An anthropomorphic pelvis phantom for MR-guided prostate interventions

Dominik F. Bauer¹ | Anne Adlung¹ | Irène Brumer¹ | Alena-Kathrin Golla¹ | Tom Russ¹ | Eva Oelschlegel¹ | Fabian Tollens² | Sven Clausen³ | Philipp Aumüller³ | Lothar R. Schad¹ | Dominik Nörenberg² | Frank G. Zöllner¹

¹Computer Assisted Clinical Medicine, Medical Faculty Mannheim, Mannheim Institute for Intelligent Systems in Medicine, Heidelberg University, Mannheim, Germany
²Department of Radiology and Nuclear Medicine, University Medical Center Mannheim, Heidelberg University, Mannheim, Germany
³Department of Radiation Oncology, University Medical Center Mannheim, Heidelberg University, Mannheim, Germany

Correspondence
Dominik F. Bauer, Computer Assisted Clinical Medicine, Medical Faculty Mannheim, Heidelberg University, Theodor-Kutzer-Ufer 1-3, Mannheim 68167, Germany.
Email: Dominik.Bauer@medma.uni-heidelberg.de

Funding information
Bundesministerium für Bildung und Forschung, Grant/Award Number: 13GW0388A and 13GW0389C

Purpose: To design and manufacture a pelvis phantom for magnetic resonance (MR)-guided prostate interventions, such as MRGB (MR-guided biopsy) or brachytherapy seed placement.

Methods: The phantom was designed to mimic the human pelvis incorporating bones, bladder, prostate with four lesions, urethra, arteries, veins, and six lymph nodes embedded in ballistic gelatin. A hollow rectum enables transrectal access to the prostate. To demonstrate the feasibility of the phantom for minimal invasive MRI-guided interventions, a targeted inbore MRGB was performed. The needle probe was rectally inserted and guided using an MRI-compatible remote controlled manipulator (RCM).

Results: The presented pelvis phantom has realistic imaging properties for MR imaging (MRI), computed tomography (CT) and ultrasound (US). In the targeted inbore MRGB, a prostate lesion was successfully hit with an accuracy of 3.5 mm. The experiment demonstrates that the limited size of the rectum represents a realistic impairment for needle placements.

Conclusion: The phantom provides a valuable platform for evaluating the performance of MRGB systems. Interventionalists can use the phantom to learn how to deal with challenging situations, without risking harm to patients.

KEYWORDS
pelvis, phantom, prostate, interventions, multimodal

INTRODUCTION

Prostate cancer is the second most common cancer in men and comprises highly aggressive and indolent varieties.¹ Multiparametric magnetic resonance imaging (mpMRI) is of high value for the detection and characterization of prostate cancer and reduces both overdiagnosis and overtreatment of indolent disease.²⁻⁴ Moreover, mpMRI can
be applied for prostate cancer management and therapy planning to localize index lesions.\textsuperscript{5,6} Accurate localization of the index lesion via mpMRI enables targeted MR-guided biopsy (MRGB) and allows for optimized radiation dose planning for brachytherapy.\textsuperscript{7,8}

Compared with traditional transrectal ultrasound (TRUS)-biopsy, which involves a random sampling of the prostate,\textsuperscript{9} mpMRI combined with targeted MRGB results in significantly fewer clinically insignificant prostate cancer (insignPCa) cases while maintaining an identical detection rate of clinically significant prostate cancer (csPCa).\textsuperscript{10} The improved disease localization of mpMRI additionally enables focal therapies for intermediate-risk prostate cancer, providing an alternative to radical treatment. This reduces overtreatment and associated permanent side effects and is an important step toward personalized medicine.\textsuperscript{11} Examples for minimal invasive focal therapies are cryoablation,\textsuperscript{12} focal laser ablation (FLA),\textsuperscript{13} transurethral ultrasound ablation (TULSA),\textsuperscript{14} high-intensity focused ultrasound (HIFU),\textsuperscript{15} irreversible electroporation (IRE),\textsuperscript{16} and brachytherapy.\textsuperscript{3}

These minimal invasive therapies often benefit from new technologies, such as robotic needle guidance, which supports inbore MRI interventions. Robotic navigation systems improve the precision of needle placements and reduce intervention time.\textsuperscript{17,18} Another advantage of robots is that the needle probe can be remotely controlled from the MRI control room with real-time MR guidance.\textsuperscript{19} Preliminary validation using imaging phantoms is a vital step for the introduction of such technologies into the clinical routine. Numerous prostate phantoms have been developed for different imaging modalities. However, these are either not embedded in a realistic model of the pelvis or are not puncturable and thus not suitable for needle interventions. Additionally, the design and development of multimodal phantoms incorporating lesions is not trivial and none of the mentioned phantoms include prostate lesions. To the best of our knowledge, only the Tissue Equivalent Ultrasound Prostate Phantom (CIRS Model 053L, CIRS Inc., Norfolk, USA)—a commercially available prostate phantom—features puncturable prostate lesions and is suitable for CT, MR, and US imaging. It also includes the urethra, the rectal wall and seminal vesicles, but no bones. The phantom is disposable and must be stored in an air-tight container to minimize desiccation. The organs are embedded in a small and lightweight box with dimensions of $11.5 \times 7 \times 9.5$ cm$^3$ and weight of approximately 900 g. However, realistic body shape and size are critical to the development of imaging protocols, and sufficient weight is required to simulate patient placement and prevent the phantom from moving during robotic needle placement.\textsuperscript{28} Nevertheless, the CIRS phantom is an appropriate phantom when realistic patient size, shape and weight are not relevant to the measurement.

In this work, we present an anthropomorphic pelvis phantom for transperineal and transrectal prostate interventions. The phantom is puncturable and the prostate and the contained four lesions are accessible through a hollow rectum. The size and shape is similar to that of a male pelvis and realistic contrast is provided in MR, CT, and US imaging. Thus, the phantom can be used for the validation of workflows in a variety of minimal invasive interventions, such as TRUS, IRE, brachytherapy seed placement, or MRGB. We used the phantom to perform an inbore MRGB with assistance of an MR-compatible remote-controlled manipulator (RCM) where we targeted a prostate lesion. The phantom does not require specific storage and is reusable even after puncturing multiple times, as the needle insertion channels can be largely removed by heating the phantom material. Furthermore, the manufacturing process allows for the creation of patient-specific phantoms.

2 \hfill METHODS

2.1 \hfill Phantom design

The phantom was designed to mimic the human pelvis incorporating bones, bladder, prostate with four lesions, urethra, arteries, veins, and six lymph nodes embedded in ballistic gelatin.\textsuperscript{29} A CAD model of the phantom is displayed in Figure 1A and the manufactured phantom is shown in Figure 1C. Except for the bladder and prostate, all organ models were obtained from segmentation of the digital XCAT phantom,\textsuperscript{30} which provides realistic human anatomies. Because prostate cancer incidence is strongly correlated with age,\textsuperscript{31} a 62-year-old male model was used. The prostate and bladder models were created by rotating 2D prostate and bladder silhouettes. The prostate has an enlarged volume of 95 ml, because older age is associated with prostate enlargement.\textsuperscript{32}

We used synthetic ballistic gelatin (10% ballistic gelatin, Clear Ballistics, Greenville, USA) as a tissue surrogate. Ballistic gelatin liquefies at 110°C and therefore can be poured into the desired shape, which it retains after cooling down. The other phantom components and the body mold must be heat-resistant, as they come into contact with the molten ballistic gelatin.

2.2 \hfill Phantom construction

In order to cast the ballistic gelatin into the shape of a pelvis, a body hull casting mold made of heat-resistant synthetic resin (High Temp Resin V2, Formlabs, Somerville, USA) was manufactured using the stereolithography (SLA) 3D printing method. The body hull casting mold
consists of 16 individual parts. This facilitated the removal of the hull after casting without damaging it. The hull shown in Figure 1D was firmly assembled with screws and sealed with high-temperature silicone. The bottom of the mold was closed with an extruded acrylic plate and sealed with high-temperature silicone. The base plate was removed after casting. Using heat-resistant adhesive, all organs were first glued together as shown in Figure 1B and then glued on the inside of the base plate. A rectum was printed with the same material as the body hull and glued to the inside of the hull. The rectum was removed after casting, leaving behind a hollow transrectal access to the prostate. The complete pelvis was not cast in one step, but in several layers, which allows the removal of air bubbles from the intermediate layers.

The bones were 3D printed via selective laser sintering (SLS) using polyamide powder filled with glass particles (PA-GF, Materialise, Leuven, Belgium). The material has excellent stiffness, high thermal resistance and tensile strength. The inside of the bones was printed less densely to simulate bone marrow. The artery and vein were printed with red and blue high impact polystyrene (EasyFil HIPS, Formfutura, Nijmegen, The Netherlands) via Fused Filament Fabrication (FFF). The urethra was printed with synthetic resin (White Resin V4, Formlabs, Somerville, USA) via SLA.

The prostate and bladder molds displayed in Figure 1E and F were printed with polylactic acid (PLA) via FFF. The bladder and prostate were molded with silicones of Shore A hardness 0 and 5, respectively. The bladder mold was coated with a silicone of Shore A hardness 13 (SF13–RTV2, Silikonfabrik, Ahrensburg, Germany) to obtain a slightly harder bladder wall. The prostate lesions and lymph nodes were also molded with the Shore A 13 silicone. Silicone color was used to color the bladder, prostate, prostate lesions, and lymph nodes with yellow, red, green, and blue, respectively. The diameter of the spherical prostate lesions is 1.2 and 1.5–2 cm for the lymph nodes.

2.3 | Multimodal imaging

T1-weighted (T1w), T2-weighted (T2w), and diffusion weighted (DWI) MRI at 3 T and CT scans of the phantom were acquired and parametric T1-, T2-, and ADC-maps were calculated. Furthermore, field inhomogeneities were characterized by calculating a $B_0$-map from a double-echo gradient echo sequence.33 The scanning parameters of the CT and MRI measurements are summarized in Table 1. The T1- and T2-times, and the CT numbers for the prostate, prostate lesions, and torso gel were determined by manual segmentation in the relaxometry maps.
and CT image, respectively. Additionally, a transcutaneous US scan of the phantom was obtained using a DC-N3 (Mindray, Shenzhen, China) US system.

2.4 | MR-guided biopsy experiment

To demonstrate the feasibility of the phantom for minimally invasive MR-guided interventions, a targeted in-bore MRGB was performed in a MAGNETOM Aera MRI scanner (Siemens Healthineers, Erlangen, Germany). The needle probe was rectally inserted and guided using an MR-compatible remote controlled manipulator (RCM, Soteria Medical, Arnhem, The Netherlands). The phantom was placed head first and prone in the scanner and the RCM was placed between the phantom’s legs. The biopsy setup of the robot and the phantom is shown in Figure 2A.

A T2w MRI image was acquired to localize the lesions and the initial position of the needle probe. The scan parameters of the interventional MRI are listed in Table 1. The T2w images were sent to a standalone computer located in the MR control room, on which dedicated software automatically detected the needle probe. The biopsy target was determined in the software and the needle probe was remotely steered towards the target position. In our experiment we only punctured one lesion using an MR-compatible titanium biopsy needle (Innovative Tomography Products, Bochum, Germany). After the needle application, a T2w MRI control scan was acquired to confirm the needle position.

3 | RESULTS

3.1 | Multimodal imaging

In Figure 3 a CT scan, T1w and T2w MRI scans, T1-, T2-, $B_0$-, and ADC-maps of the phantom are shown. The positions of the prostate lesions are indicated by red arrows. The prostate lesions are visible in CT and T2w MRI and are not detectable in T1w MRI. Only small air bubbles on the surface of the lesions indicate the position of the lesions in the T1w image. The same air bubbles are visible to a lesser extent in the CT and T2w images. With a CT number of 500 HU, the bones have a high contrast in CT imaging and yield no signal in MRI.

The phantom’s quantified T1- and T2-relaxation times, and CT numbers are compared to literature values in Table 2. Since the lesions in the T1w MRI image and the T1-map showed no contrast to the prostate, the same T1-time was measured for the prostate and the prostatic lesions. The phantom’s T1-times are 21% and 7% smaller than the lowest values and 44% and 28% smaller than the median values reported in human prostate and prostatic lesions, respectively.
T2 times are in very good agreement with literature values, and an increased T2-time of the prostate lesions results in their desired hypointense signal. A realistic hyperdense contrast between prostate and lesions is achieved in CT; however, the absolute CT numbers measured in the phantom are 140 HU higher than for real tissue. The $B_0$-map indicates high frequencies between the phantom’s legs due to the air gap and low frequencies for the silicone organs. The low ADC values in the ADC-map shows that there is very little diffusion in the phantom, which is underlined by a reference measurement of an agarose diffusiom phantom in Supporting Information Figure S3.

A US scan of the phantom is shown in Figure 3, where the prostate is outlined in red. The good visibility in US makes the phantom viable for interventional US applications.
TABLE 2  T1- and T2-relaxation times, and CT numbers of prostate and lesions

|                | Prostate Phantom | Literature | Prostate lesions Phantom | Literature | Ballistic gelatin Phantom |
|----------------|------------------|------------|--------------------------|------------|---------------------------|
| T1 [ms]        | 961 ± 69         | 1666 (1222–2343) | 961 ± 69                 | 1328 (1037–1532) | 230 ± 8                   |
| T2 [ms]        | 158 ± 9           | 139 ± 26    | 101 ± 11                 | 107 ± 18   | 62 ± 2                     |
| CT # [HU]      | 185 ± 16          | 45 ± 17    | 259 ± 17                 | Hyperdense | −180 ± 16                  |

T1- and T2-relaxation times, and CT numbers of prostate, prostate lesions, and torso gelatin. The values and uncertainty are either given as mean ± standard deviation or as median (min-max).

3.2  MR-guided biopsy experiment

In a transrectal MRGB experiment, we punctured a prostate lesion with a biopsy needle. The T2w MRI scan in Figure 2B shows the initial position of the needle probe in yellow and the target position in blue. The whole cross section of the rectum, needle probe, prostate, and prostate lesion are visible in this sagittal scan. The position of the placed biopsy needle is displayed in the T2w MRI control scan in Figure 2C. The needle appears thick due to susceptibility artifacts. The scan shows that the lesion was hit, but the center was missed by 3.5 mm. We did not take a biopsy sample in order to spare the phantom from unnecessary damage.

4  DISCUSSION

An anthropomorphic pelvis phantom incorporating a prostate with four lesions was developed. The realistic size of the pelvis allows evaluation of complete clinical workflows from patient positioning to imaging and intervention. The manufacturing process includes additive manufacturing techniques, enabling reproducibility and patient-specific anatomies.

The phantom is reusable, because most of the damages can be removed after usage by remelting the ballistic gelatin. Damages on the surface can be eradicated with a hot air dryer and puncture channels can be removed using a hot metal rod. The phantom can also be remelted as a whole in an oven after reapplying the body hull. However, damage to the silicone structures (prostate, lesions, lymph nodes, and bladder) cannot be repaired.

Since ballistic gelatin mimics the properties of muscle tissue, the phantom simulates realistic feedback during needle interventions. Pepley et al reported similar needle insertion forces for ballistic gelatin and cadaveric tissue. Compared to the prostate, a harder silicone was used for the prostate lesions, because tumors are stiffer than normal prostate tissue. The harder silicone has a higher density and therefore yields a higher signal in CT and enables lesion visibility in US and potentially in elastography. The bladder, urethra, and bones serve as risk structures for needle interventions. Since bones and the urethra are solid, they realistically restrict possible needle paths. The lymph nodes act as additional percutaneous needle targets, with blood vessels as risk structures. With its realistic needle feedback, the phantom is useful for training surgical staff in prostate biopsies and other procedures. In the future, it is conceivable to integrate deformations to simulate organ motion. However, simultaneous suitability for needle interventions is difficult to achieve.

Our results demonstrate that the artificial pelvis shows human-like contrast in several MRI sequences and CT. Due to their high contrast, the bones provide high quality landmarks in MRI and CT, which facilitates multimodal image registration. The high visibility of the prostate lesions in T2w MRI scans in combination with the hollow rectum is central for targeted prostate interventions. The contrast of the lesions is consistent with reality, as prostatic lesions appear hypointense in T2w scans and are not detectable in T1w scans. T1w imaging is mainly used to delineate bones and lymph nodes, for which the phantom provides an excellent contrast in the T1w scan. Quantification of relaxation times for prostate and prostate showed excellent agreement of T2-times compared to literature values, whereas the T1-times of the phantom are too small. Nonetheless, the discrepancy of T1-times is still acceptable, since we achieved desired contrasts in the T1w and T2w MRI scans. Prostate lesions usually exhibit a decrease in ADC value. Our phantom shows very little diffusion and the lesions are not visible in the ADC-map. Nevertheless, since the lesions are well detectable in T2w imaging, we do not need to rely on DWI to locate the lesions. Manipulating the relaxation times and diffusion properties of silicones is a challenging task, because additives like contrast agent often do not mix well and settle during the curing process. Agarose gels are a great alternative to silicones, because it is easy to manipulate T1-, T2-times, and ADC value by varying the concentrations of agarose, gadolinium trichloride and sucrose. However, agarose gels were not suitable for our biopsy phantom, because as shown in Supporting Information Figure S1, they suffer from dehydration and mold-buildup, which substantially reduces their life span.
The synthetic ballistic gelatin and silicones used in our phantom do not require specific storage. Our oldest phantom made from these materials is now three years old and we have yet to see any noticeable age

In the transrectal MRGB experiment, we hit the targeted prostate lesion, but missed the center by 3.5 mm. The reason for this inaccuracy is that the RCM stops moving when the needle probe experiences resistance, and therefore cannot reach its target position. This is an intended feature of the robot to increase patient safety. The limited size of the rectum therefore represents a realistic impairment for the needle placement. In future experiments we will lubricate the needle probe to reduce the resistance. Additionally, the center of rotation of the needle probe can be adjusted manually. By iteratively moving the probe and acquiring T2w MRI scans, the needle placement accuracy can be increased. In this regard, the limited size of the rectum is valuable for the training of interventionists, as they can gain experience with such a challenging situation without causing discomfort or harm to patients. Another reason for the inaccurate needle placement could be needle bending, but we believe its contribution to be minor.

The good visibility of prostate and prostate lesions in US makes it possible to use the phantom for the validation of US imaging workflows and US-guided interventions. These include MRI-US fusion and TRUS-biopsy, for which the transrectal access is particularly convenient. Moreover, the multimodal properties of the phantom enable the verification of MR-to-CT synthesis, which is essential for MR-only radiotherapy treatment planning.44

5 | CONCLUSIONS

We have designed and manufactured a reusable pelvis phantom that is suitable for MRI, CT and US imaging and exhibits realistic imaging properties for prostate and prostate lesions. The phantom has been used to perform an inbore MRGB with assistance of an MR-compatible RCM. We have been able to hit a prostate lesion after locating it with MR imaging. Difficulties targeting the lesion have been identified and can be mitigated in the future. The phantom can be used for a variety of minimal invasive interventions and in the future will be used for the validation of an MR-guided brachytherapy seed placement workflow using the RCM.

ACKNOWLEDGEMENTS

This research project is part of the Research Campus M2OLIE and funded by the German Federal Ministry of Education and Research (BMBF) within the Framework “Forschungscampus: public-private partnership for Innovations” under the funding code 13GW0388A and 13GW0389C.

ORCID

Dominik F. Bauer http://orcid.org/0000-0002-8781-2882

REFERENCES

1. Sung H, Ferlay J, Siegel RL, et al. Global cancer statistics 2020: globocan estimates of incidence and mortality worldwide for 36 cancers in 185 countries. CA: A Cancer J Clin. 2021;71:209-249.
2. Dickinson L, Ahmed HU, Allen C, et al. Magnetic resonance imaging for the detection, localisation, and characterisation of prostate cancer: recommendations from a european consensus meeting. Eur Urol. 2011;59:477-494.
3. Rosenkrantz AB, Taneja SS. Prostate MRI can reduce overdosage and overtreatment of prostate cancer. Acad Radiol. 2015;22:1000-1006.
4. Stabile A, Giganti F, Rosenkrantz AB, et al. Multiparametric MRI for prostate cancer diagnosis: current status and future directions. Nat Rev Urol. 2020;17:41-61.
5. Le JD, Tan N, Shkolyar E, et al. Multifocality and prostate cancer detection by multiparametric magnetic resonance imaging: correlation with whole-mount histopathology. Eur Urol. 2015;67:569-576.
6. Radtke JP, Schwab C, Wolf MB, et al. Multiparametric magnetic resonance imaging (MRI) and MRI-transrectal ultrasound fusion biopsy for index tumor detection: correlation with radical prostatectomy specimen. Eur Urol. 2016;70:846-853.
7. Noureldin M, Eldred-Evans D, Khoo C, et al. MRI-targeted biopsies for prostate cancer diagnosis and management. World J Urol. 2020;1-7.
8. Wang J, Tanderup K, Cunha A, et al. Magnetic resonance imaging basics for the prostate brachytherapist. Brachytherapy. 2017;16:715-727.
9. Matlaga BR, Eskew LA, McCullough DL. Prostate biopsy: indications and technique. J Urol. 2003;169:12-19.
10. van der Leest M, Cornel E, Israël B, et al. Head-to-head comparison of transrectal ultrasound-guided prostate biopsy versus multiparametric prostate resonance imaging with subsequent magnetic resonance-guided biopsy in biopsy-naive men with elevated prostate-specific antigen: a large prospective multicenter clinical study. Eur Urol. 2019;75:570-578.
11. Connor M, Gorin M, Ahmed H, Nigam R. Focal therapy for localized prostate cancer in the era of routine multi-parametric MRI. Prostate Can Prostatal Diseases. 2020;23:232-243.
12. Woodrum DA, Kawashima A, Karnes RJ, et al. Magnetic resonance imaging-guided cryoablation of recurrent prostate cancer after radical prostatectomy: initial single institution experience. Urology. 2013;82:870-875.
13. Eggener SE, Yousuf A, Watson S, Wang S, Oto A. Phase ii evaluation of magnetic resonance imaging guided focal laser ablation of prostate cancer. J Urol. 2016;196:1670-1675.
14. Chin JL, Billia M, Relle J, et al. Magnetic resonance imaging-guided transurethral ultrasound ablation of prostate tissue in patients with localized prostate cancer: a prospective phase 1 clinical trial. Eur Urol. 2016;70:447-455.
15. Chaussy CG, Thüroff S. High-intensity focused ultrasound for the treatment of prostate cancer: a review. J Endourol. 2017;31:S-30.
16. van den Bos W, Scheltema MJ, Srinivardana AR, et al. Focal irreversible electroporation as primary treatment for localized prostate cancer. BJU Int. 2018;121:716-724.
17. Bomers J, Bosboom D, Tigelaaar G, Sabisch J, Fütterer J, Yakar D. Feasibility of a 2nd generation MR-compatible
magnetic resonance in Medicine

18. Smakic A, Rathmann N, Kostrzewa M, Schönberg SO, Weiß C, Diehl SJ. Performance of a robotic assistance device in computed tomography-guided percutaneous diagnostic and therapeutic procedures. Cardiovasc Intervent Radiol. 2018;41:639-644.

19. Schouten MG, Ansems J, Renema WKJ, Bosboom D, Scheenen TW, Fütteler JI. The accuracy and safety aspects of a novel robotic needle guide manipulator to perform transrectal prostate biopsies. Med Phys. 2010;37:4744-4750.

20. Chiu T, Xiong Z, Parsons D, Folkert MR, Medin PM, Hrycushko B. Low-cost 3d print-based phantom fabrication to facilitate interstitial prostate brachytherapy training program. Brachytherapy. 2020;19:800-811.

21. Hungr N, Long JA, Beix V, Troccaz J. A realistic deformed prostate phantom for multimodal imaging and needle-insertion procedures. Med Phys. 2012;39:2031-2041.

22. Lindner U, Lawrentschuk N, Weersink RA, et al. Construction and evaluation of an anatomically correct multi-image modalitv compatible phantom for prostate cancer focal ablation. J Urol. 2010;184:352-357.

23. Long JA, Daenen V, Moreau-Gaudry A, Troccaz J, Rambeaud JJ, Descotes JL. Prostate biopsies guided by three-dimensional real-time (4-d) transrectal ultrasonography on a phantom: comparative study versus two-dimensional transrectal ultrasound-guided biopsies. European urology. 2007;52:1097-1105.

24. Neumann W, Bichert A, Fleischhauer J, et al. A novel 3d printed mechanical actuator using centrifugal force for magnetic resonance elastography: Initial results in an anthropomorphic prostate phantom. Plos one. 2018;13:e0205442.

25. Cunningham JM, Barberi EA, Miller J, Kim JP, Glide-Hurst CK. Development and evaluation of a novel MR-compatible pelvic end-to-end phantom. J Appl Clin Med Phys. 2019;20:265-275.

26. Niebuhr N, Johnen W, Echner G, et al. The adam-pelvis phantom—an anthropomorphic, deformable and multimodal phantom for MR-GRT. Phys Med Biol. 2019;64:04NT05.

27. Valladares A, Beyer T, Rausch I. Physical imaging phantoms for simulation of tumor heterogeneity in PET, CT, and MRI: An overview of existing designs. Med Phys. 2020;47:2023.

28. Doyle AJ, Sullivan F, Walsh J, King DM, Cody D, Browne JE. Development and preliminary evaluation of an anthropomorphic trans-rectal ultrasound prostate brachytherapy training phantom. Ultrasound Med Biol. 2021;47:833-846.

29. Bauer DF, Oelschlegel E, Golla AK, et al. An anthropomorphic pelvis phantom for prostate brachytherapy and biopsy. Proc Int Soc Mag Reson Med. 2021;29.

30. Segars WP, Sturgeon G, Mendonca S, Grimes J, Tsui BM. 4d xcat phantom for multimodality imaging research. Med Phys. 2010;37:4902-4915.

31. Leitzmann MF, Rohrmann S. Risk factors for the onset of prostatic cancer: age, location, and behavioral correlates. Clin Epidemiol. 2012;4:1.

32. Zhang SJ, Qian HN, Zhao Y, et al. Relationship between age and prostate size. Asian J Androl. 2013;15:116.

33. Jezzard P, Balaban RS. Correction for geometric distortion in echo planar images from $b_0$ field variations. Magn Reson Med. 1995;34:65-73.

34. Weidner AM, Michaely HJ, Lemke A, et al. Value of multi-parametric prostate MRI of the peripheral zone. Zeitschrift für Medizinische Physik. 2011;21:198-205.

35. Baur AD, Hansen CM, Rogasch J, et al. Evaluation of $T_2$ relaxation time in prostate cancer and benign prostate tissue using a modified look-locker inversion recovery sequence. Sci Rep. 2020;10:1-8.

36. Dinh AH, Souchon R, Melodelima C, et al. Characterization of prostate cancer using $T_2$ mapping at 3 t: a multi-scanner study. Diagnos Intervent Imaging. 2015;96:365-372.

37. D’Souza WD, Madsen EL, Unal O, Vigen KK, Frank GR, Thomadsen BR. Tissue mimicking for multi-material imaging modality prostate phantom. Med. Phys. 2001;28:688-700.

38. Batur A, Kerimoglu U, Ataseven H. Hounsfield unit density in the characterisation of bile duct lesions. Polish J Radiol. 2019;84:e397.

39. Pepley DF, Sonntag CC, Prabhu RS, et al. Building ultrasound phantoms with modified polyvinyl chloride: a comparison of needle insertion forces and sonographic appearance with commercial and traditional simulation materials. Simulation Healthcare: J Soc Simula Healthcare. 2018;13:149.

40. Zhang M, Nigwekar P, Castaneda B, et al. Quantitative characterization of viscoelastic properties of human prostate correlated with histology. Ultrasound Med Biol. 2008;34:1033-1042.

41. Neumann W, Lietzmann F, Schad LR, Zöllner FG. Design of a multimodal (1 h/23 na MR/CT) anthropomorphic thorax phantom. Zeitschrift für Medizinische Physik. 2017;27:124-131.

42. Hattori K, Ikemoto Y, Takao W. Development of MRI phantom equivalent to human tissue for 3.0-t MRI. Med Phys. 2013;40.

43. Lavdas I, Behan KC, Papadaki A, McB Robbie DW, Aboagye EO. A phantom for diffusion-weighted mri (dw-MRI). J Magn Reson Imaging. 2013;38:173-179.

44. Zimmermann L, Buschmann M, Herrmann H, et al. An MR-only acquisition and artificial intelligence based image-processing protocol for photon and proton therapy using a low field MR. Zeitschrift für Medizinische Physik. 2021;31:78-88.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of the article at the publisher’s website.

FIGURE S1 Dehydrated agarose prostate. Dehydrated and moldy agarose prostate inside the prostate mold

FIGURE S2 Unedited ultrasound scan. Unedited ultrasound image of the prostate without annotations

FIGURE S3 DWI measurement. Diffusion-weighted imaging (DWI) of the pelvis phantom (left) and reference agarose phantom (right). The ADC-maps in the top row show that there is very little diffusion in our pelvis phantom ($ADC \approx 0.05 \cdot 10^{-3} \text{mm}^2/\text{s}$) compared to the agarose phantom ($ADC \approx 2 \cdot 10^{-3} \text{mm}^2/\text{s}$). Typical ADC values for the prostate range between $1 \cdot 10^{-3} \text{mm}^2/\text{s}$ and $2 \cdot 10^{-3} \text{mm}^2/\text{s}$. The b50 and b800 scans of the pelvis phantom confirm this observation, as they hardly differ from each other

How to cite this article: Bauer DF, Adlung A, Brumer I, et al. An anthropomorphic pelvis phantom for MR-guided prostate interventions. Magn Reson Med. 2022;87:1605–1612. https://doi.org/10.1002/mrm.29043