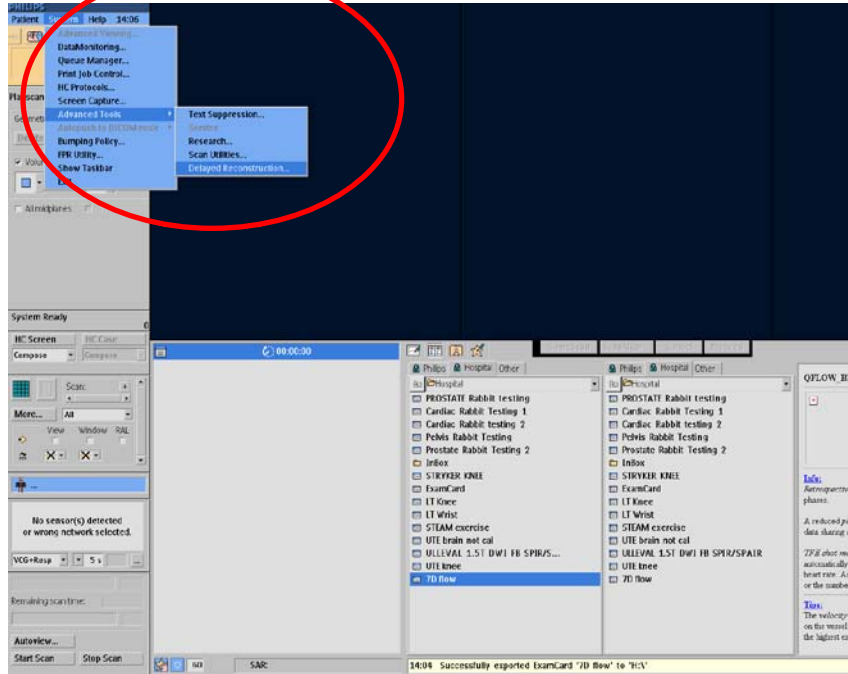
$ modify ,IEX_PC_delrec_pars
    EX_PC_image_types = "MGU_ITYP_PHASE";
    EX_PC_recon_flow_dirs = "MPUPC_DIR_RL";
$!
$ wait_proceed "CHOOSE VALVES SCAN!"
$ reconstruct RL_VALVES_Volunteer_3_Trial_2_MA, select
$!
$ modify ,IEX_PC_delrec_pars
    EX_PC_image_types = "MGU_ITYP_PHASE";

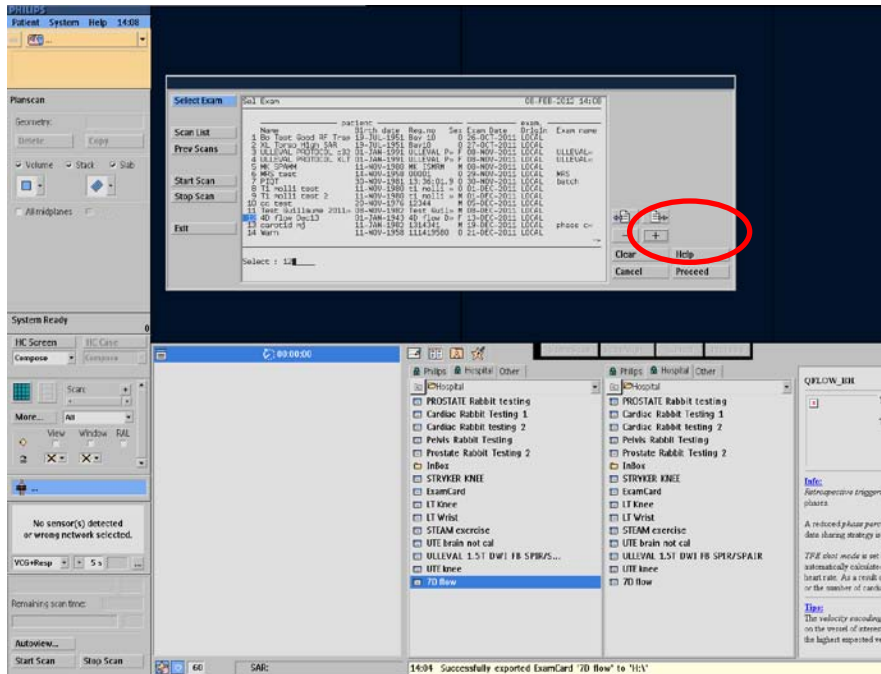
```

```
EX_PC_recon_flow_dirs    = "MPUPC_DIR_FH";  
$!  
$ wait_proceed "CHOOSE VALVES SCAN!"  
$ reconstruct FH_VALVES_Volunteer_3_Trial_2_MA, select  
$ restore_site_values  
$!  
$ wait_proceed "Check 1 BATCH COMPLETE"
```

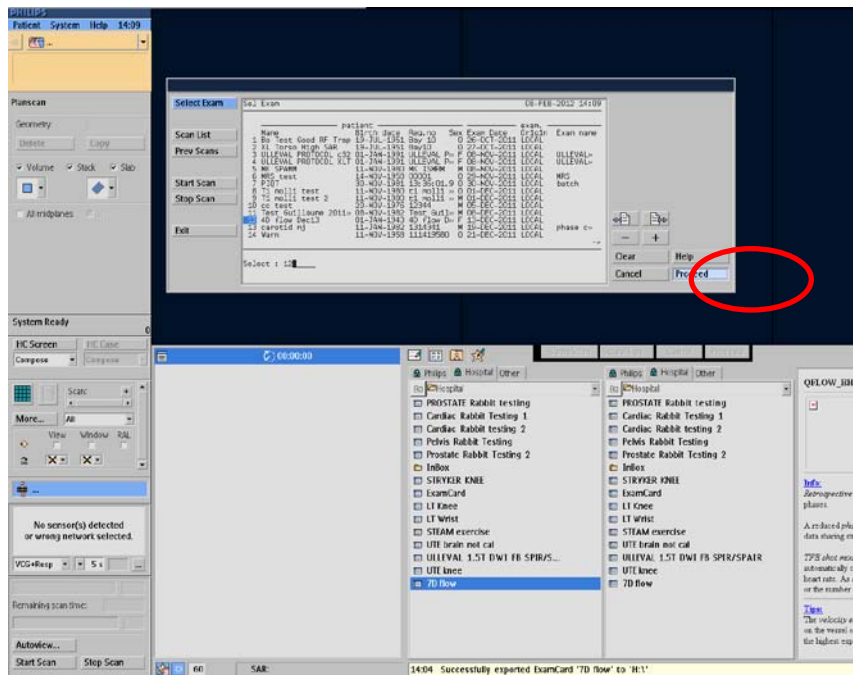
(B) MANUAL DELAYED RECONSTRUCTION INSTRUCTION

1. Using the Reconstructor on the MR system (or remotely), go to “System,” ”Advanced Tools,” “Delayed Reconstruction.”

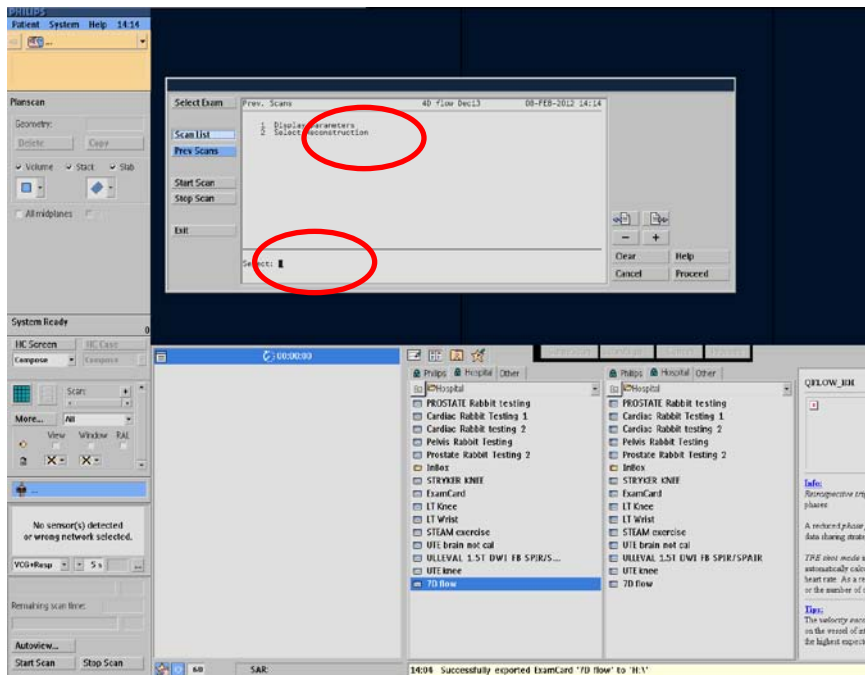
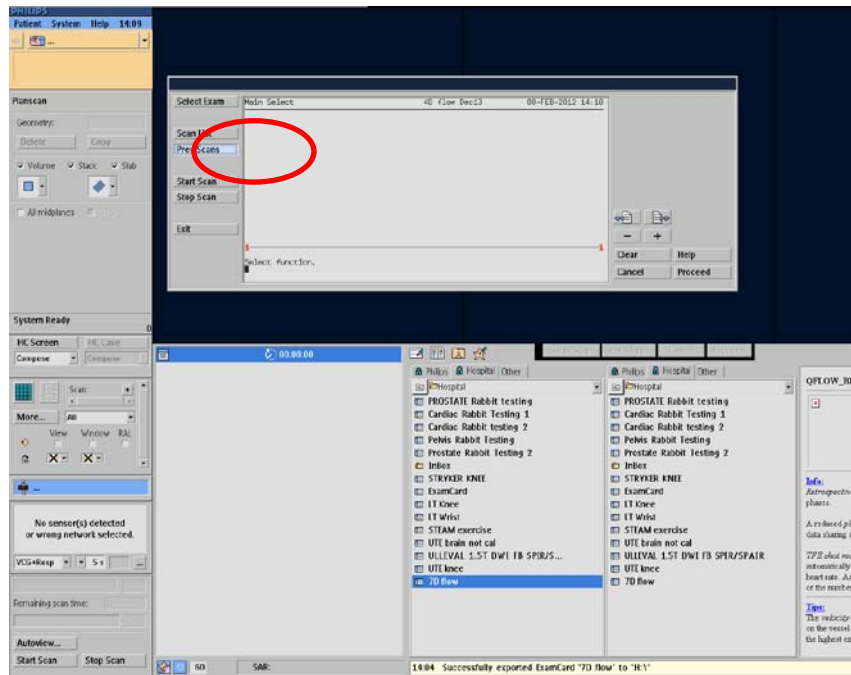




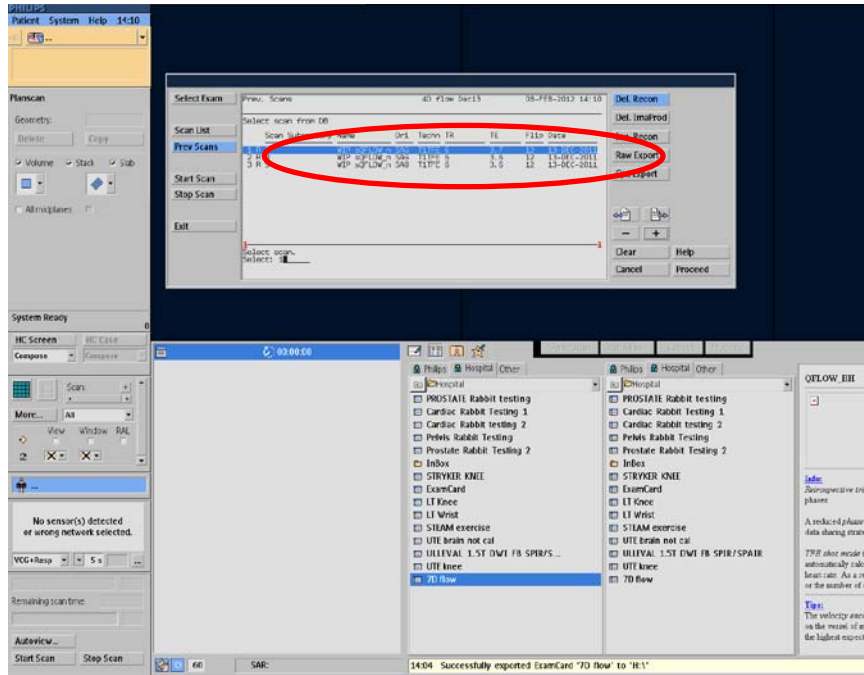
4. Click “Proceed.”



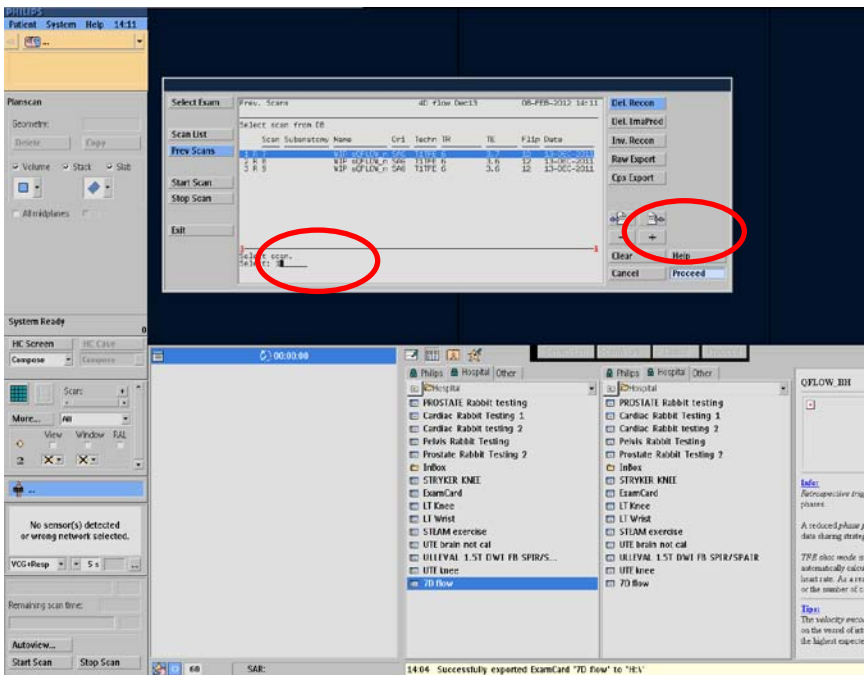
5. Click the “Previous Scan” button, and select #2, “Delayed Reconstruction”



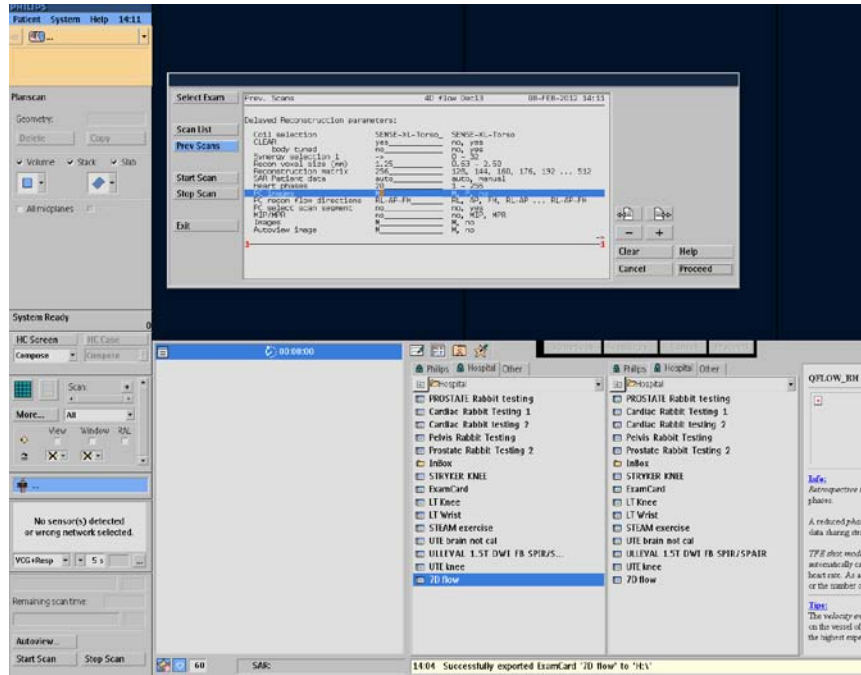
6. Three sets of data will appear.



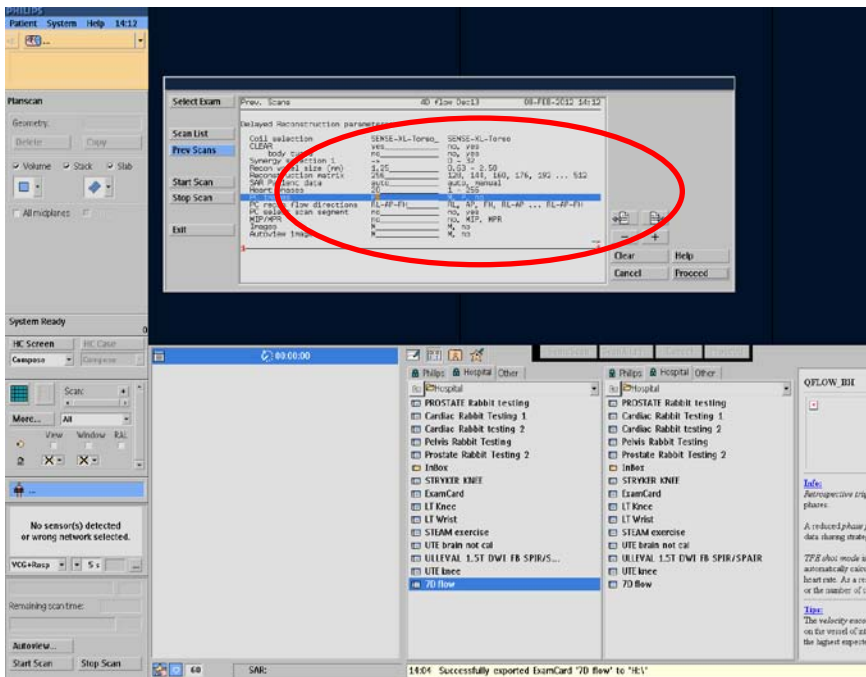
7. Pick the first exam, using the “+/-” buttons, and “Proceed.”



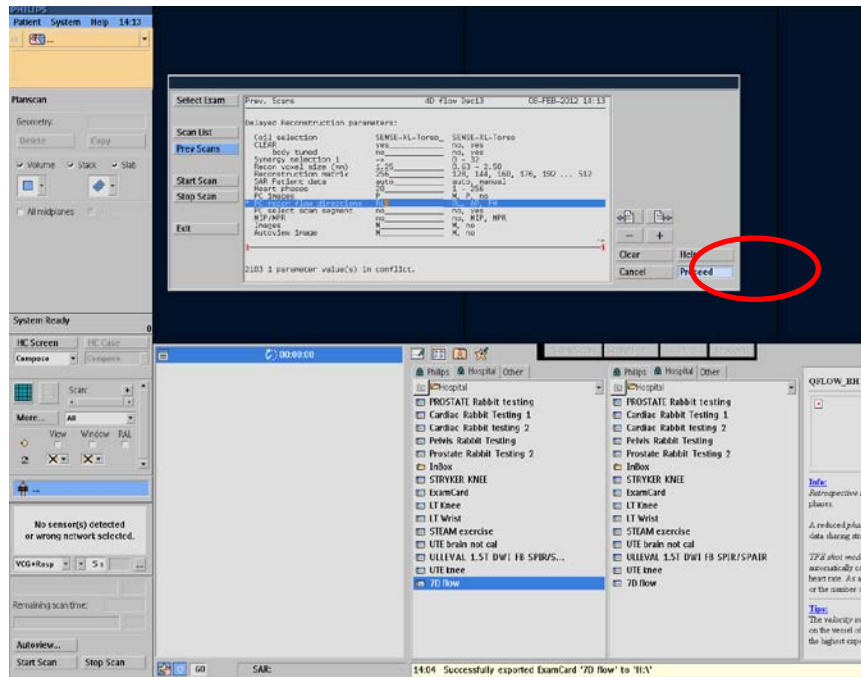
8. A list of parameters will appear.



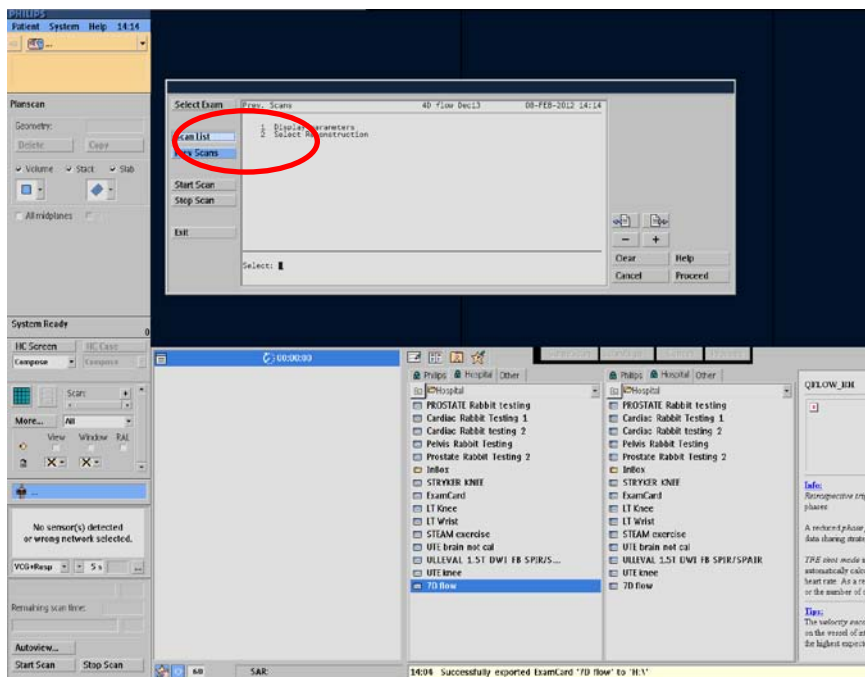
9. Change the parameter PC images from “M” (magnitude) to “P” (phase).

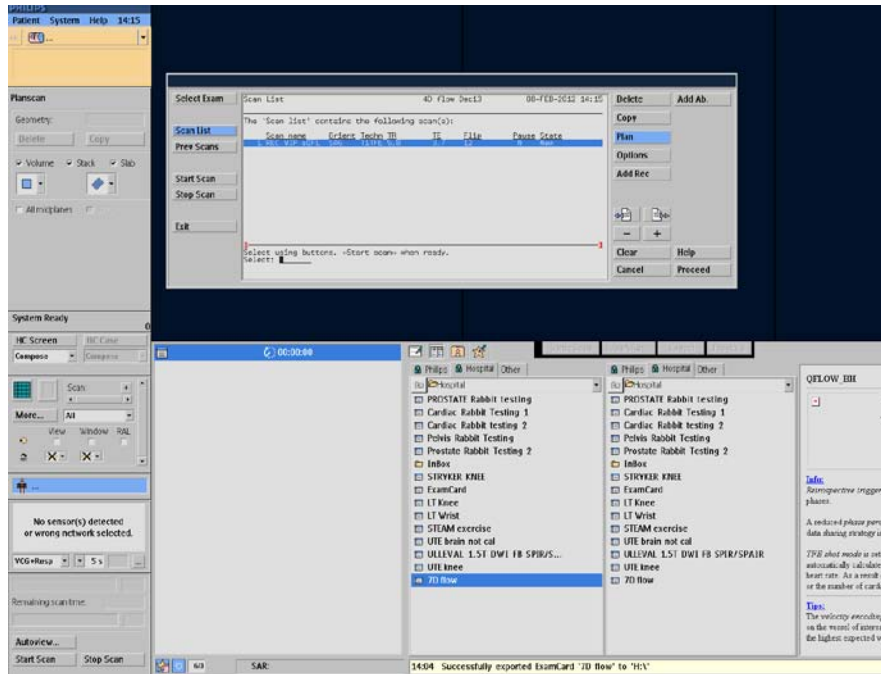


1. Click “Proceed.”

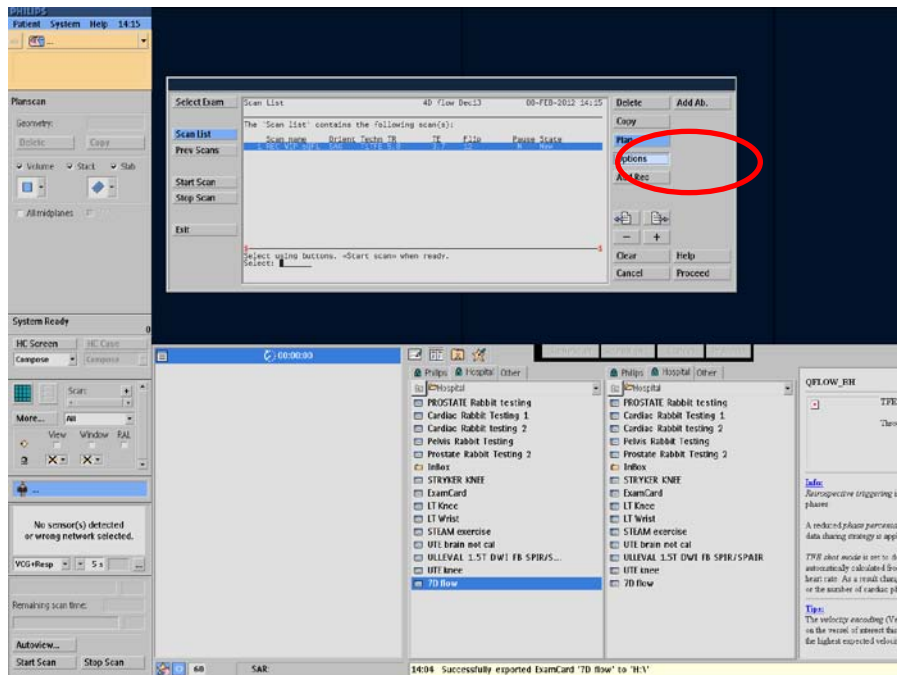


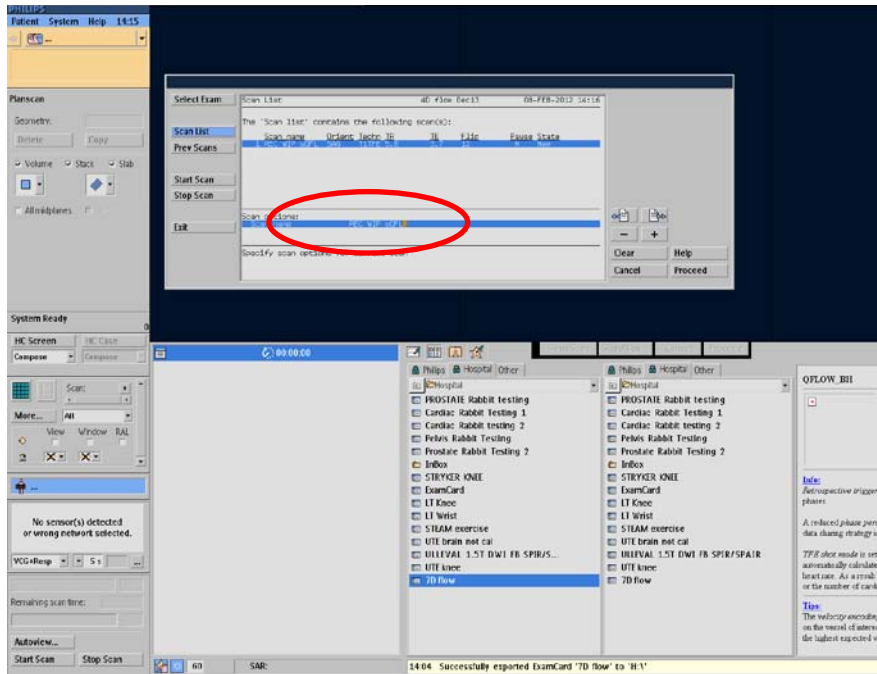
2. Click “Scan List”.



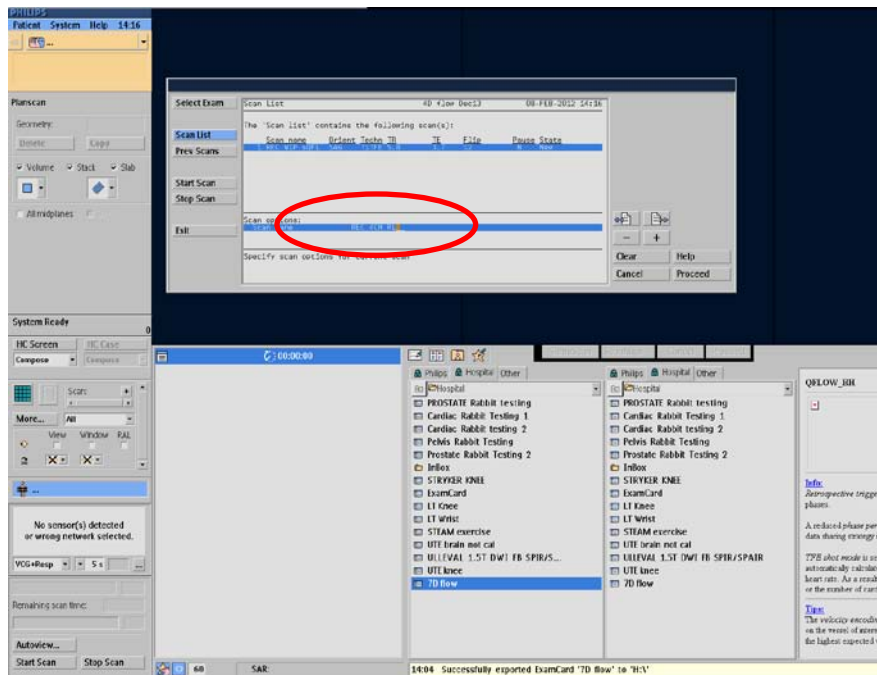


3. Click “Options”, then “Rename.”

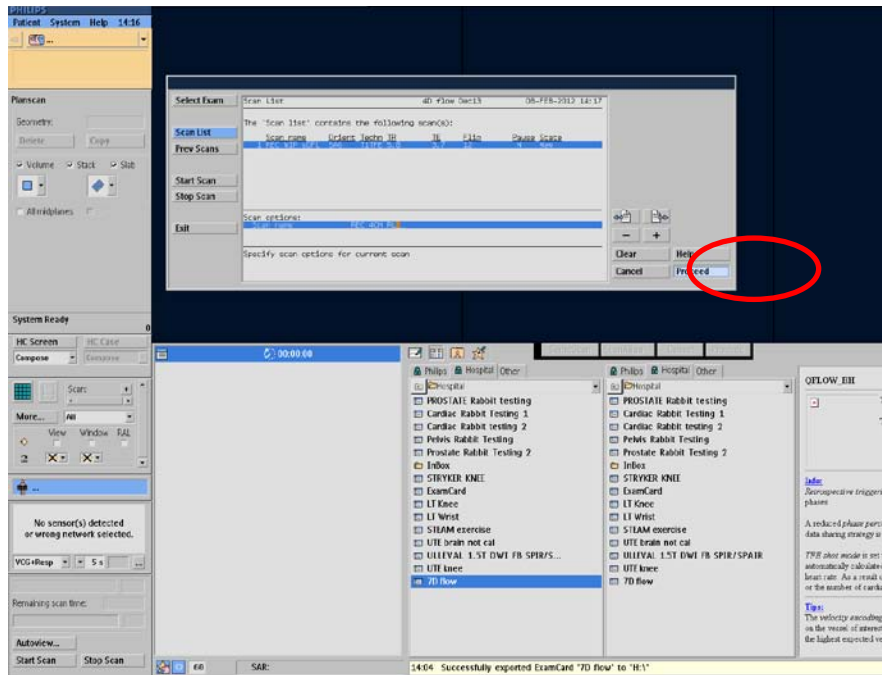




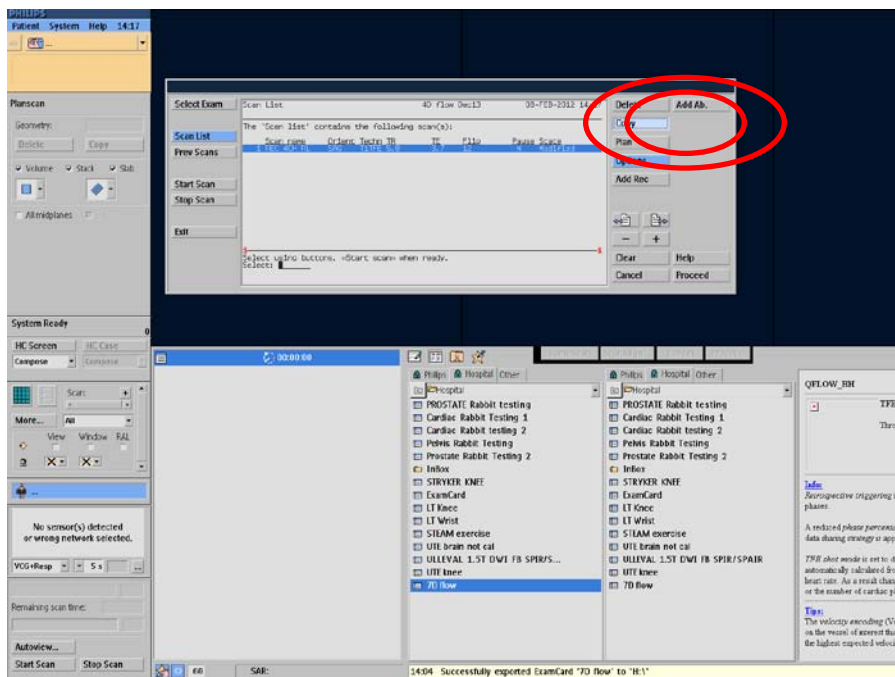
4. Rename file to “REC 4CH RL.”

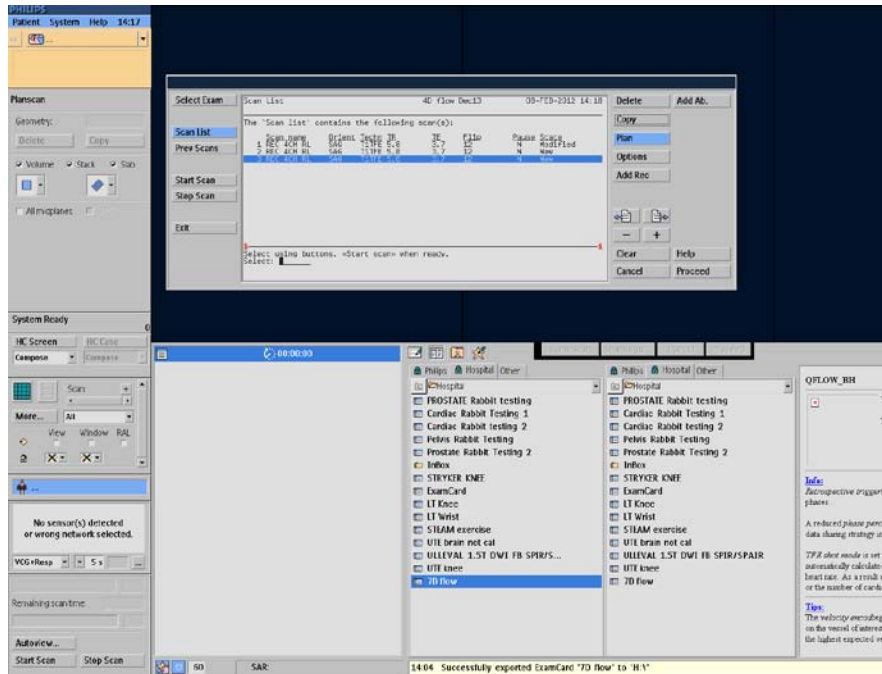


5. Click “Proceed.”

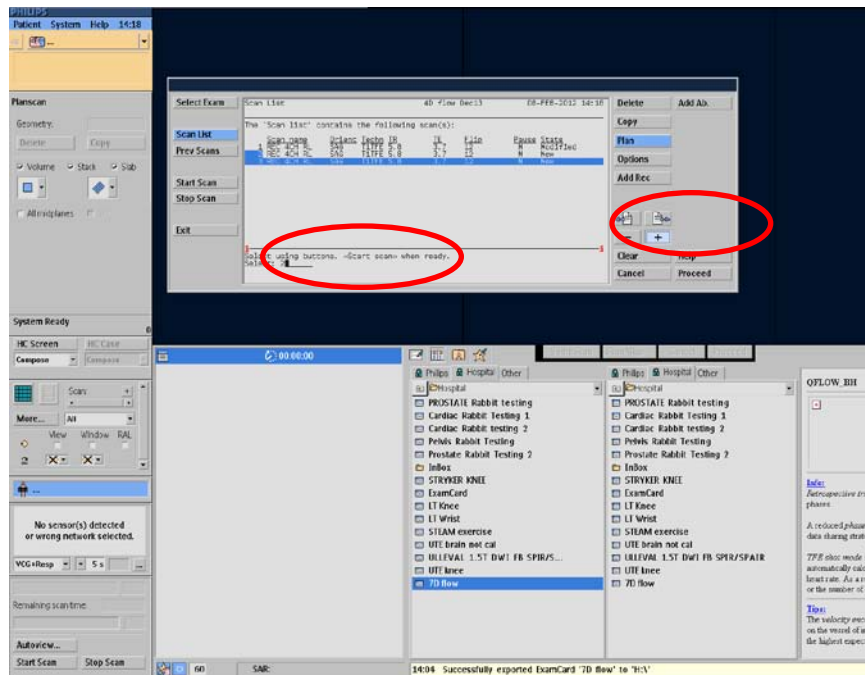


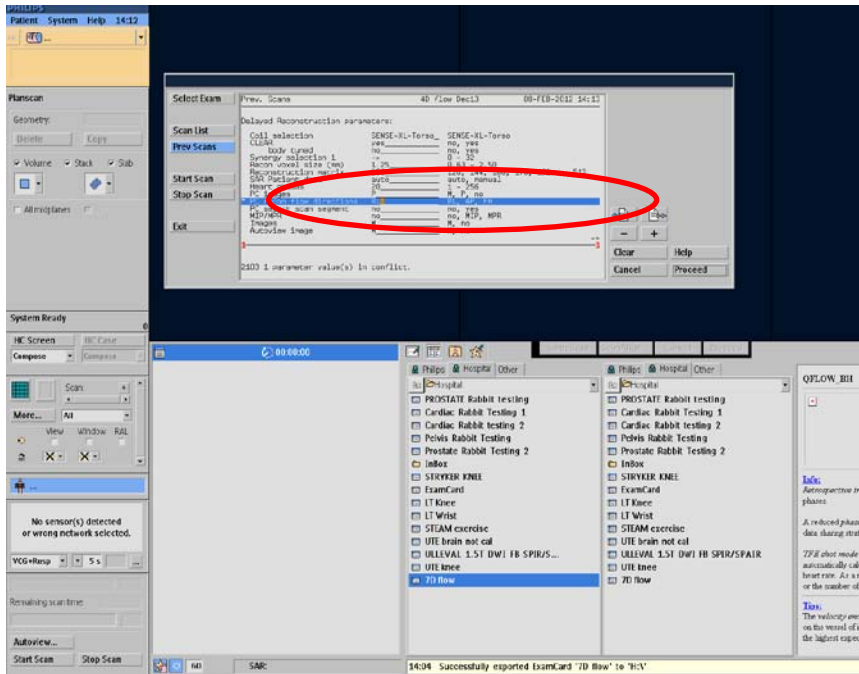
6. Copy the exam 2 times using the “Copy” button.



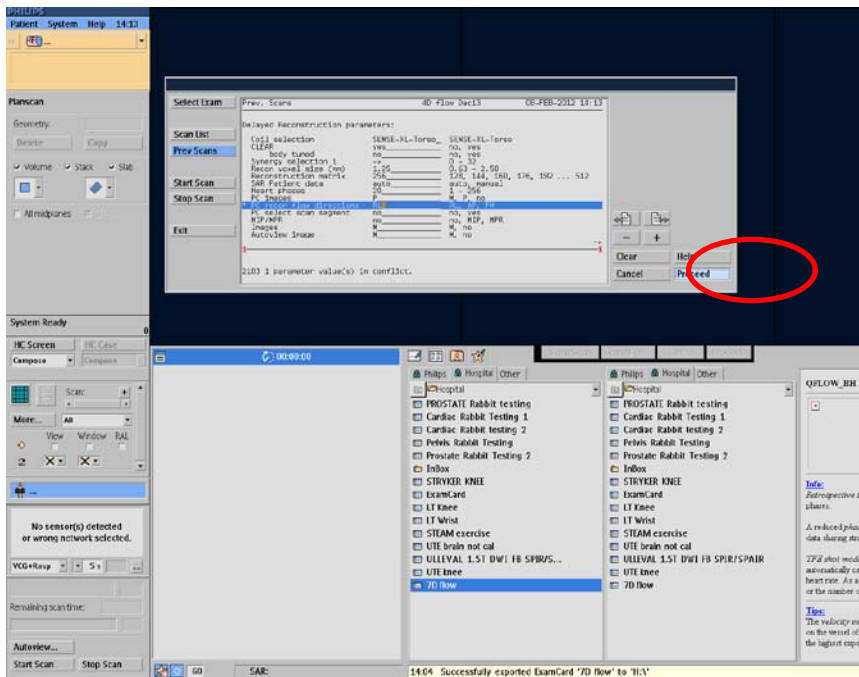


7. Select the second exam using the “+/-“ buttons, and “Proceed.”



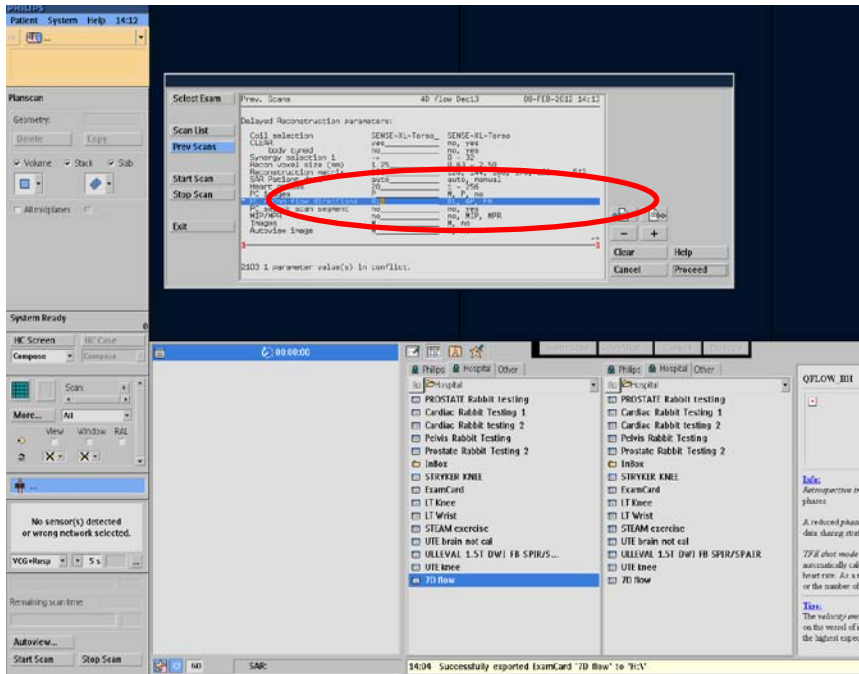


10. Click "Proceed."

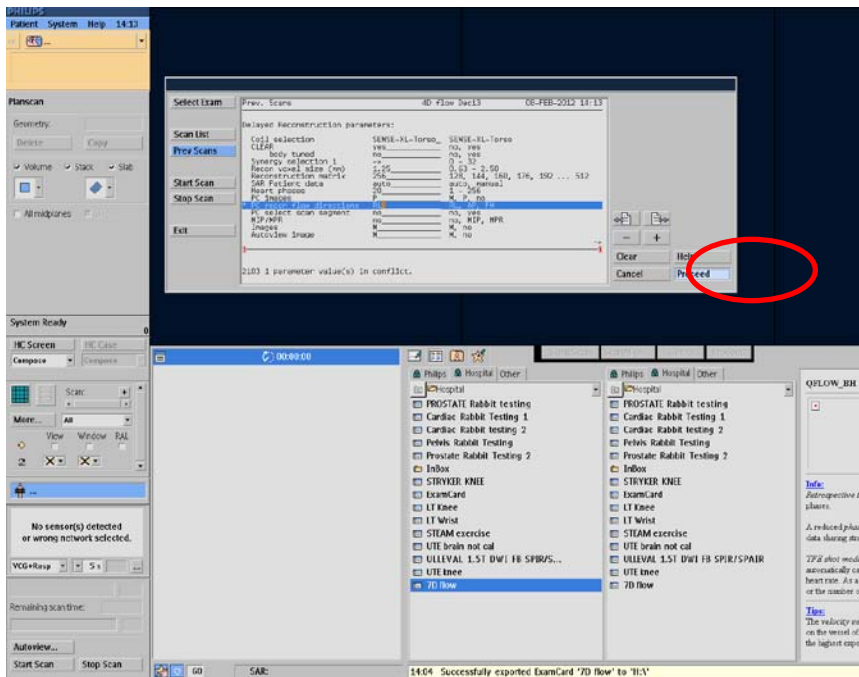


11. Click Scan List, select the third file.

12. Click "Options", then "Rename."

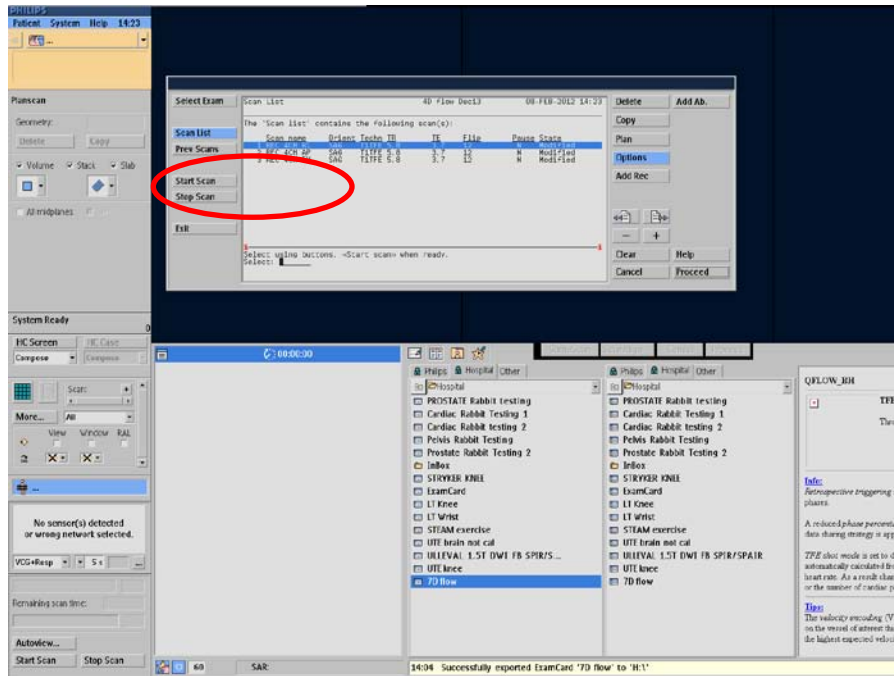


14. Click “Proceed.”



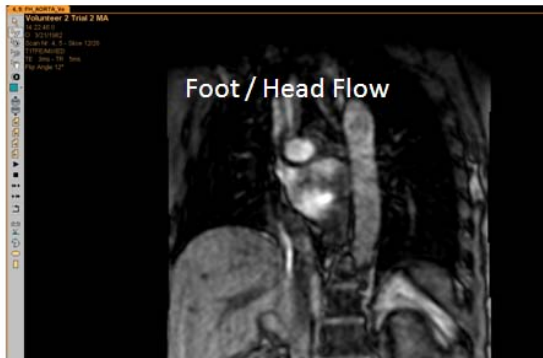
15. Click “Proceed.”

16. Click “Start Scan” to proceed with the reconstruction of all three data sets.



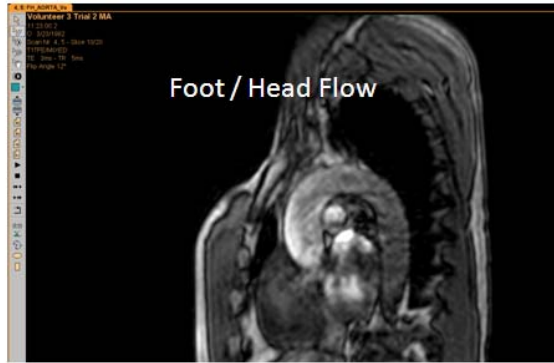
(C) VOLUNTEER SCANS NOT PREVIOUSLY REFERENCED

Volunteer 2, Trial 2, Aorta



Magnitude Scans –
Shows anatomy

Volunteer 3, Trial 2, Aorta



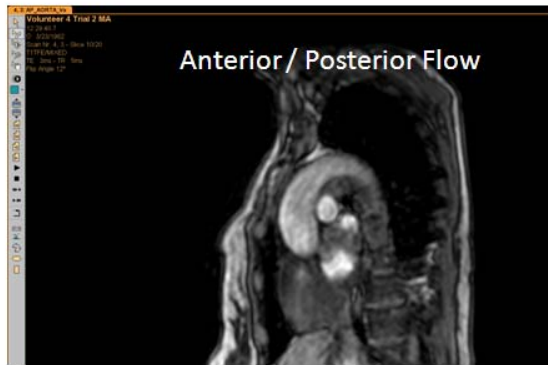
Magnitude Scans—
Shows anatomy

Volunteer 3, Trial 2, Aorta



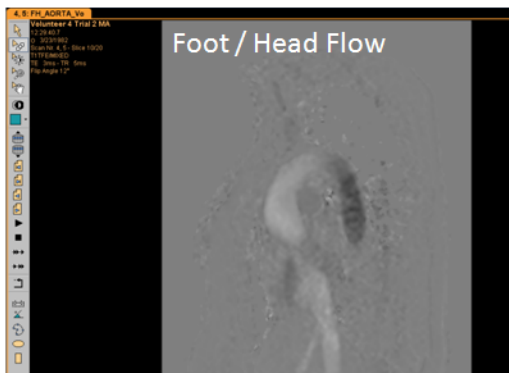
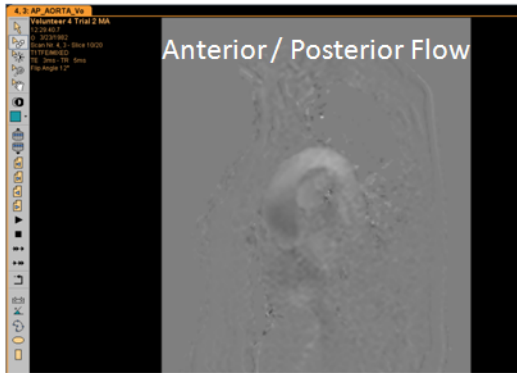
Phase Encoded Scans – Light / Dark areas indicate magnitude of flow in the specified direction.

Volunteer 4, Trial 2, Aorta



Magnitude Scans –
Shows anatomy

Volunteer 4, Trial 2, Aorta



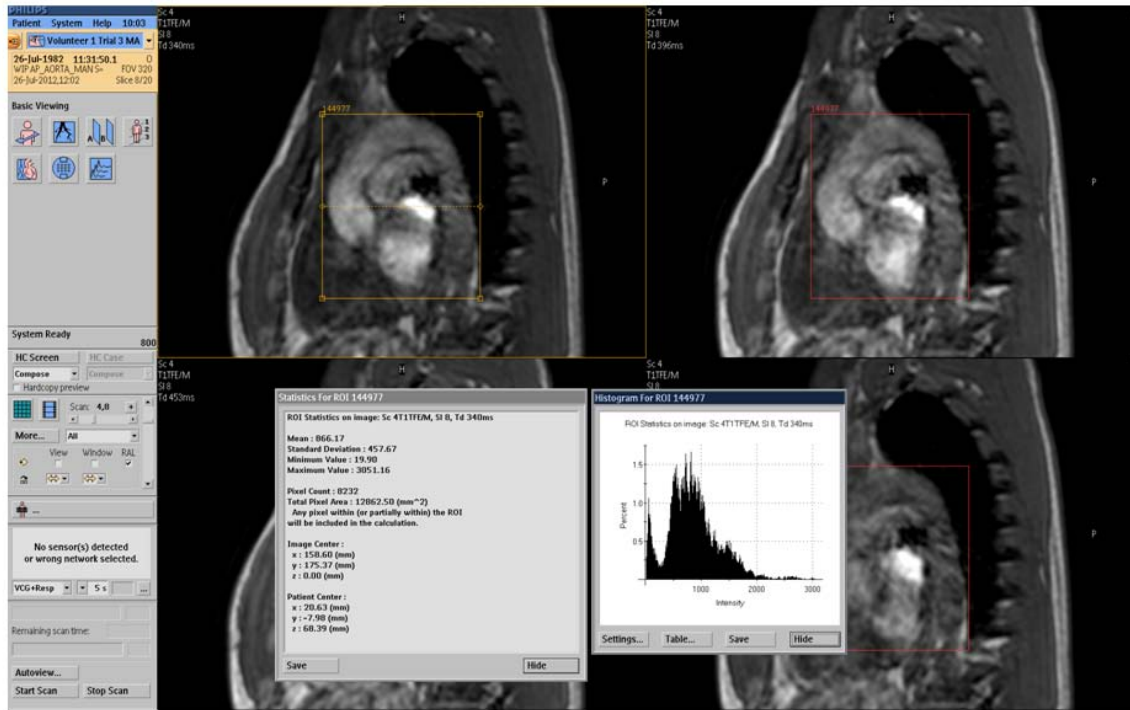
Phase Encoded Scans – Light / Dark areas indicate magnitude of flow in the specified direction.

Volunteer 4, Trial 2, Valves

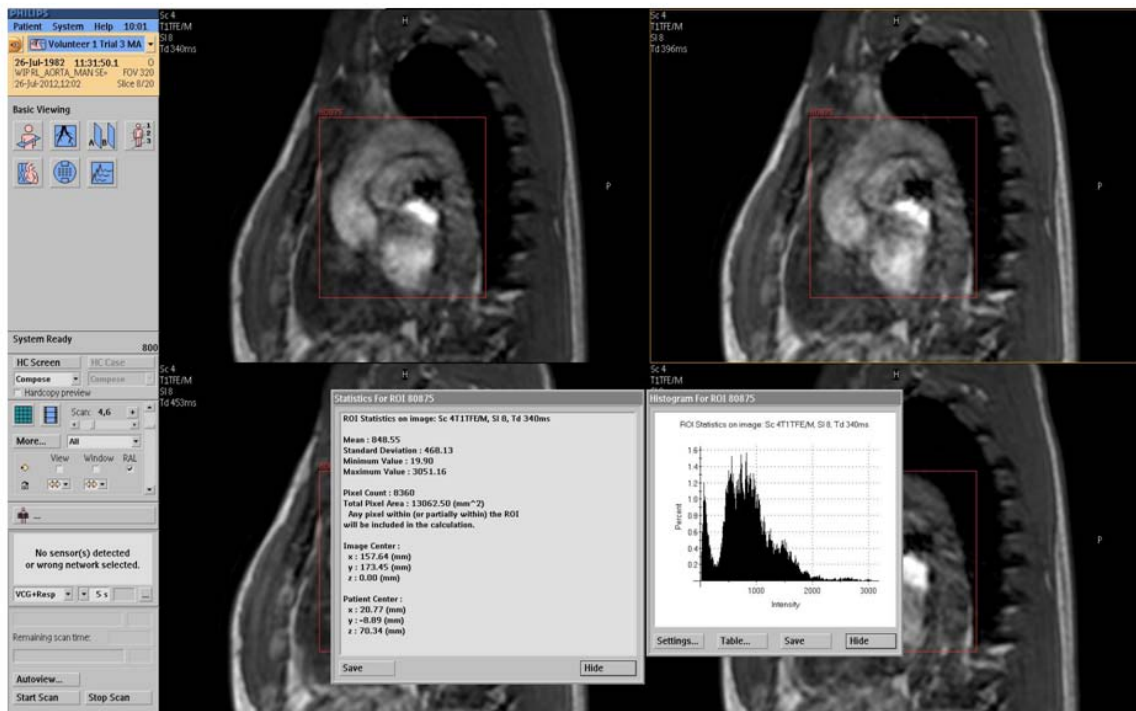


Phase Encoded Scans – Light / Dark areas indicate magnitude of flow in the specified direction.

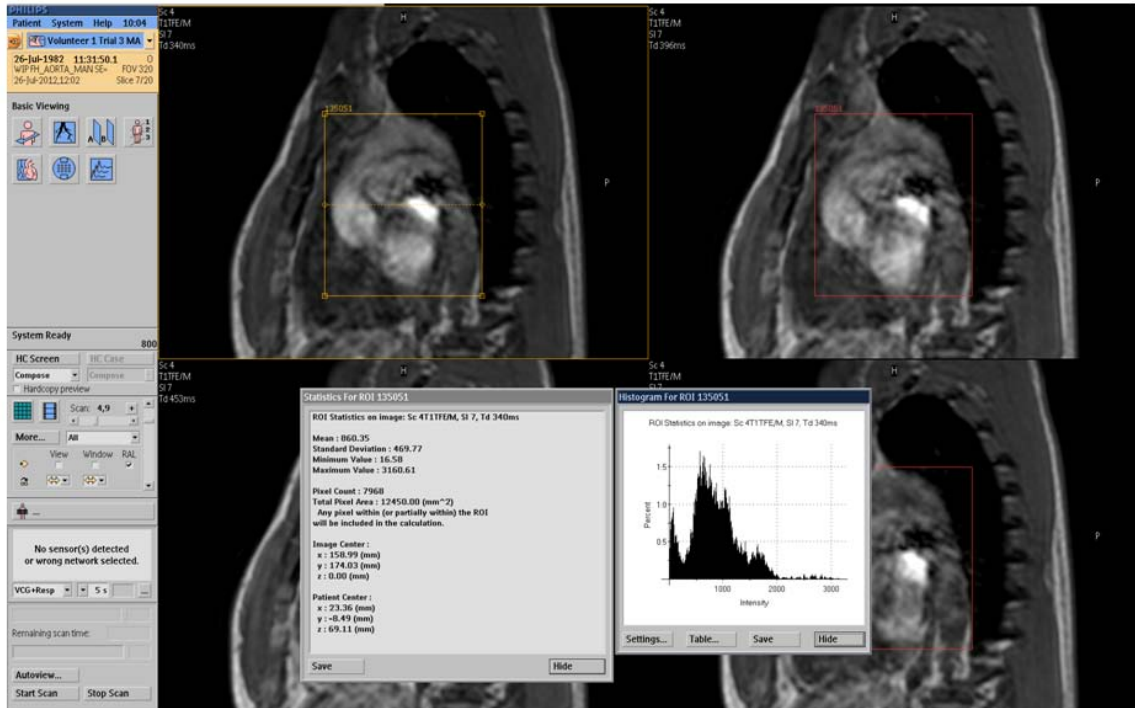
Volunteer 1, Trial 3, Aorta – AP Magnitude – Manual Reconstruction



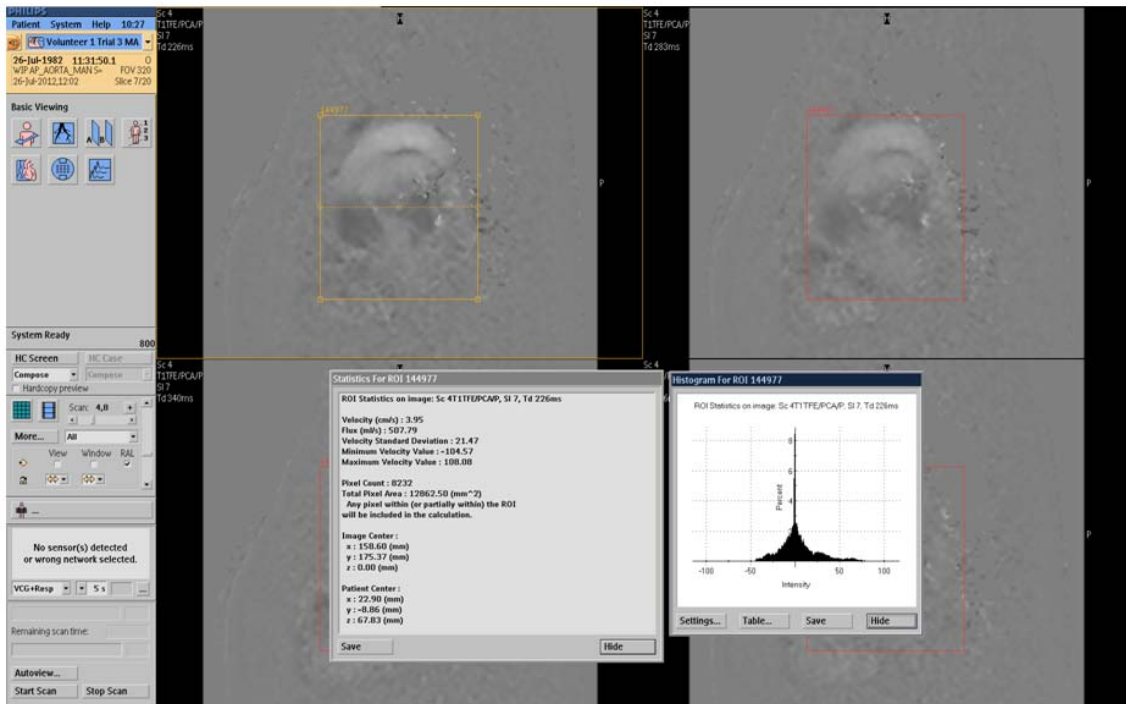
Volunteer 1, Trial 3, Aorta – RL Magnitude – Manual Reconstruction



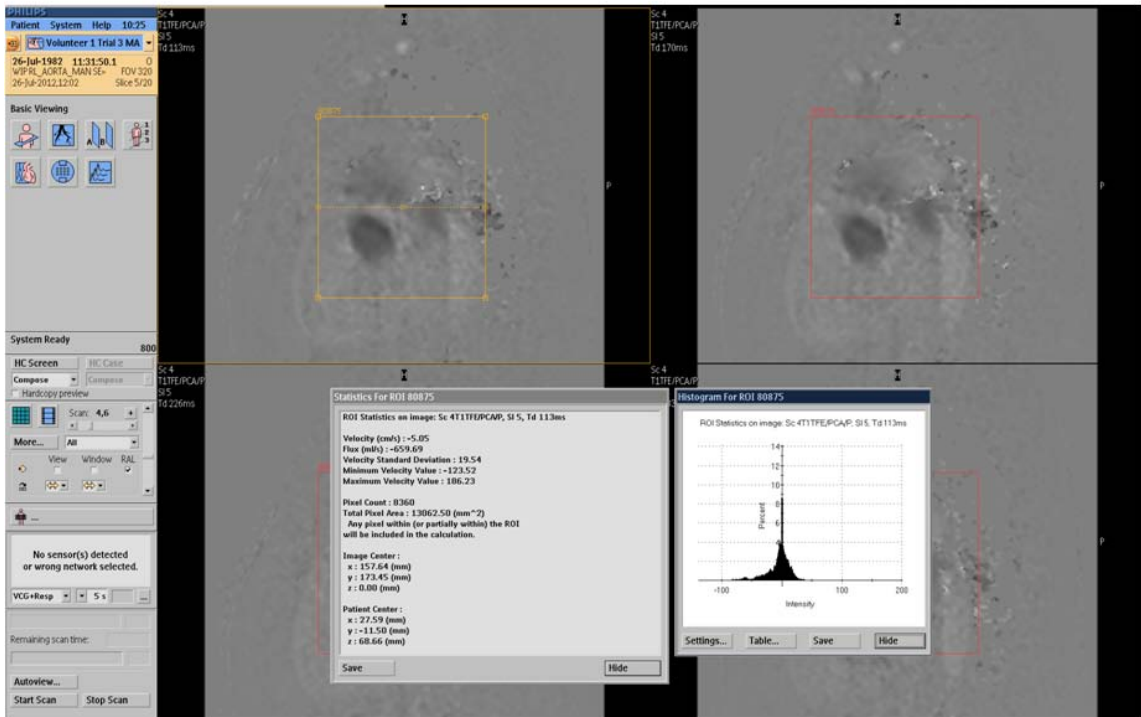
Volunteer 1, Trial 3, Aorta – FH Magnitude – Manual Reconstruction



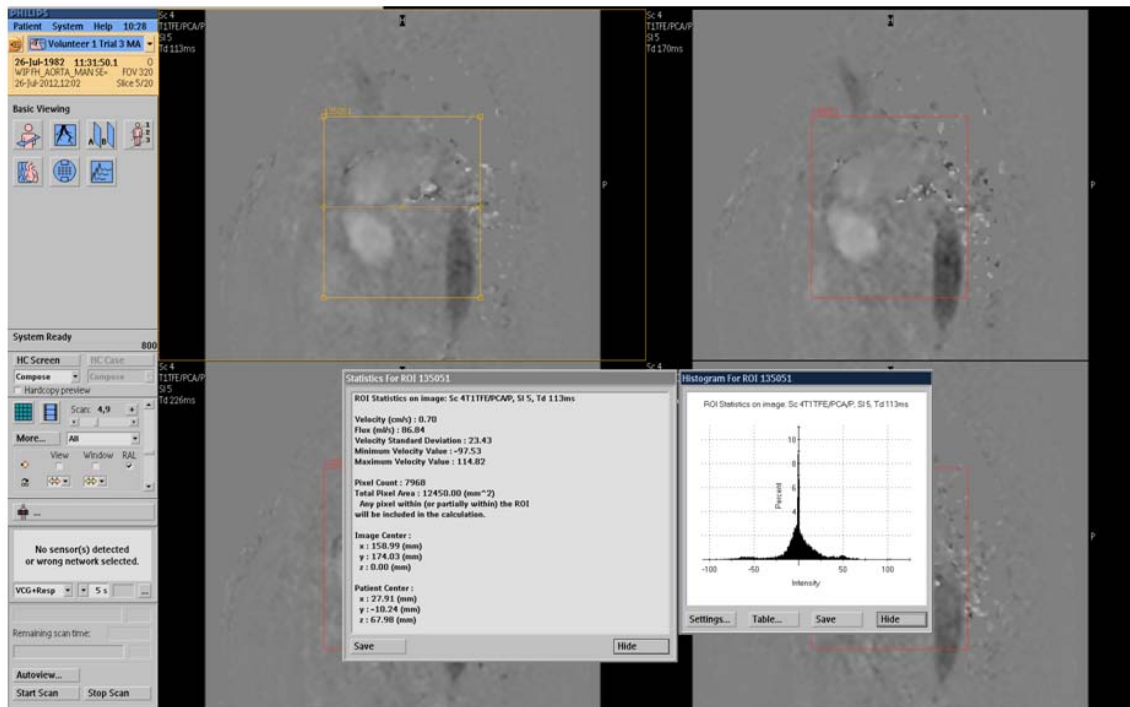
Volunteer 1, Trial 3, Aorta – AP Phase – Manual Reconstruction



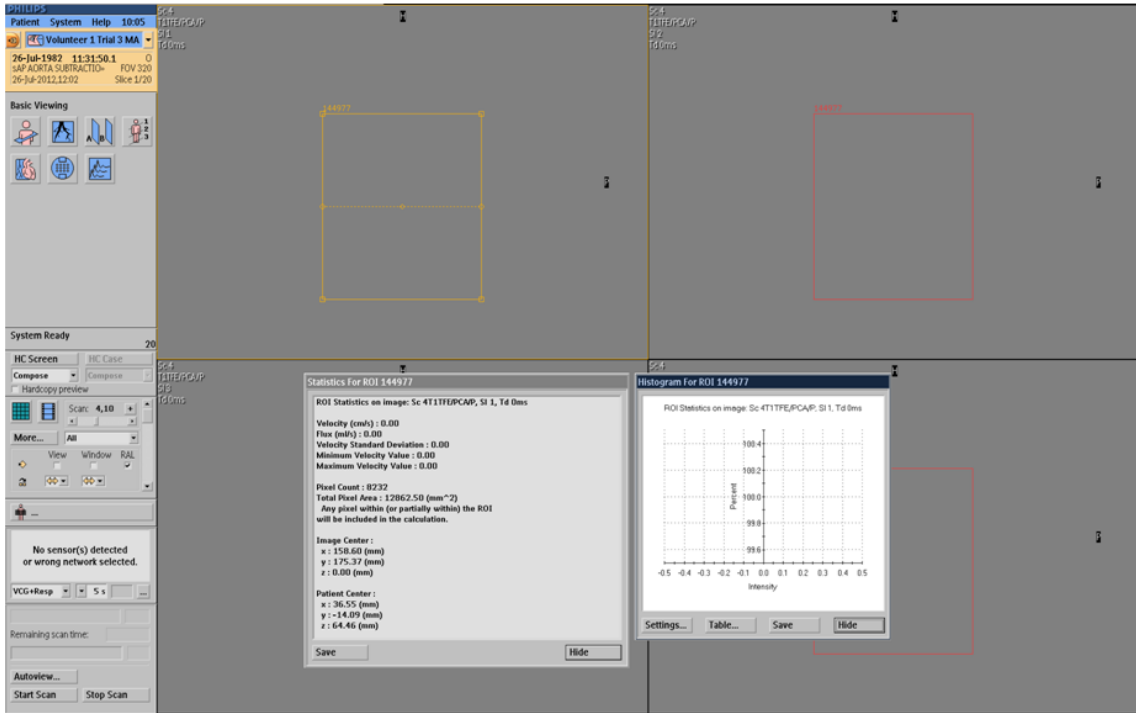
Volunteer 1, Trial 3, Aorta – RL Phase – Manual Reconstruction



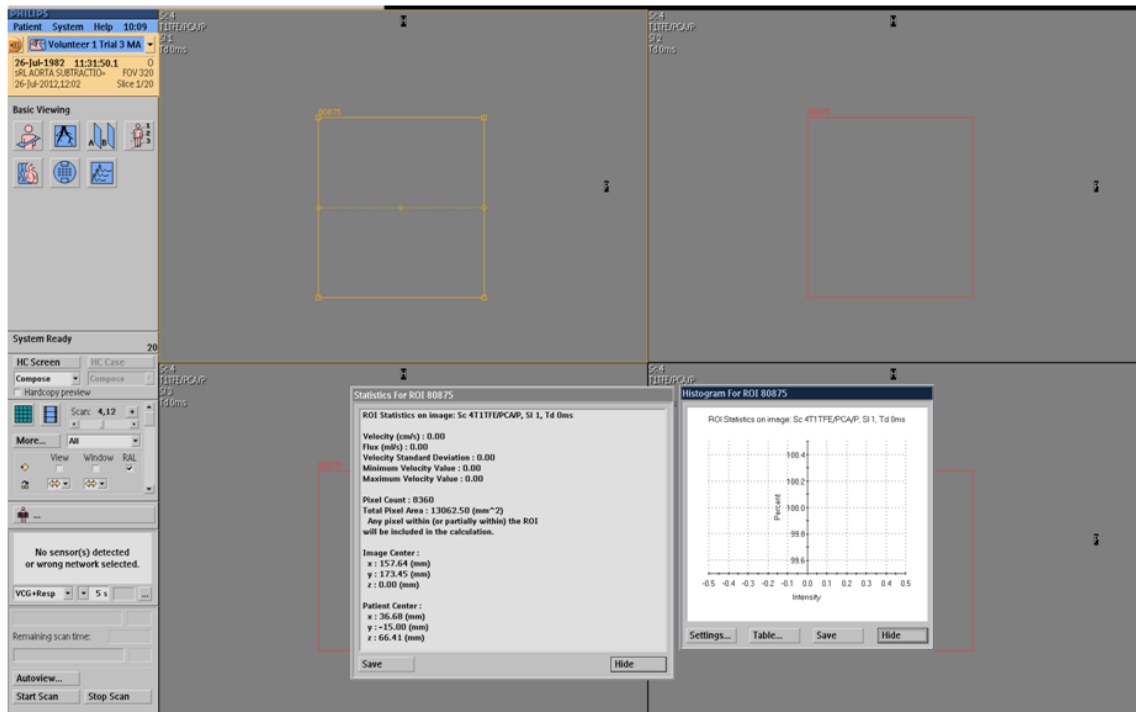
Volunteer 1, Trial 3, Aorta – FH Phase – Manual Reconstruction



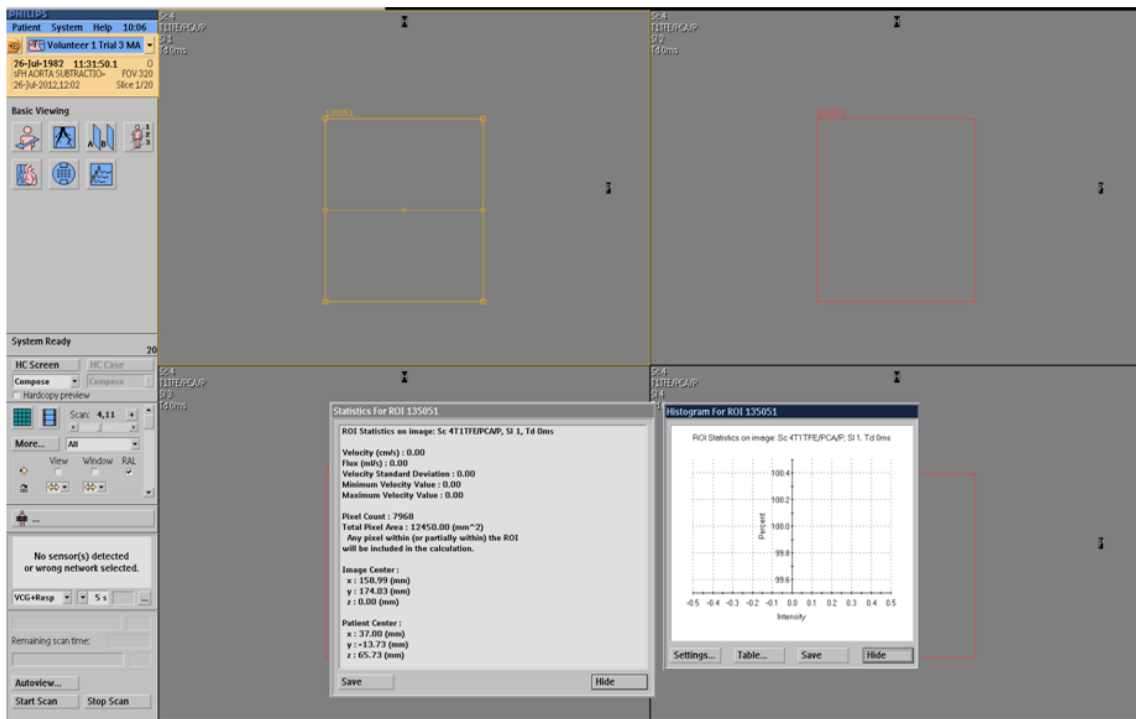
Volunteer1, Trial 3, Aorta – AP Phase – Manual Reconstruction – Automated Reconstruction



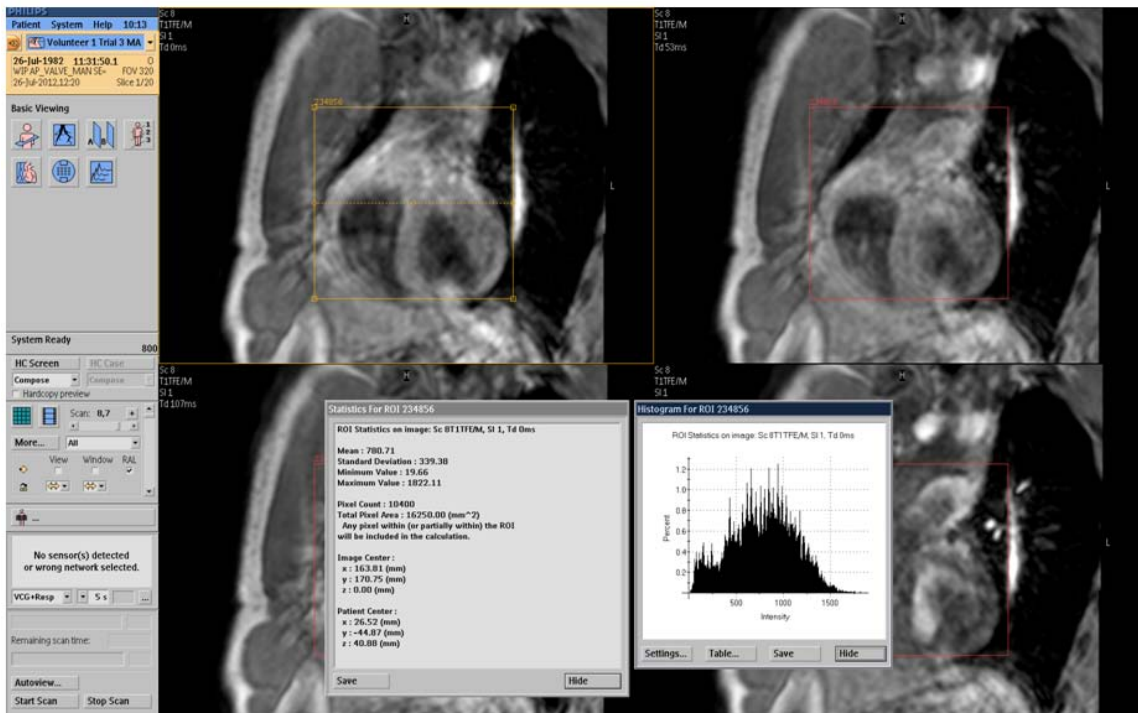
Volunteer1, Trial 3, Aorta – RL Phase – Manual Reconstruction – Automated Reconstruction



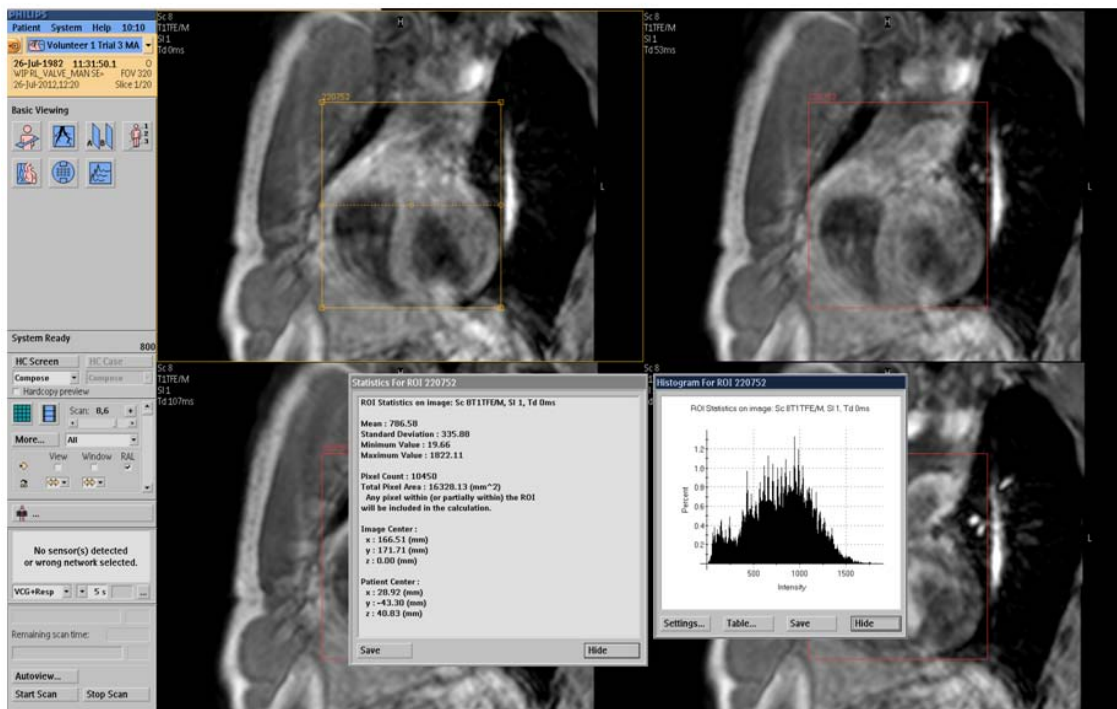
Volunteer 1, Trial 3, Aorta – FH Phase – Manual Reconstruction – Automated Reconstruction



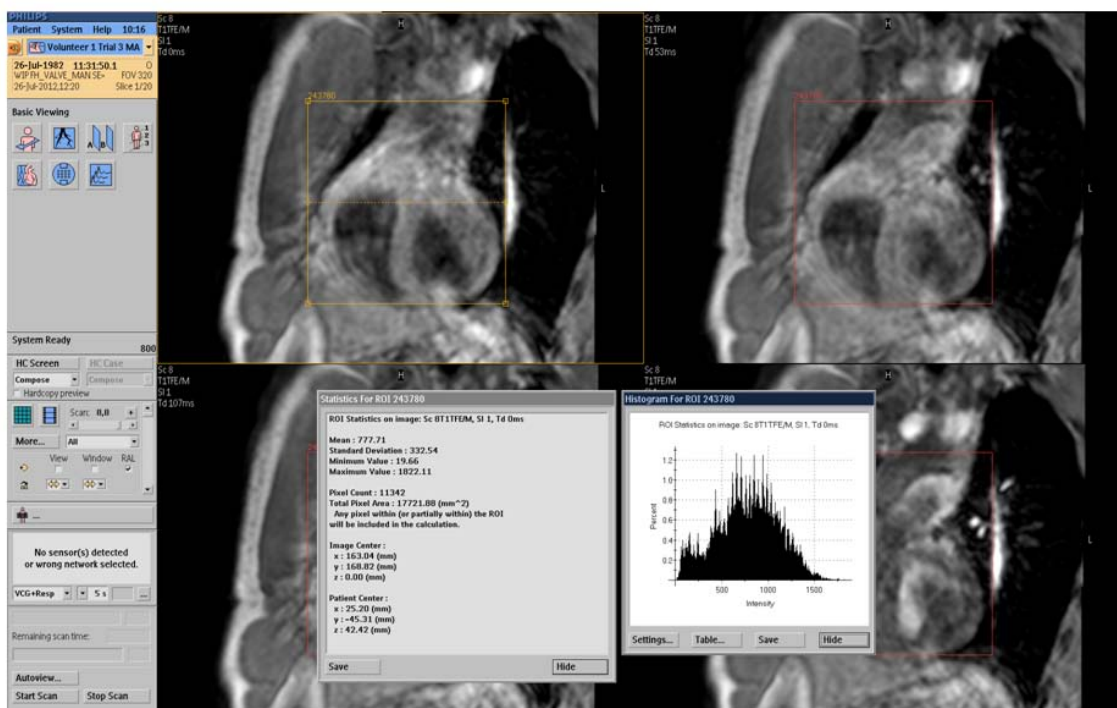
Volunteer 1, Trial 3, Valves – AP Magnitude – Manual Reconstruction



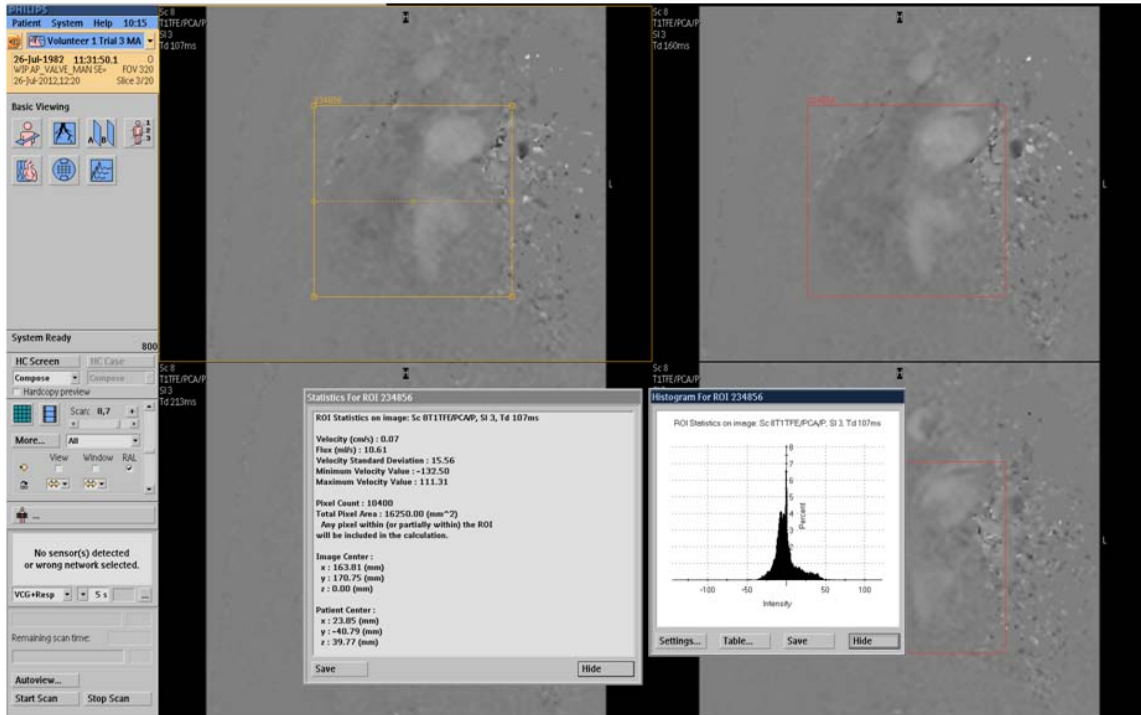
Volunteer 1, Trial 3, Valves – RL Magnitude – Manual Reconstruction



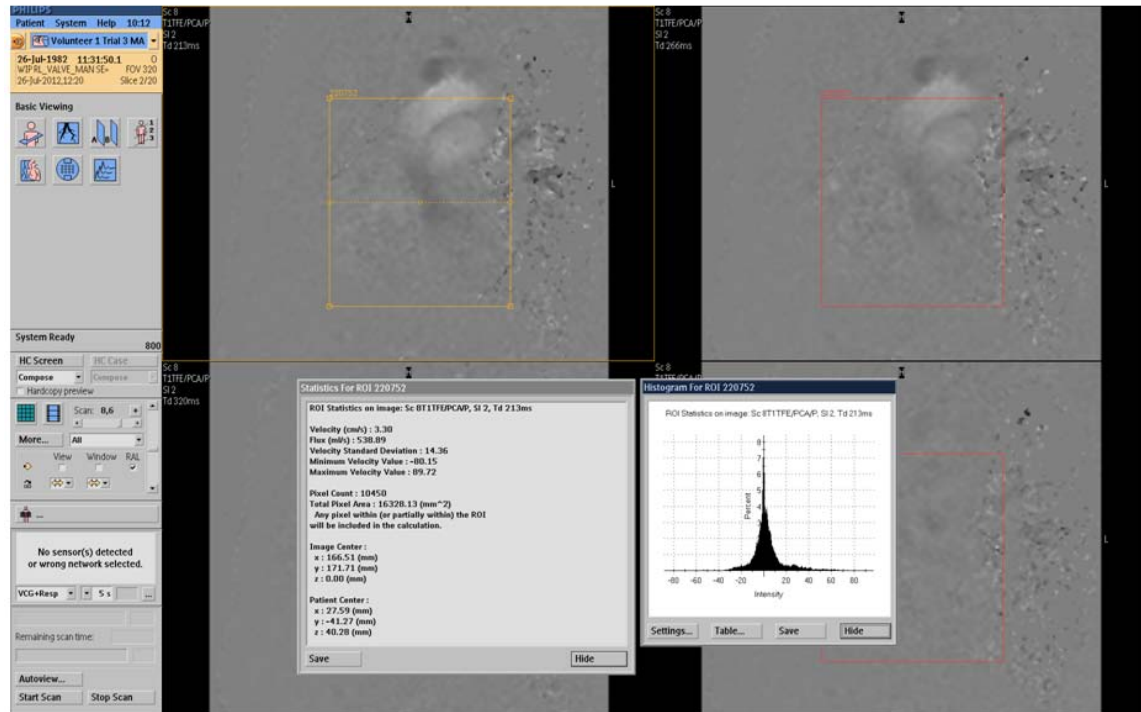
Volunteer 1, Trial 3, Valves – FH Magnitude – Manual Reconstruction



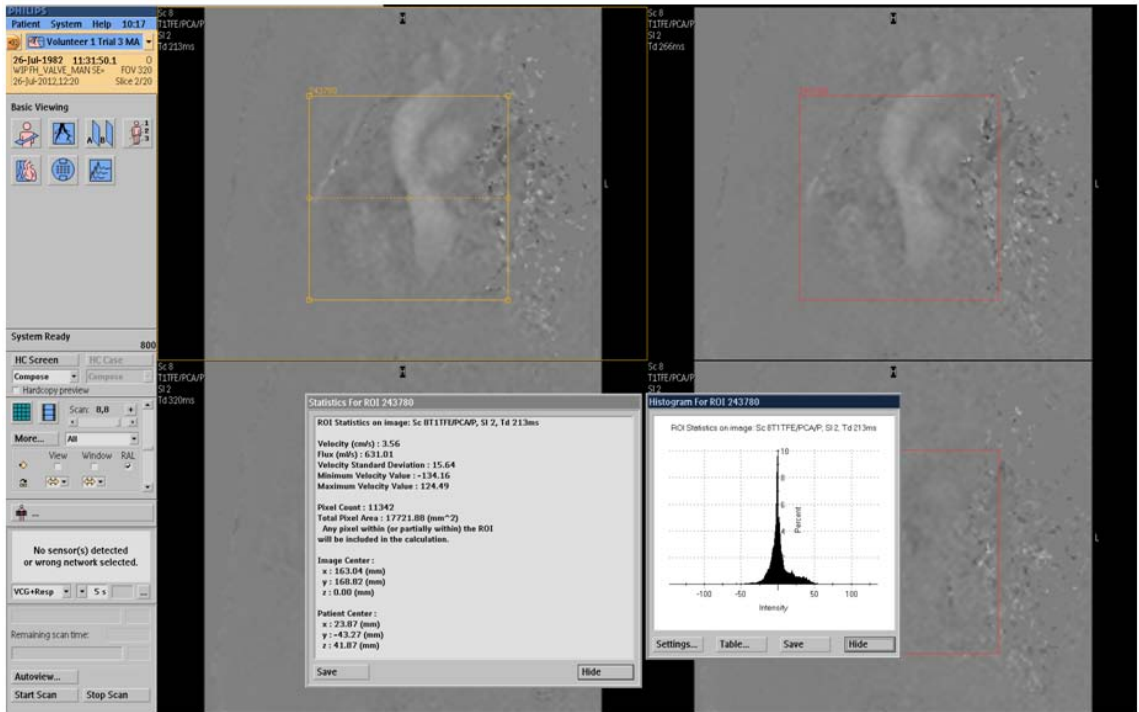
Volunteer 1, Trial 3, Valves – AP Phase – Manual Reconstruction



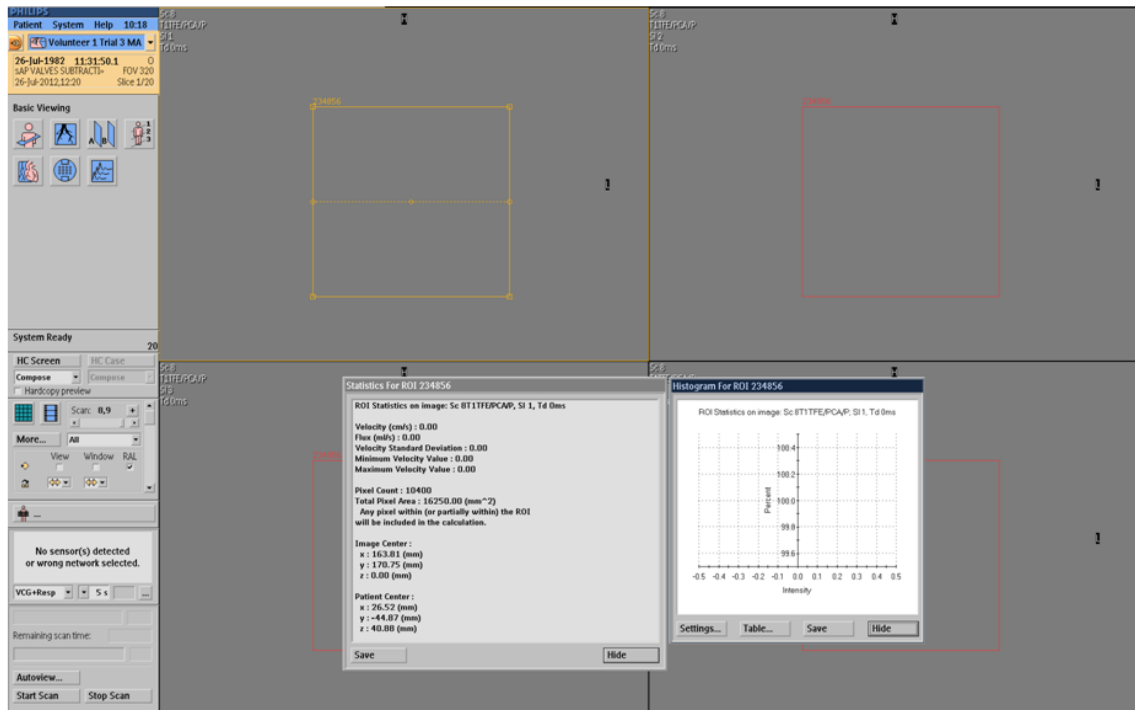
Volunteer 1, Trial 3, Valves – RL Phase – Manual Reconstruction



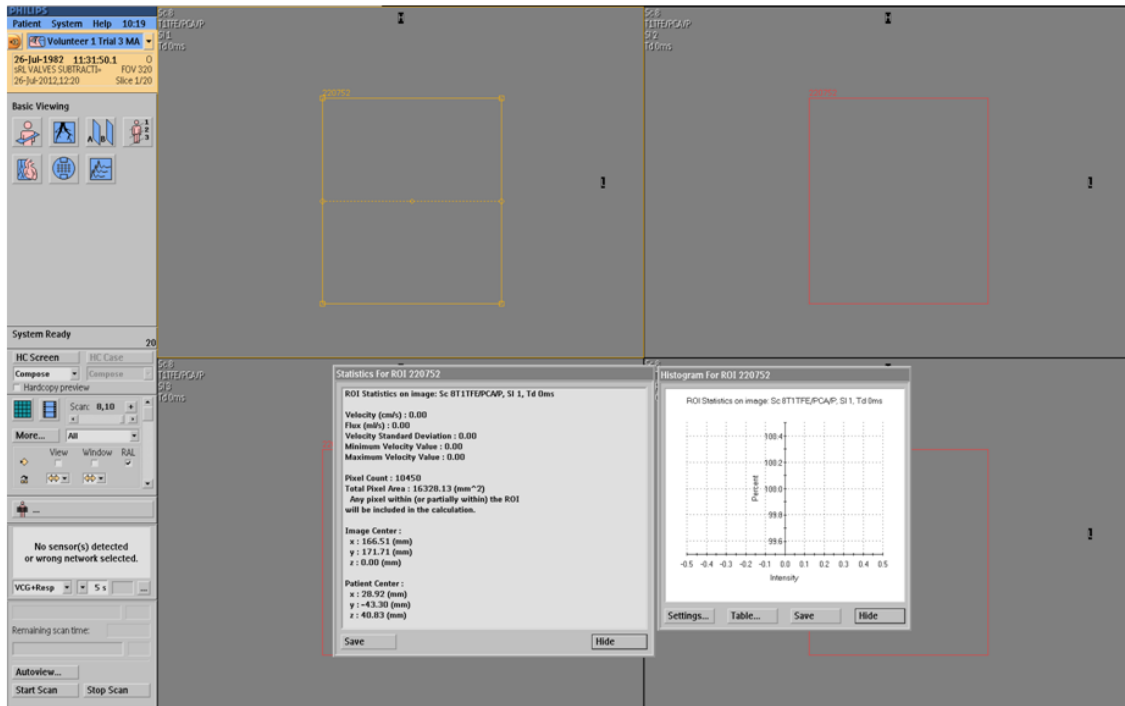
Volunteer 1, Trial 3, Valves – FH Phase – Manual Reconstruction



Volunteer 1, Trial 3, Valves – AP Phase – Manual Reconstruction – Automated Reconstruction



Volunteer 1, Trial 3, Valves – RL Phase – Manual Reconstruction – Automated Reconstruction



Volunteer 1, Trial 3, Valves – FH Phase – Manual Reconstruction – Automated Reconstruction

