Standardized Acquisition Protocol for Whole-Body Quantitative MRI of Muscle

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Read this first!

⬅️ Use the left panel for navigation.

This document currently serves 3 purposes:

1) Facilitate discussions across collaborators to come to a consensus and develop a generic acquisition protocol for whole-body quantitative MRI of muscle.
2) Facilitate drafting of the generic acquisition protocol for whole-body quantitative MRI of muscle manuscript.

Collaborators with the link can request permission to comment and edit (with Suggestion mode). Please email Ananya Goyal (agoyal5@stanford.edu) to request access.

If you have a gmail account, please log in so that your name will appear on the edits. This will make it easier for discussions. Thank you for your contributions.

Use a comment to add references, and we will take care of it.

Authors (Add your name and affiliation; Author order will change)

<u>Insert affiliations as footnote:</u> insert → footnote

Co-authors are included if:
They provided significant contributions to the manuscript, and/or they contributed to the multi-site dataset generated by the generic acquisition protocol.

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Abstract

Whole-body muscle magnetic resonance imaging (MRI) is important for assessing systemic musculature changes across a variety of diseases, as the modality gains broader clinical indications and becomes more accessible and widely adopted. However, whole-body muscle imaging presents several challenges, including a lack of standardization across protocols, variability in hardware and coil configurations, differences in scanner and vendor capabilities, and lastly, considerations for patient comfort and scan duration. Overcoming these limitations is essential for reliable, reproducible and comparable muscle imaging in both research and clinical practice.

In this paper, we present a Whole-body Dixon MRI protocol that allows for rapid acquisition from head to toe, across vendors and coils. In a companion paper, this protocol was used to acquire data from 3 vendors across X centers, in Y patients. All key details of the whole-body Dixon protocol and dataset are available in an open-access document that can be found at XXXX.com. The protocol will serve as a starting point for researchers and clinicians implementing new whole body muscle imaging or region-specific muscle imaging initiatives so that, in the future, inclusion of whole-body protocols will become more common in the clinics and neuromuscular research. The protocol could be easily implemented by any trained MR technician or by a researcher/clinician familiar with MRI acquisition, and adapted for higher resolution scans for smaller anatomy.

Introduction

Clinical and Functional Importance of Muscle Health (Para1)

- Muscle mass and quality are critical for mobility, strength, and metabolic health.
- Muscle loss (sarcopenia) is associated with aging, chronic disease, frailty, and reduced quality of life.
- Changes in muscle composition (e.g., fat infiltration or myosteatosis) are linked to metabolic disorders (diabetes, obesity), cancer cachexia, and musculoskeletal pain.
- Early detection of muscle abnormalities can guide preventive strategies, rehabilitation, and interventions for aging, injury recovery, and chronic disease.

Whole-Body Dixon Muscle MRI (Para2)

Why whole-body?

- Muscle diseases and systemic conditions (e.g., muscular dystrophies, myopathies, cachexia) often affect multiple regions and require a global view of muscle distribution.
- Whole-body imaging allows for regional comparison, asymmetry detection, and tracking systemic involvement (e.g., in neuromuscular disorders or chronic inflammation).
- This protocol is a starting point for whole-body, but can be optimized for region-specific imaging.

Current muscle imaging

- Dixon techniques provide rapid, quantitative separation of fat and water, enabling estimation of fat fraction and lean muscle volume.
- Dixon MRI is non-invasive, repeatable, and applicable across the lifespan.
- *DTI? But not including in our protocol so maybe not*

This protocol will support population-scale studies of muscle health across age, sex, and disease states. Our goal is to develop a generic acquisition protocol for whole-body quantitative MRI of muscle across the most common MR manufacturers to assess muscle morphometry and composition. This project was inspired by recent work in the spinal cord MRI field led by collaborator, Dr. Julien Cohen Adad. The spinal cord generic acquisition protocol publication was published in Nature Protocols, and the open-source companion dataset was published in Scientific Data.

Need for Standardized Protocol (Para3)

- Despite growing interest in muscle MRI for various applications, there is no widely adopted standardized protocol for whole-body imaging.
- Variability in acquisition parameters, scanner models, anatomical coverage, and image processing methods limits the ability to compare findings across studies, time points, vendors, or research sites
- This lack of harmonization is a barrier to the development of normative reference data and limits multi-center research efforts.
- Standardized Dixon-based muscle MRI protocols, paired with reproducible segmentation and quantification tools, are essential for obtaining consistent, high-quality data that can support population studies, clinical trials, and integration into routine care.

Development of the Protocol

Protocol Goals (Para1)

This document describes the conduction of a whole-body MRI exam developed for the open MuscleMap project.
The purpose is to acquire image data that allow potential segmentation of whole organs, whole bones, or, in particular, of whole muscles, to determine muscle volumes and enable biomechanical or morphological studies.
This protocol version aims to maximize the comfort of the examined person, who is positioned in supine position and can freely breathe throughout the examination, which should fit into a 1h scan slot.
Complete image acquisition involves 3 separate examinations with intermediate repositioning.

Metrics (Para2)

1) Morphometry: Muscle Size/ Volume/ CSA
    a) How to measure
    b) Changes associated with different diseases, aging, etc.

2) Composition: Intramuscular Fat/ Fat Fraction/ Lean Muscle Mass
    a) How to measure
    b) Changes associated with different diseases, aging, etc.

Considerations (Para3)

Ability to assess muscle size and intramuscular fat within individual muscles across the whole body

To enable accurate and clinically meaningful assessments, the protocol must allow quantification of both muscle size and intramuscular fat content at the level of individual muscles throughout the body. This granularity is important for capturing regional patterns of muscle involvement in systemic diseases, asymmetries in chronic pain or injury, and subtle changes with aging or intervention. This also allows for users to adapt and optimize the whole-body protocol for specific regional MRI, based on their chosen applications.

Use of vendor-supplied (product) Dixon sequences to improve generalizability and availability
Using vendor product sequences improves generalizability across scanners and institutions, simplifies multi-center deployment, and avoids the need for custom pulse programming or post-processing pipelines (which creates a barrier for widespread use). Ensuring broad availability and compatibility also helps with future integration into clinical workflows.

Patient Comfort, Safety, and Total Scan Time
Whole-body imaging can be physically demanding, especially for older adults or individuals with chronic conditions. Patient comfort is also a consideration in terms of motion artifacts and heating due to long scans. Therefore, the target is to keep total acquisition time within 60 minutes, optimizing anatomical coverage, spatial resolution, and image quality. For only the whole-body protocol, total scan time is <20 minutes; each of the higher resolution scans adds further scan time (neck ~4 minutes, ankle ~4 minutes, and arm ~12 minutes)

Proton-Density Fat Fraction / Contrast and Choice of TR and TE and Flip Angle
There is a need to optimize the contrast (depends on values of TR, TE and FA) for detecting proton density fat fraction (PDFF) while minimizing bias from T1 effects. There is a trade-off when using T1-weighted, 2-point Dixon sequences, as they will not reflect the true fat fraction, but they are more widely available and shorter than more complex, multi-Dixon sequences. In this paper, we also acquire 1) T1-weighted scans with lower flip angles (to make the contrast closer to PD-weighted) and 2) multi-point Dixon IDEAL scans (GE), to compare quantified fat fraction in a small subset of scan participants.

Use of Dual-Echo Versus Multi-Echo Sequence
While multi-echo Dixon sequences allow for more accurate and flexible fat quantification and correction for confounding factors like T2* decay, they may not be available on all platforms and typically require longer scan times. In contrast, dual-echo Dixon sequences are more widely available and can substantially reduce scan duration, making them a practical choice for large-scale or clinically integrated protocols. There are trade-offs between accuracy, availability, and efficiency, which have been considered when designing the protocol. In this paper, we also acquire multi-point Dixon IDEAL scans (GE), to compare quantified fat fraction in a small subset of scan participants.

3D versus 2D
Depending on sequence availability, 3D sequences are preferable since they offer higher SNR and contiguous coverage. While they typically require longer scan times and may be more sensitive to motion artifacts, we are able to achieve sub-2-minute scans per bed regardless.

Isotropic versus anisotropic voxels
Isotropic voxels support flexible reformatting and 3D analysis but typically require longer scan times, while anisotropic voxels can speed up acquisition and are often sufficient for axial muscle acquisitions.

Spatial Resolution
We need spatial resolution to be high enough to differentiate individual muscles but be balanced with scan time and SNR. For the overall whole body, we can get away with coarser resolution (1.6mm isotropic acquired);

however for anatomical regions such as the neck, ankles, and arms, which all have smaller muscles, we need a higher resolution scan (0.8mm isotropic acquired), which we perform separately.

Apodization

Apodization filters should be applied carefully to reduce Gibbs ringing without degrading edge definition critical for muscle segmentation. We decided to go with medium apodization while balancing with blurring artifacts. Gibbs ringing will not affect muscle volume, but fat fraction (due to signal artifacts).

Axial Slice Orientation

We utilized axial acquisitions, due to their alignment with natural cross-sectional anatomy of most major muscle groups, and the ability to visualize bilateral symmetry and ease of combining multi-bed acquisitions. Further, axial plane acquisitions are used for image segmentation using MuscleMap.

Phase-Encoding Directions

Attention must also be given to phase-encoding directions, especially in regions prone to motion or susceptibility artifacts (e.g., abdomen, shoulders). Where possible, phase encoding should be oriented to minimize distortion of muscular structures, and gradient nonlinearity corrections should be applied. Therefore, for the overall whole-body protocol, neck and ankles, the phase-encoding is in the A/P direction, while for the arms, it is in the A/P direction.

Free-Breathing versus Breath Hold

For protocol flexibility and patient comfort, free-breathing acquisitions are preferred over breath-holds, particularly for covering the thorax/ abdomen regions in a single pass. Free-breathing acquisitions reduce motion burden and are more suitable for patients with limited respiratory capacity.

Acquisition Order

Whole-body muscle MRI should be acquired in a head-to-toe direction. This approach minimizes the time-dependent effects of muscle deformation due to body position. When a subject lies supine, muscle shape and size, especially in the lower extremities, can change gradually over time due to fluid shifts and compression against the table. By imaging the lower body later in the scan, these changes may be more consistent across participants. Since we will also keep the timing consistent, these metrics should be comparable across subjects and vendors. [cite : https://pubmed.ncbi.nlm.nih.gov/8213193/]

Applications

MUSCLE:

Whole-body muscle MRI using Dixon techniques enables comprehensive assessment of muscle volume and fat infiltration across all major muscle groups in the body. This has broad research and clinical applications.

- In aging populations, it can help quantify sarcopenia and identify early markers of weakness/ fragility.
- In metabolic disease, such as obesity or type 2 diabetes, it allows investigation of regional muscle fat infiltration (myosteatosis) and its association with insulin resistance.
- It can also be used to monitor body composition changes during weight loss or treatment with GLP-1 receptor agonists.
- In neuromuscular disorders (inflammatory myopathies, Amyotrophic Lateral Sclerosis ALS, Duchenne’s, Spinal muscular atrophy SMA), it enables tracking of disease progression and treatment response.

- Whole-body muscle imaging is also increasingly relevant in chronic pain research, where muscle degeneration, asymmetry, or altered composition may contribute to pain and disability.
- It also supports research on injury recovery, athletic performance, and muscle adaptation in response to training or disuse.
- Clinically, it can help inform personalized rehabilitation strategies, surgical planning, and monitoring of systemic muscle-wasting conditions such as cancer cachexia or chronic inflammatory diseases.

NON-MUSCLE:
Given that we are imaging the whole-body, there are many non-muscle applications, especially in areas of inflammation and cancer:
1) CANCER: bone metastases, hematological abnormalities/ cancers affecting bone such as leukemia, lymphoma, and myeloma, monitor tumor response and off-target effects
2) INFLAMMATION: Axial Arthritic Disease, Rheumatoid arthritis
3) JUVENILE DISORDERS: Osteomyelitis and SAPHO syndrome, (fast whole-body MRI is way safer for children than DCE/ PET/ CT/ Xray, especially if they get frequent scans)
4) OSTEOPOROSIS: recent research showing changes in fat fraction/ adiposity of bones- vertebrae, femoral head and neck- are linked to porosity changes and indicative of degraded bone quality

Comparison with Other Methods

Discuss strengths and weaknesses of conventional T1 and T2 weighted non-Dixon MRI, CT, ultrasound, and impedance-based muscle and fat measures

Experimental Design

Overview of Sequences: Dixon MRI Across Vendors

1) GE
    a) Liver Volume Accelerated Flex Acquisition (LAVA Flex)
    - Type of sequence
    - Origin/ features

    b) IDEAL

2) Siemens:
    a) Volumetric Interpolated Breath-hold Examination (VIBE) DIXON

3) Philips: modified DIXON (mDIXON)

[cite: The next generation fat-free imaging]

Whole-Body Head to Toe Sequence Parameters

GE	Siemens	Philips

Parameter Name	Value	Parameter Name		Value	Parameter Name	Value
Sequence Family	Gradient Echo					
Pulse	LAVA	Sequence		3D FLASH / VIBE		
Imaging Option	ARC, Flex	Acceleration Mode		GRAPPA		
EDR	*On*			N / A		
ARC	*On*			N / A		
Fast	*On*			N / A		
Flex	*On*			N / A		
Scan Plane	Axial	Orientation		Transversal		Axial
Frequency (A/P) FOV	48.0 cm	Frequency (A/P) FOV		410 mm		
Phase (R/L) FOV	1.0	Phase (R/L) FOV		121.9 %		
No Phase Wrap	1.00	Phase Oversampling		35 %		
Slice Thickness	0.80	Slice Thickness		0.8 mm		
No Slab Wrap	1.0	Slice Oversampling		23. 1 %		
Frequency Direction	A/P					
		Phase Encoding Dir.		R >> L		
TR	3.9	TR		3.68 ms		
# Slabs	1	# Slabs		1		
Slices per Slab	416	Slices per Slab		416		
# of TES(s) per scan	2	Contrasts		2		
		Fat-Water Contrast		Dixon		
		Reconstruction		Magnitude		
TE	Minimum	TE1		1.23 ms		
TE2	2.2	TE2		2.46 ms		
Flip Angle	8.0	Flip Angle		8 deg		
		3D Reordering		Standard		
		Raw Filter		Off		
		Elliptical Filter		On		
		Distortion Correction		3D		
Intensity Correction	PURE	Normalize		Prescan		
Calibration In Prescan	On					

Intensity Filter	None					
		Image Filter		Off		
Frequency	300	Base Resolution		256		
Phase	300	Phase Resolution		100%		
Slice Resolution	50.00 %	Slice Resolution		50 %		
		Interpolation		On		
NEX	1.00	Averages		1		
Bandwidth	+/- 166.67 kHz	Bandwidth/Pixel		1300 Hz/Px		
Excitation Mode	Selective	Excitation		Slab-sel.		
Shim	Auto	B0 Shim		Standard		
		B1 Shim		TrueForm		
RF Drive Mode	Preset					
Total Factor		2				
		Reference Scans		Integrated		
Acceleration Phase	2	Acceleration Factor PE		2		
		Reference Lines PE		24		
Acceleration Slice	1	Acceleration Factor 3D		1		
		Phase Partial Fourier		Off		
		Slice Partial Fourier		Off		
		Asymmetric Echo		Off		
		Elliptical Scanning		On		
		Sequence Name		fl		
		Dimension		3D		
		RF Pulse Type		Fast		
		Readout Mode		Bipolar		
		Optimization		Opp/In		
		Gradient Mode		Fast		
		RF Spoiling		On		
		Breast Application		Off		
		Phase Enc. Order		Lines in Slices		

		Incr. Gradient Spoiling		On		
		Set-n-Go Protocol		On / 7 steps		
		(Table) Position		L0.0 mm A80.0 mm St 1: F1801.2 mm St 2: F1542.4 mm St 3: F1283.6 mm St 4: F1024.8 mm St 5: F766.0 mm St 6: F507.2 mm St 7:F248.4 mm		
Coil(s)	Head/Neck Spine (table) 2 Body Arrays	Coil(s)		Head/Neck Spine (table) 2 Body Arrays Peripheral Angio		
Effective Resolution	1.6 mm ✕ 1.6 mm ✕ 1.6 mm	Encoded Resolution		1.6 mm ✕ 1.6 mm ✕ 1.6 mm		
Interpolated Resolution	0.8 mm ✕ 0.8 mm ✕ 0.8 mm	Interpolated Resolution		0.8 mm ✕ 0.8 mm ✕ 0.8 mm		
Acquisition Time	1:28/bed	Acquisition Time		2:49 / step		
Number of beds	7	Number of beds		7		

Neck, Upper Limb, and Feet Sequence Parameters

Higher resolution as compared to whole-body to allow for better imaging of small muscles

GE		Siemens		Philips	
Sequence Family	Gradient Echo				
Pulse	LAVA				
Imaging Option	ARC, Flex				
EDR	*On*				
ARC	*On*				
Fast	*On*				
Flex	*On*				
Scan Plane	Axial		Axial		Axial
Frequency FOV (cm)	?				
Phase FOV	?				
No Phase Wrap	1.00				
Slice Thickness	0.80				
No Slab Wrap	1.0				
Frequency Direction	R/L or A/P We used A/P				

TR	3.9				
# Slabs	1				
Slices per Slab	416				
# of TES(s) per scan	2				
TE	Minimum				
TE2	2.2				
Flip Angle	8.0				
Intensity Correction	PURE				
Calibration In Prescan	On				
Intensity Filter	None				
Frequency	340				
Phase	340				
Slice Resolution	50.00				
NEX (Averages)	1.00				
Bandwidth	166.67				
Excitation Mode	Selective				
Shim	Auto				
RF Drive Mode	Preset				
Acceleration Phase	2				
Acceleration Slice	1				
Coil(s)	Neck- Head/Neck & Body Array Arm, Ankle- Body Array				
Effective Resolution	0.8 mm ✕ 0.8 mm ✕ 1.6 mm				
Interpolated Resolution					
Acquisition Time	1:28/bed				

Hardware

Choice of coils based on availability

Example: Signal comparison between 2 Blanket arrays vs 2 Rigid coils for GE

Shimming

Bore Size Considerations

Other Field Strengths

Optimization for Other Body Regions or Muscles of Interest

Future Directions

Heterogenous Open Source Companion Dataset
Through collaborations across vendors and sites, we have generated a large, open-source standardized whole-body musculoskeletal MRI dataset across the lifespan with diverse representation by sex, gender, race, and ethnicity, enabled through crowdsourced datasets from our global network of musculoskeletal researchers. This dataset will serve as a valuable resource for benchmarking, algorithm development, and validation across institutions.

Automated Open Source Muscle and Bone Segmentation Tools
In parallel to developing a standardized whole-body MRI protocol, we have developed and continue to improve an automated, open-source segmentation tool, MuscleMap (https://github.com/MuscleMap), for segmentation of muscles and bones. This toolbox enables fast and standardized quantification of muscle metrics at scale.
Normative Modeling
Using these tools, we can create normative models that define healthy ranges for muscle size and composition across the lifespan, which can be used as a reference for early disease detection, performance benchmarking, and personalized clinical decision-making.

Techniques for Faster, Better Imaging
With continued innovations in the field of whole-body MRI, such as AI-based image reconstruction, motion artifact removal, and denoising, and compressed sensing, we can continue to make whole-body MRI faster and better in terms of image quality, making it more feasible for both research and clinical use.

Materials

Manufacturers and Protocol Leads

- General Electric (Ananya Goyal, Stanford University, agoyal5@stanford.edu)
- Siemens (Daniel Nanz, Balgrist, daniel.nanz@balgristcampus.ch)
- Philips (Site, First Name Last Name, email)

Equipment

- MRI scanner: a whole-body GE, Siemens, or Philips 3T MRI scanner

This whole-body Dixon MRI protocol is performed in three sections: 1) Head to Toe Whole Body, 2) High Resolution Neck Scan, and 2) High Resolution Left Arm and Left Ankle (or Right Arm and Right Ankle).

The protocol is unusual in that – in all 3 scans – it is to always image the same volume over the system's patient table in relation to the table's home position. After landmarking and table-advancing into the magnet, no scan-region planning by the operator is required. The operator starts all scans exactly as they are already planned – ideally without opening the corresponding series in the graphical user interface. This was set up in an attempt to standardize data acquisition and maximize reproducibility.
All 3 examinations acquire a series of overlapping, axial (transverse) oriented 3D volumes that are automatically combined after acquisition of all 7 (head-to-toe scan) or 3 (left and right arm) or 1 (neck and ankle) scanning stations.
In the case of the head-to-toe scan, virtually the whole bore volume is scanned – irrespective of specifics of the participant's body geometry. For the separate scans of the left and right arm, the imaged volume is correspondingly smaller.
In all 3 examinations, the main acquisition is a multi-station 3D gradient-echo 2-point Dixon acquisition, that generates 4-5 image series at each station (water-only, fat-only, in-phase, opposed-phase, and for some scanners, fat-fraction images) and that will attempt to combine image series of each type into a corresponding series that maps the full imaged volume.

Procedure

Equipment setup - Timing: 2 min

Head to Toe

Participant Positioning and Immobilization

<u>Position</u>: Supine Head First
Support the participant's elbows with soft pads.
Protect their ears- ear plugs and headphones. Usually it is feasible to fit headphones into the 20-channel head-neck array. Help stabilize the head with pads/ cushions. Ideally, the examined person would not move at all during the whole duration of the step-wise multi-station acquisition.
The body is positioned at the center of the scanner bed from head to toes without any coronal tilt.
No pads under legs - except support provided by a dedicated coil, e.g., peripheral angiography coil.
Hands supinated at sides with weights. Have thumbs pointing outward.
Make sure the emergency squeeze ball is within reach.
Participants have also experienced heating during the whole-body scans, which may be mitigated by switching on the internal bore fans.
Pads between patient and scanner bore.

Equipment Preparation

Coils

. Head-Neck Array (e.g., 20 or 64 channel)
. Body-Array 1 (e.g., 18 or 32 channel)
. Body-Array 2 (e.g., 18 or 32 channel)
. (Spine integrated in table) (32 channel)
. Peripheral angio (36 channel)- optional (for GE, we did not use this).

Coil Placement

GE placement diagrams:

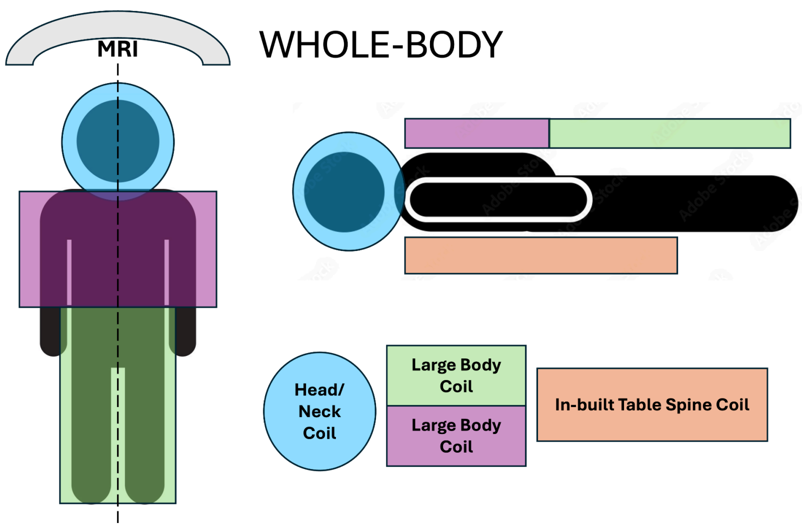


Table. Exemplary outlines of coils that can be used for each of the 7 beds for the whole-body and specific neck scans.

Coil	**GE**	**Siemens**	**Philips**
Whole Body- Head to Toe			
Head	Head-Neck Array, Spine integrated in table	Head-Neck Array	
Neck	Head-Neck Array, Spine integrated in table, Body-Array 1	Head-Neck Array, Spine integrated in table, Body-Array 1	
Chest	Spine integrated in table, Body-Array 1	Spine integrated in table, Body-Array 1	
Abdomen	Spine integrated in table, Body-Array 1	Spine integrated in table, Body-Array 2	
Pelvis	Spine integrated in table, Body-Array 1 (maybe, depends on sub height),	Body-Array 2 Peripheral angiography	

	Body-Array 2		
Thighs	Body-Array 2	Peripheral angiography	
Shin	Body-Array 2	Peripheral angiography	

Landmark

Bring the patient table into the home position, i.e., up at full height and as far out of the bore as possible. Switch on the positioning laser in this position, without advancing the table towards the magnet. Press the large round button (symbol) until the laser light is switched off and the table advances into the scan position. Landmark at the forehead or top of head. This technically doesn't matter since the multi-bedlocalizer and scan protocol will go through the whole bore volume.

Participant Communication

Inform them that the table will move autonomously, first quite a long way towards, into, and through the magnet, followed by step-wise movements, interleaved with acquisitions, out of the bore.
In some positions with the head being outside the magnet on the back side, the examined person will be exposed to cold air from the ventilation system. The protocol is set up to minimize the likelihood of the examined person to experience muscle twitching that could be triggered by a rapid switching of magnetic field-gradient strength. Instruct them to relax as far as possible and to breathe normally.

Localizer

5-station whole body localizer with automatic stitching. Details in Supplementary

Image Acquisition

See Protocol Design, Section 2.

Neck

Participant Positioning and Immobilization

The participant positioning remains the same- the participant doesn't move as we change the coils/ coil placement. We have two options here: 1) move the previously used Body-Array 1 for the Whole-Body protocol to cover more of the neck instead of the abdomen, or 2) replace Body-Array 1 with a smaller coil to fit the neck area and curve around.

Equipment Preparation

Coils

. Head-Neck Array (e.g., 20 or 64 channel)
. Body-Array 1 (e.g., 18 or 32 channel)
. (Spine integrated in table) (32 channel)

Coil Placement

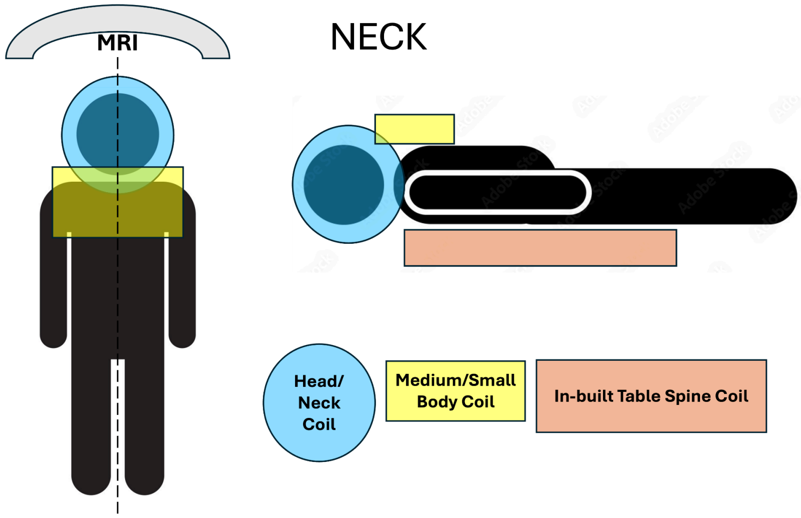


Table. Outlines which coils are used for each of the 7 beds for the whole-body and specific neck scans.

Coil	**GE**	**Siemens**	**Philips**
Higher-resolution Neck Scans			
Neck	Head-Neck Array, Spine integrated in table, Body-Array		

Landmarking

The participant positioning remains the same- the participant doesn't move , so we do not need to do any new landmarks.

Participant Communication

Same as before. But, this time the scan is much shorter (<5 minutes).

Localizer

A 2-station localizer (the first two stations from the multi-station localizer) can be run if needed/ if the participant has moved. This will ensure coverage from head to shoulder.

Image Acquisition

See Protocol Design, Section 3.

Upper Limb

Participant Positioning and Immobilization

Position the shoulder coil as close to the bore midline as possible- the subject’s arm will also be at the center of the bore line. Further, without the head coil determining the start location, move the pillow/ head further up, to get a bigger coverage of the ankles.
Support the participant's elbows with soft pads. Protect their ears. The examined person should not move the examined arm, including the hand during the whole duration of the step-wise multi-station acquisition. Even for people with extensive MRI experience that is not a very common requirement.

Equipment Preparation

Coils

. Shoulder Large or Small (e.g., 16 channel) OR Body-Array (e.g., 18 or 32 channel)
. Spine integrated in table (32 channel) - Maybe, depending on arm length

Coil Placement

If using both shoulder and body coil: Place the upper end of the upper body-array coil 1 directly under the examined volunteer's chin so that it also covers the shoulder coil.
If using only the flexible body coil: wrap it around the shoulder at an angle to also get coverage of the hand.

Have example figures for GE, Siemens, and Philips

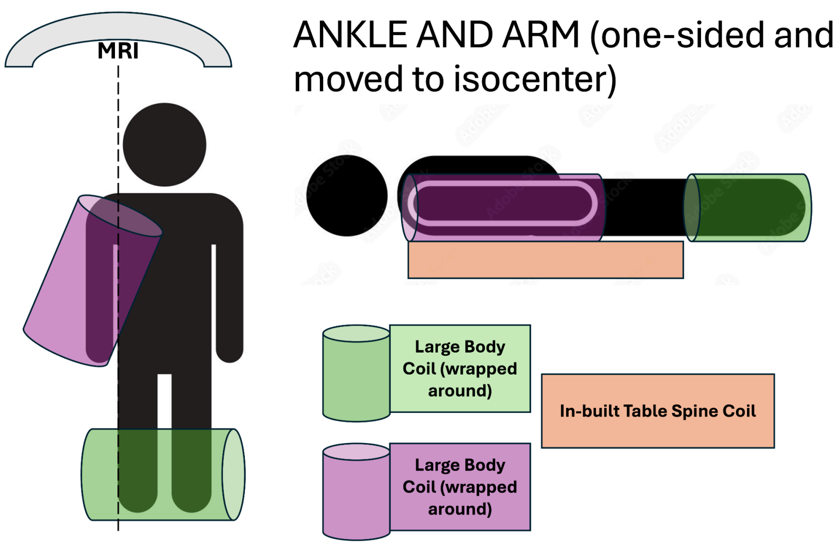


Table. Outlines which coils are used for each of the 7 beds for the whole-body and specific neck scans.

Coil	**GE**	**Siemens**	**Philips**
Higher-resolution Arm and Ankle Scans			
Arm	Body-Array 1		

Ankles	Body-Array 2		

Landmarking

Bring the patient table into the home position, i.e., up at full height and as far out of the bore as possible. Switch on the positioning laser in this position, without advancing the table towards the magnet. Press the large round button (symbol) until the laser light is switched off and the table advances into the scan position. Can landmark at the top of the head again.

Participant Communication

Inform them that the table will move autonomously, first quite a long way towards, into, and through the magnet, followed by step-wise movements, interleaved with acquisitions, out of the bore. In some positions with the head being outside the magnet on the back side, the examined person will be exposed to cold air from the ventilation system. The protocol is set up to minimize the likelihood of the examined person to experience muscle twitching that could be triggered by a rapid switching of magnetic field-gradient strength. Instruct them to relax as far as possible and to breathe normally.

Localizer

5-station whole body localizer with automatic stitching (same as whole-body, useful for both arm and ankle acquired together). Details in Supplementary

Image Acquisition

See Protocol Design, Section 3.

Feet

Participant Positioning and Immobilization

Same as before. Both the arm and corresponding ankle will be aligned with the center of the MRI bore.

Equipment Preparation

Coils

. Body-Array 1 (e.g., 18 or 32 channel) OR Shoulder Large or Small (e.g., 16 channel)
. Body-Array 2 (e.g., 18 or 32 channel)
. Spine integrated in table (32 channel)

Coil Placement

If using only the flexible body coil: wrap it around the ankle(s) based on the size of the coil.

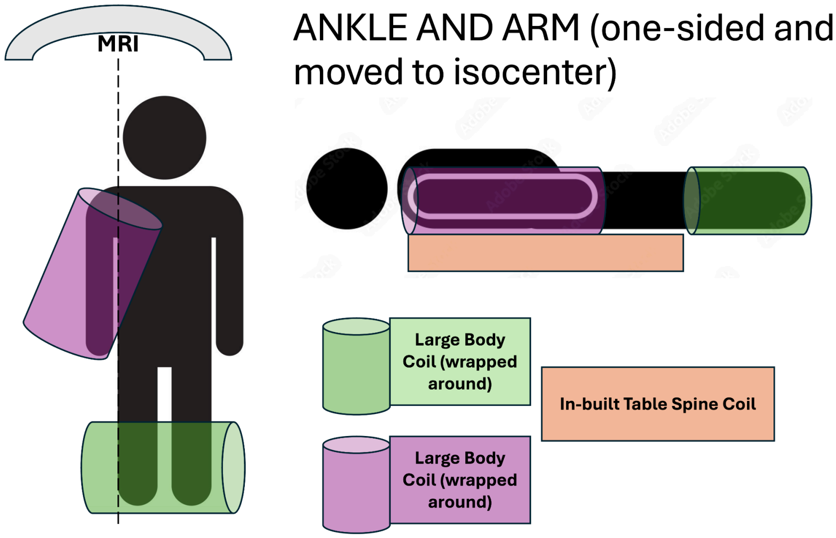


Table. Outlines which coils are used for each of the 7 beds for the whole-body and specific neck scans.

Coil	**GE**	**Siemens**	**Philips**
Higher-resolution Arm and Ankle Scans			
Arm	Body-Array 1		
Ankles	Body-Array 2		

Landmarking

Same landmark as the arm scan- we do not need to move the patient.

Participant Communication

Same as the arm scan- the subject needs to stay still in order to avoid motion artifacts and consequent issues with automatic stitching of multi-bed images.

Localizer

Use the same localizer as the arm (5-bed for whole-body).

Image Acquisition

See Protocol Design, Section 3.

Troubleshooting

Maintaining Participant Comfort

The whole-body protocol is 15 minutes long, with higher resolution scans for other anatomies adding more time, which can help with participant comfort. Some people have reported overheating and sweating- make sure to switch the bore fans on. Keep in communication with participants throughout the scan. If participants are warm, limit blanket usage. You can also allow for short breaks between body regions.

Tall Participants

We may need to adjust the number of slices and FOV for taller participants.
Separate Ankle Scans will be needed since not feasible to do whole-body (scan table limitations)- also can move the participants to go in the foot direction first for lower-body scans.

Large Wide/Obese Participants

FOV will need to be adjusted for wider participants, but these depend on scanner limitations. More care needs to be taken into consideration, especially when accounting for aliasing/ wrap-around artifacts.

Small Participants/Children

For smaller/ shorter participants, including children, less beds can be used.

Imaging Around Metal?

Other Special Populations?

Breathing Artifacts

If the abdomen and thorax scans show extreme breathing motion artifacts, you can instruct participants to use shallow breathing. One can also consider scanning with breath hold or respiratory gating (but this will depend on the purpose and quality of images). Apodization?

Fat-Water Swap Artifacts

A significant number (≈ 10% in our experience) of Dixon fat-water images have a fat-water swapping artifact due to a computational error in areas of field inhomogeneity where the signal is incorrectly assigned to fat or water. We will want to reduce the presence of this artifact. Discuss options to fix fat-water swap artifact. Repeat scan (time feasible) or post-processing. Would SatPad help? Would voluming shimming help?

Minimizing Distortion

Minimizing Muscle Twitching

Issues with Stitching Postprocessing

If it is not feasible to automatically stitch images together on the scanner, there are off-scanner tools available, such as XX. Further, it is important to have 10-20% overlap between beds to ensure the most accurate stitching.

Hardware Limitations

Don’t have a bunch of flex coils, can use one but move it between scans. Optimize the protocol based on individual coil availability and scanner coil channel limitations.

Offline Image Reconstruction

In case it is not feasible to reconstruct the fat/water images on the scanner automatically, here are some ways of robustly doing the reconstruction from individual TE images:

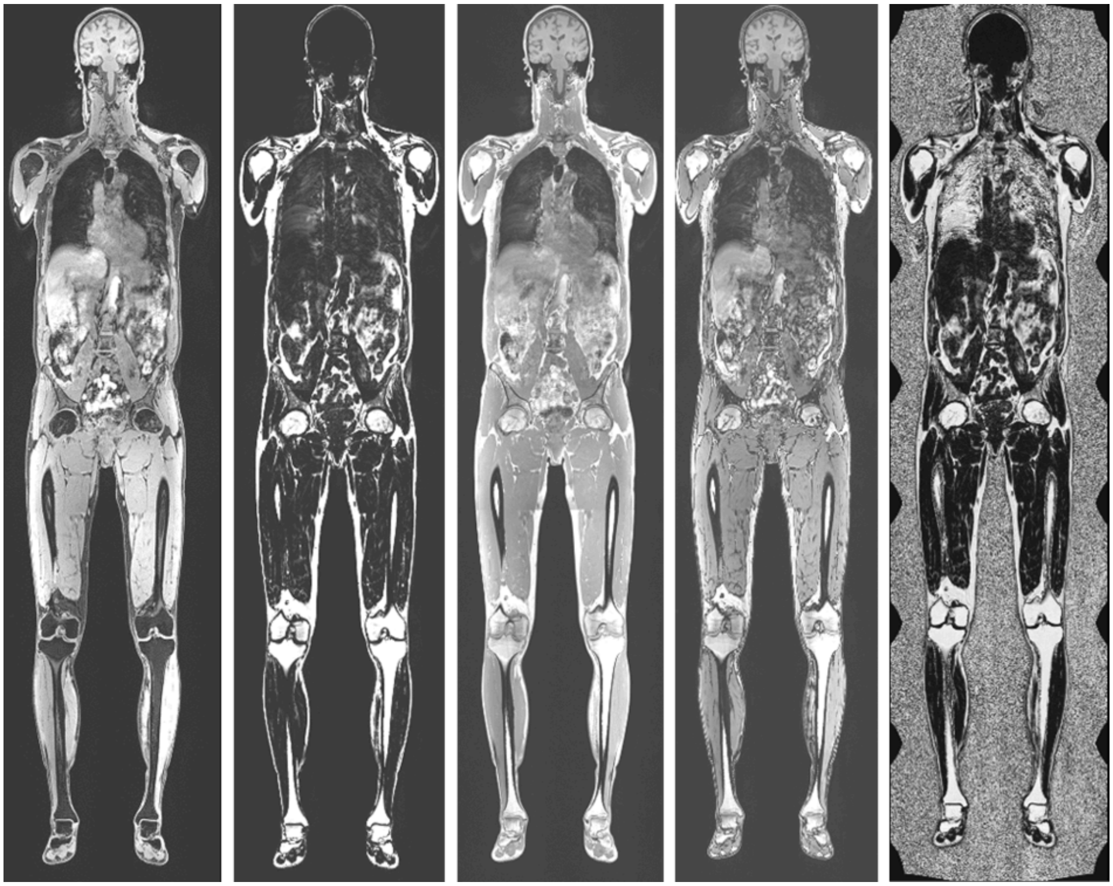
- QMRI Tools

Anticipated Results

In this section, we show examples of good-quality scans for each of the specified protocols for each scanner. Additional examples of good-quality data with interactive 3D visualization/ muscle segmentations are shown in the XXX website (xxx).

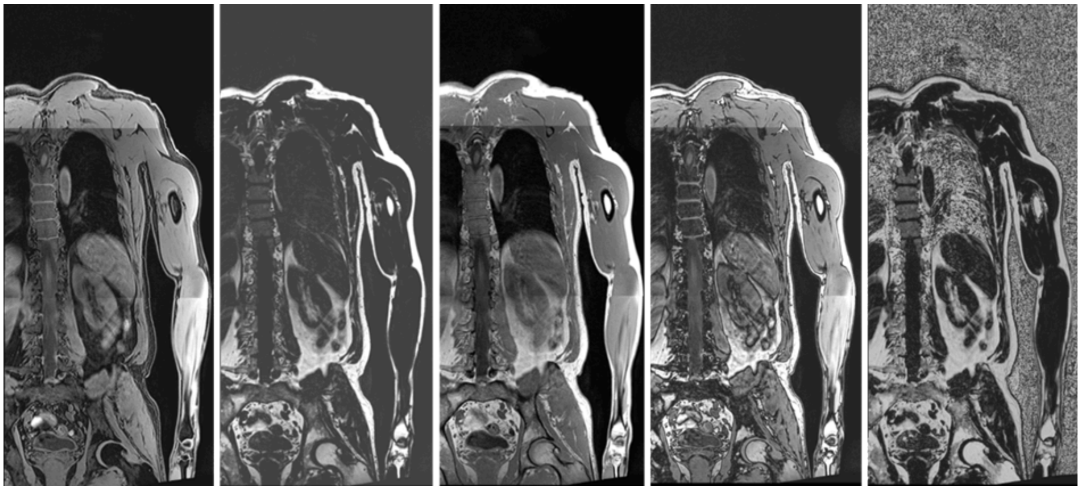
Good Quality Head to Toe Images

Figure ## illustrates good-quality whole-body Dixon MRIs for all three manufacturers. Panel A: GE, Panel B: Siemens, Panel C: Philips. Images are acquired in the axial plane, combined together in one series, and reformatted in the sagittal and coronal planes.



Good Quality Neck Images

Good Quality Upper Limb Images



Good Quality Foot Images

References

1. Lecouvet F. E. (2016). Whole-Body MR Imaging: Musculoskeletal Applications. Radiology, 279(2), 345–365. https://doi.org/10.1148/radiol.2016142084
2.

Supplementary Materials

Supplement 1: Open-Source Companion Dataset

Inclusion Criteria

Males and Females
20 to 79 years old

Exclusion Criteria

PLACEHOLDER

We will ask collaborators to try to recruit a diverse sample from their site (i.e., not all young college students). Goal is to get 3M, 3F: 2M/2F with exactly reproduced (to your best abilities) , and then 1M/1F with different FA (3-6 degrees), to have heterogenous sample.

Descriptors

Age
Sex
Height (cm)
Weight (kg)
Ethnic and Racial Background

Ethics

Each site contributing data will ensure that data were collected in compliance with their local institutional review board and that the participants provided written informed consent and the de-identified datasets are allowed to be shared with external collaborators.

Supplement 2: Body Regions and Muscles of Interest

Notes: *Identifying the body regions and muscles of interest will help us to determine the imaging parameters such as field of viewls and spatial resolution for the generic acquisition protocol. At this time, <u>we are not developing</u> a protocol with sufficient resolution and contrast for all muscles in the body. We will need to choose those muscles that we can confidently segment with the current imaging capabilities and that we feel are the most clinically important. We will need to keep the length of the acquisition reasonable and determine the appropriate trade-off between image quality and acquisition time. If muscles should be grouped together, please list them on the same bullet point.*

- Neck
    - Multifidus/Semispinalis Cervicis

    - Semispinalis Capitis
    - Longus Capitis/Longus Colli
    - Sternocleidomastoid
    - Levator Scapula
    - Trapezius
    - Splenius Capitis
- Shoulder
    - Supraspinatus
    - Infraspinatus
    - Subscapularis
    - Teres Minor
    - Teres Major
    - Deltoid
    - Levator Scapula
- Arm
    - Biceps Brachii (Long Head and Short Head)
    - Triceps Brachii (Lateral Head, Long Head, and Medial Head)
    - Brachialis
    - Brachioradialis
- Forearm
    - Flexor Digitorum Superficialis/Flexor Digitorum Profundus/Flexor Carpi Ulnaris/ Palmaris Longus/Flexor Carpi Radialis/Flexor Pollicis Longus
    - Extensor Digitorum/Extensor Carpi Radialis Longus/Extensor Carpi Radialis Brevis/Extensor Carpi Ulnaris/Extensor Pollicis Longus/Abductor Pollicis Longus
- Hand
- Thorax
    - Erector Spinae
    - Multifidus
    - Psoas Major
- Abdomen
    - Erector Spinae
    - Multifidus
    - Psoas Major
    - Quadratus Lumborum
    - Rectus Abdominis
- Pelvis
    - Gluteus minimus
    - Gluteus medius
    - Gluteus maximus
    - Tensor fasciae latae
    - Pelvic Floor
        - Levator Ani
        - Obturator Internus
- Thigh
    - Rectus Femoris/Vastus Medialis/Vastus Lateralis/Vastus Intermedius
    - Adductor Brevis/Adductor Magnus/Adductor Longus
    - Biceps Femoris/Semitendinosus/Semimembranosus
    - Sartorius

    - Gracilis
- Leg
    - Tibialis Anterior/Extensor Digitorum Longus
    - Peroneous Longus/Peroneus Brevis
    - Tibialis Posterior (include popliteus?)
    - Flexor Hallucis Longus
    - Soleus
    - Gastrocnemius (Medial and Lateral Heads)
- Foot

Supplement 3: Multi-bed Localizer Scan Parameters