Evaluation of BoneMRI for surgical spine planning and navigation

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Abstract*—*Purpose: **To qualitatively evaluate the performance of BoneMRI —a synthetic Computed Tomography (CT) scan— for surgical planning and navigation in the spine and to determine the potential added value of BoneMRI compared to an isotropic 3D T1 Magnetic Resonance (MR) sequence.**

Materials and methods: **In this study patients who received dorsal stabilisation using a screw and rod system on the lumbar or sacral spine were included. For each patient an MRI was performed, including an isotropic 3D T1 MR, and synthetic CT images were reconstructed from a T1-weighted multiple gradient-echo scan using the BoneMRI software. Surgical planning of the screws was performed. BoneMRI was evaluated by three observers, through a questionnaire and with results following a likert scale, on the visualisation of anatomical structures, the confidence during preoperative planning and the added value during planning. The obtained scores were examined by means of a contingency table; the interrater reliability was examined with the intraclass correlation coefficient; and statistical tests were calculated to study the possibility of correlation between different variables.**

Results and Discussion: **24 patients were included in the study and in total 110 screws were placed in the lumbar and S1 vertebrae. BoneMRI showed adequate visualisation of anatomical regions in 90% of all scored vertebrae and good to excellent interrater reliability between the three observers was found (ICC: 0.85 to 0.96). BoneMRI showed to be capable to perform screw planning with confidence, was capable to visualise pathologies and showed to be an added value compared to the isotropic 3D T1 MR scan.**

Conclusion: **BoneMRI produces adequate qualitative image quality and showed an added value for surgical planning in the spine.**

***Index Terms*—Lumbar spine, Synthetic Computed Tomography, Magnetic Resonance Imaging, Surgical Planning, Qualitative analysis.**

I. INTRODUCTION

SINCE the emergence of Computed Tomography (CT) in the 1970s, imaging diagnostics and image-based treatment planning have been continuously evolving. CT scans are the modality of choice for examining the patient's osseous structures for surgical planning and navigation, due to their high-resolution of the bony structure, fast acquisition, relatively low cost, and widespread availability. However, CT patients are exposed to ionising radiation, which can be a contraindication in daily practice, and this modality fails when adequate soft-tissue contrast is required [1].

On the contrary, Magnetic Resonance (MR) Imaging is the first option for diagnostics of degenerative spine disorders, as it has demonstrated relatively high sensitivity and specificity for soft tissue imaging without exposing the patient to any radiation, but it is still limited when acquiring the patient's bony morphology. A combination of both techniques has therefore been used in the past years for diagnosis and treatment planning of different spine pathologies, to obtain a complete high-quality scan of the patient's anatomy [1], [2].

However, acquiring two different image modalities increases the workflow complexity, time, costs, and patient burden. In order to prevent additional examinations, different techniques and new technologies were studied to obtain high-quality unimodal images of soft and bone tissue with MRI[1]. Two different approaches were assessed in this study.

On the one hand, the BoneMRI technology developed by MRIguidance B.V. [3] generates MR-based synthetic CT data by estimating Hounsfield units (HU) values directly from the intensities of the MR images. It uses a sagittal 3-dimensional T1-weighted radio-frequency-spoiled multiple gradient echo sequence (3D T1w-MGE) and a machine learning algorithm to generate 3D synthetic CT images. This approach has already been validated in the cervical spine, lumbar spine, pelvis, and sacroiliac joints [4]–[8].

This innovative technique for synthetic CT generation provides quantitative CT-like contrast, does not need specialised technical requirements, and allows the scans to be post-processed as a CT-like image, thus being efficiently introduced in the current workflow for treatment planning and navigation in the spine [4], [7].

On the other hand, isotropic 3D T1 MR is a 3D MR fast spin-echo sequence that employs T1 contrast to visualise bone tissue without exposing the patient to radiation [9]. It can be obtained from a MR scan with no need for specialised technical requirements but does not provide quantitative CT-like contrast.

To investigate the possibility to incorporate BoneMRI in the current workflow for surgical planning and navigation of spine surgery, screws were planned in the lumbar and sacral spine by employing a planning software. The aim of this research is to qualitatively evaluate the performance of BoneMRI for surgical planning in the spine and determine the potential value of BoneMRI compared to an isotropic 3D T1 MR sequence.

II. Materials and methods

THIS prospective study was approved by the local ethics committee. All patients signed written informed consent.

A. Participants

The study population consisted of patients who received dorsal stabilisation in the Augustinian hospital in Cologne using a screw and rod system on the lumbar or sacral spine. Patients were excluded from the study if they were under age 18, didn't sign the patient's consent, present any intolerances or known restrictions that make it impossible to participate, or if an MRI could not be performed on them.

B. Study protocol

A standard MRI scan, with a modified scan protocol to include a generally applicable radiofrequency-spoiled T1-weighted multiple gradient-echo (T1w-MGE) sequence for synthetic CT reconstruction, and an isotropic 3D T1 MR sequence, were acquired with a Magnetom Aera 1.5T MRI system (Siemens Healthineers AG, Erlangen, Germany).

The T1w-MGE acquisition parameters were: echo times of 2.1, and 4.2 ms, a repetition time of 7 ms, a total acquisition time of 4 min 18 s, flip angle of 10° and voxel size of 0.5mm × 0.5mm × 1mm.

The T1w-MGE scans were processed by a product version of the BoneMRI software [3] (BoneMRI, MRIguidance BV, Utrecht, the Netherlands) to create the synthetic CT images.

The BoneMRI and isotropic 3D T1 MR were used to plan the screws for spine surgery by a medical specialist in orthopaedics and trauma surgery, and employing the Brainlab spinal planning software [10] (Brainlab AG, Munchen, Germany).

The Brainlab image registration software (Brainlab AG, Munchen, Germany) was used to automatically fuse the scans to an X-ray based 3D intra-operative scan performed by the surgeon. The planned screws were evaluated in the 3D intra-operative image, considered a ground truth scan.

Finally, three observers graded the placement of the screws and the quality of the images with respect to surgery planning by filling out a questionnaire.

The complete protocol is summarised in Figure 1.

C. Questionnaire

The surgeon who performed the planning and two others, who are either specialised in orthopaedics, trauma surgery or neurosurgery, independently evaluated the visualisation accuracy and feasibility of surgical planning with BoneMRI. A qualitative assessment was performed in the form of a questionnaire with results given on a five-point likert scale (1=strongly disagree; 2=disagree; 3=neutral; 4=agree; 5=strongly agree).

Additionally, the BoneMRI images were compared to the isotropic 3D T1 MR scans by the three observers, to identify any added value of BoneMRI for surgical planning.

Based on discussion with clinical experts, the questionnaire is compiled out of relevant questions for the image requirements needed for surgical planning. The 3 questions included were the following:

1 *BoneMRI provides adequate visualisation of the following structures useful for surgical planning:*
   - a) *Pedicles*
   - b) *Anterior and posterior walls*
   - c) *Vertebral endplates*

2 *Preoperative planning on BoneMRI:*
   - a) *I would be able to plan the screw length with confidence.*
   - b) *I would be able to plan the screw diameter with confidence.*
   - c) *I would be able to plan the screw position with confidence.*

3 *Preoperative planning on BoneMRI vs. isotropic 3D T1 MR:*
   - a) *BoneMRI provides a better visualisation of relevant osseous landmarks and access points.*
   - b) *BoneMRI provides a better visualisation of relevant osseous pathologies.*
   - c) *Is pathology present.*
   - d) *With BoneMRI I would be more confident in the choice of surgical approach.*
   - e) *With BoneMRI I would be more confident in the choice of screw fixation method.*
   - f) *With BoneMRI I would be more confident to prevent potential pedicle breach.*

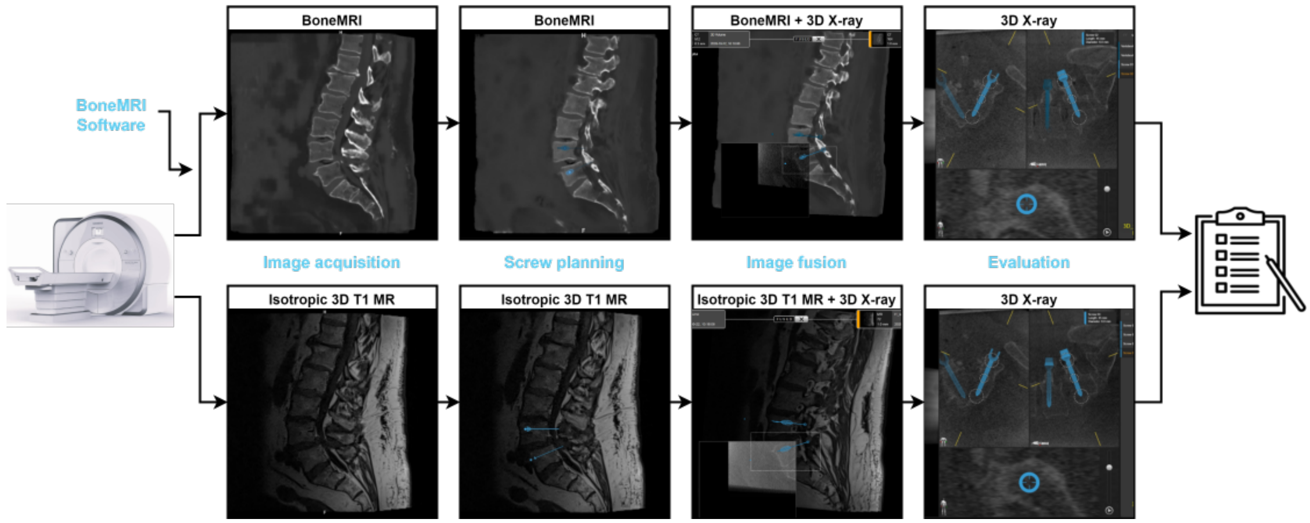

Fig. 1. Graphical overview of the image study protocol for a single subject.

g) *I feel better prepared for surgery if I use BoneMRI for pre-operative planning.*

h) *BoneMRI provides added value for pre-op planning.*

For each patient, the questions were scored by the three observers. Questions 1(a-c) were about the visualisation of every vertebrae level from L1 to S1 in every patient —one score per vertebra—; questions 2(a-c) assessed the preoperative planning for every patient or scan; questions 3(a-h) compared the planning with BoneMRI or isotropic 3D T1 MR. Notice that question 3c results are binary (Yes/No), as opposed to the rest which are ranked.

D. *Statistical analysis*

Data were analysed using R (version 4.1.3), and all the functions are defined in R-project and irr package [11], [12].

Although likert scales are ordinal variables, several authors have demonstrated that this type of data, when having five or more categories, can be used as continuous without having any major changes in the analysis [13]–[17]. For this reason, and an easier interpretation of the results, scores were considered continuous variables and not normally distributed, and thus non-parametric analyses for numeric data were employed.

First, the percentage of scores obtained for each statement was examined through a contingency table.

Interrater reliability was assessed, between the three observers, by calculating the intraclass correlation coefficient (ICC) based on a two-way-mixed model, absolute agreement and single measures [18]. The 95% confidence intervals (CI) of this coefficient were also reported.

In addition, a correlation analysis was performed to determine whether the vertebra level influenced the obtained score in question 1(a-c). In other words, to check if the different vertebrae obtained statistically different scores. Because the data follows a non-normal distribution and is paired, the Friedman test was employed to perform a multi-level analysis between all the vertebra levels. If the results from the previous analysis were significant, the scores were compared between one vertebra level and the other levels by using a Wilcoxon signed-rank test, to investigate which had obtained a significantly lower score. Both statistics were calculated following a two-sided alternative and with a significant level of 0.05.

The association was further assessed between the presence of pathology and the likert scores of questions 2(a-c) and 3(a-h), to determine whether the presence of a pathology, as based on the answer of question 3c., significantly changes the scores of the formulated questions. For this purpose, the Wilcoxon rank-sum test (two-sided alternative and alpha = 0.05) was calculated between two independent variables —scores when pathology is present or not.

To increment the sample size, the correlation tests were performed combining the results from the three observers as independent data.

III. Results

THE analysis of the questionnaire was divided into two different sections: the visualisation of the anatomical structures —Question 1(a-c)— and the confidence and added value provided by the BoneMRIs, and in comparison with the isotropic 3D T1 MR scans — Questions 2(a-c) and 3(a-h), respectively.

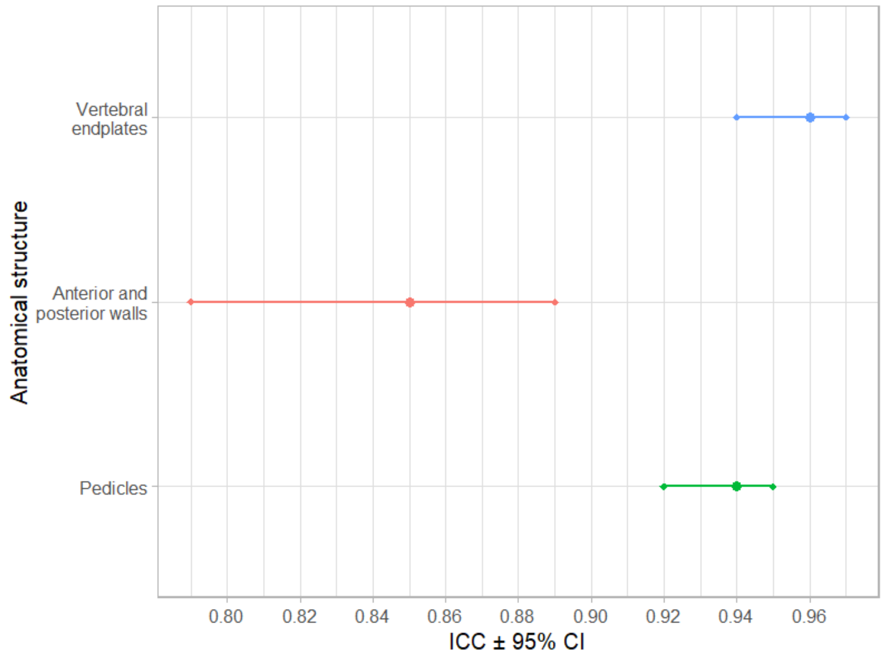

Fig. 2. Intraclass correlation coefficient (±95% CI) of the scores, between the three observers and differentiated by the anatomical structure.

24 patients (mean age = 61.8±11 years; 14 men and 10 women) were included in the study; 110 screws were placed in L1 to S1 vertebrae. The percentages of screws placed in each vertebra were: L1-2%, L2-4%, L3-9%, L4-33%, L5-38% and S1-14%; showing a higher number of screws were placed in vertebrae L4 and L5.

A. *Part 1: Visualisation of anatomical structures*

The first part of the questionnaire asked whether BoneMRI provided adequate visualisation of the different anatomical structures in vertebrae L1 to L5 and S1. The scores are reported as percentages for the three observers combined in Table I, where the scores 1-2 and 4-5 were pooled together.

TABLE I
PERCENTAGES OF THE DIFFERENT SCORES OBTAINED BY THE THREE OBSERVERS WITH RESPECT TO THE STATEMENT "BONEMRI PROVIDES ADEQUATE VISUALISATION OF THE FOLLOWING STRUCTURES USEFUL FOR SURGICAL PLANNING".

	% (strongly) agree	% neutral	% (strongly) disagree
Pedicles	97	0	3
Anterior and posterior walls	94	2	4
Vertebral endplates	96	1	4

Likert scores: 1=strongly disagree; 2=disagree; 3=neutral; 4=agree; 5=strongly agree. Scores 1-2 and 4-5 were pooled together when calculating the percentages.

A good to excellent interrater reliability was found when comparing the data between observers. Figure 2 reports the intraclass correlation coefficients of the scores, between the three observers and differentiated by the anatomical structure.

Figure 3 shows the scores differentiating between the different vertebrae levels (L1-5 and S1). For ease of visualisation, the data was represented as percentages, ranked from 50 to 100%. The correlation analysis on the influence of the vertebra level showed significant results, p-values obtained by the multi-level Friedman test were 0.002, 0.000 and 0.001 for the pedicles, anterior and posterior walls and vertebral endplates, respectively.

The further analysis on the correlation for each vertebrae level showed a significant difference between L5 and S1 for the pedicles, anterior and posterior walls and the endplates, and the other vertebrae levels. The p-values obtained in the Wilcoxon signed-rank test are reported in Table II.

B. *Part 2: Confidence and added value*

The second part of the questionnaire was about preoperative planning on BoneMRI and compared it with isotropic 3D T1 MRI. The scores for the individual statements are reported in Table III as percentages, for the three observers combined, and pooling scores 1-2 and 4-5.

The observers encountered pathology in 64% of the patients.

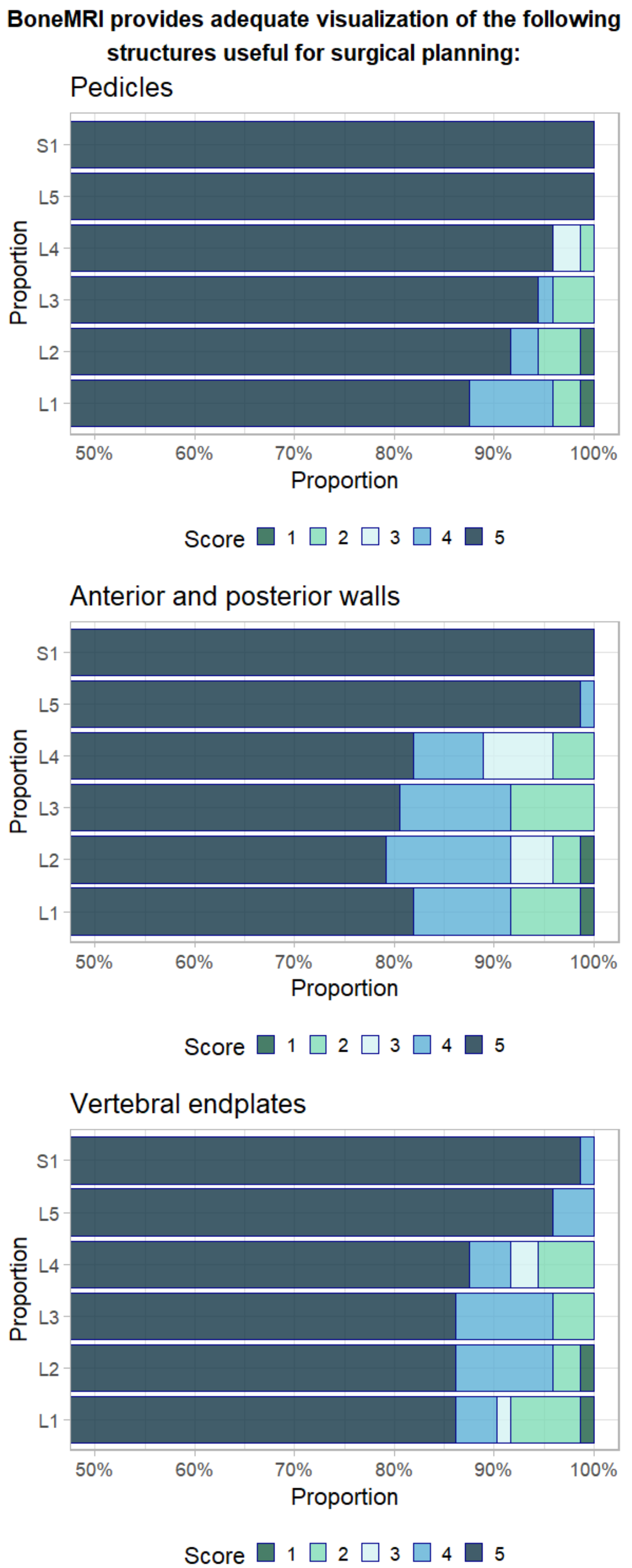

Fig. 3. Percentages of the scores obtained (from 50 to 100%) by the three observers with respect to the statement, differentiated by the anatomical structure and vertebra level.

TABLE II
P-VALUES OF THE WILCOXON SIGNED-RANK TEST PERFORMED BETWEEN THE SCORES FOR EACH VERTEBRA LEVEL, WITH RESPECT TO THE STATEMENT "BONEMRI PROVIDES ADEQUATE VISUALISATION OF THE FOLLOWING STRUCTURES USEFUL FOR SURGICAL PLANNING".

P-value — Pedicles						
	L1	L2	L3	L4	L5	S1
L1	-	0.850	0.438	0.227	**0.007**	**0.007**
L2		-	0.629	0.309	**0.034**	**0.034**
L3			-	0.149	0.089	0.089
L4				-	0.174	0.174
L5					-	NaN
S1						-
P-value — Anterior and posterior walls						
	L1	L2	L3	L4	L5	S1
L1	-	0.792	0.943	1.000	**0.002**	**0.001**
L2		-	0.837	0.947	**0.001**	**0.001**
L3			-	0.705	**0.001**	**0.001**
L4				-	**0.002**	**0.001**
L5					-	1.000
S1						-
P-value — Vertebral endplates						
	L1	L2	L3	L4	L5	S1
L1	-	0.129	0.294	0.659	**0.014**	**0.007**
L2		-	0.886	0.918	**0.020**	**0.007**
L3			-	0.345	**0.019**	**0.007**
L4				-	**0.031**	**0.013**
L5					-	0.346
S1						-

Bold text indicates a significant result (alpha = 0.05).

Moderate, good and excellent interrater reliability was found for most statements when comparing the data between the three observers, except for the confidence on the choice of screw fixation method in which a poor interrater reliability was found. The intraclass correlation coefficients of the data, differentiated by the statement, are presented in Figure 4.

Lastly, the Wilcoxon rank-sum test was obtained for every statement to assess whether the presence of a pathology significantly changes the scores of the formulated questions. A significant value was found for the statement on visualisation of pathologies, screw fixation method and feeling better prepared for the surgery. Results are shown in Table IV.

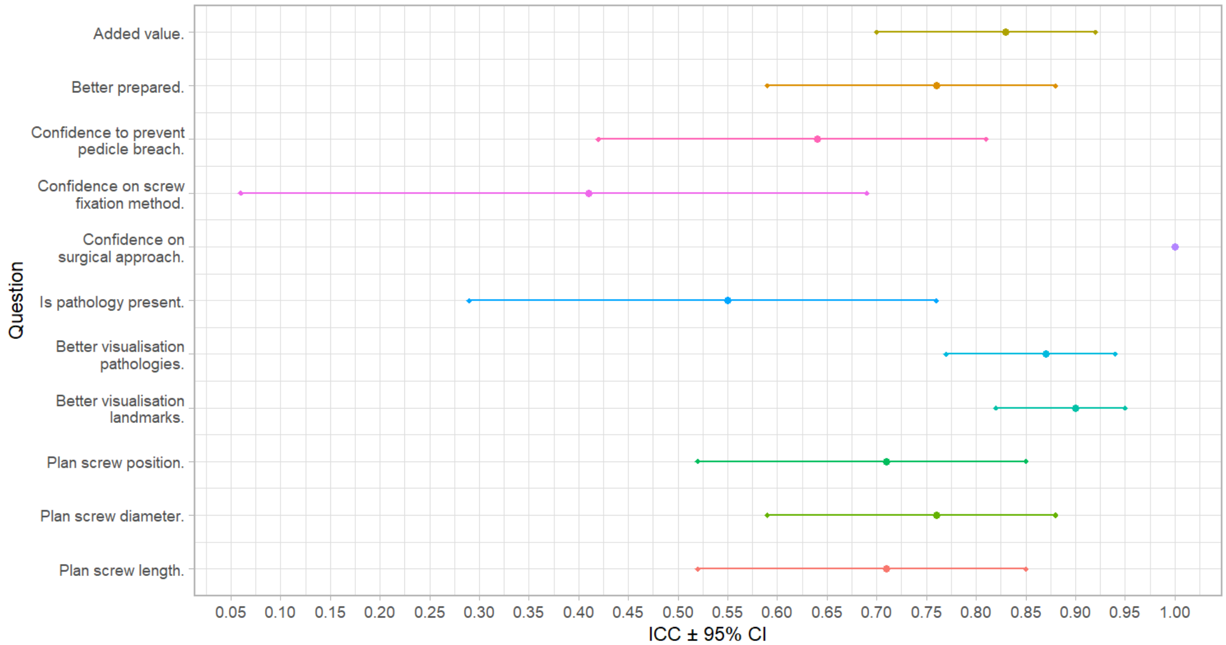

Fig. 4. Intraclass correlation coefficient (±95% CI) of the scores with respect to the statements, between the three observers and differentiated by the statement.

TABLE III
PERCENTAGES OF THE DIFFERENT SCORES OBTAINED BY THE THREE OBSERVERS WITH RESPECT TO THE STATEMENTS.

	% (strongly) agree	% neutral	% (strongly) disagree
Plan screw length	94	6	0
Plan screw diameter	92	8	0
Plan screw position	94	6	0
Better visualisation landmarks	94	6	0
Better visualisation pathologies	94	6	0
Confidence in surgical approach	4	96	0
Confidence in screw fixation method	90	10	0
Confidence to prevent pedicle breach	88	12	0
Better prepared	97	3	0
Added value	99	1	0

Likert scores: 1=strongly disagree; 2=disagree; 3=neutral; 4=agree; 5=strongly agree. Scores 1-2 and 4-5 were pooled together when calculating the percentages.

TABLE IV
P-VALUES OF THE WILCOXON RANK-SUM CORRELATION TEST PERFORMED BETWEEN THE SCORES AND THE PRESENCE OF PATHOLOGY, WITH RESPECT TO THE STATEMENTS.

	P-value
Plan screw length	0.948
Plan screw diameter	0.507
Plan screw position	0.948
Better visualisation landmarks	0.287
Better visualisation pathologies	**0.000**
Confidence in surgical approach	0.205
Confidence in screw fixation method	**0.014**
Confidence to prevent pedicle breach	0.412
Better prepared	**0.047**
Added value	0.309

Bold text indicates a significant result (alpha = 0.05).

IV. Discussion

THE results demonstrate that BoneMRI provides adequate visualisation of the relevant anatomical structures of the vertebrae and shows an added value for surgery planning.

However, some BoneMRIs were not adequately reconstructed, and therefore the anatomical structures could not be distinguished in these scans. An example where the observers could not correctly visualise the structures —score 2— for the vertebrae L1 to L4 is shown in sections B and D of Figure 5, as opposed to a perfect visualisation —score 5— in sections A and C of the figure. The axial views (C and D) correspond to vertebra level L3.

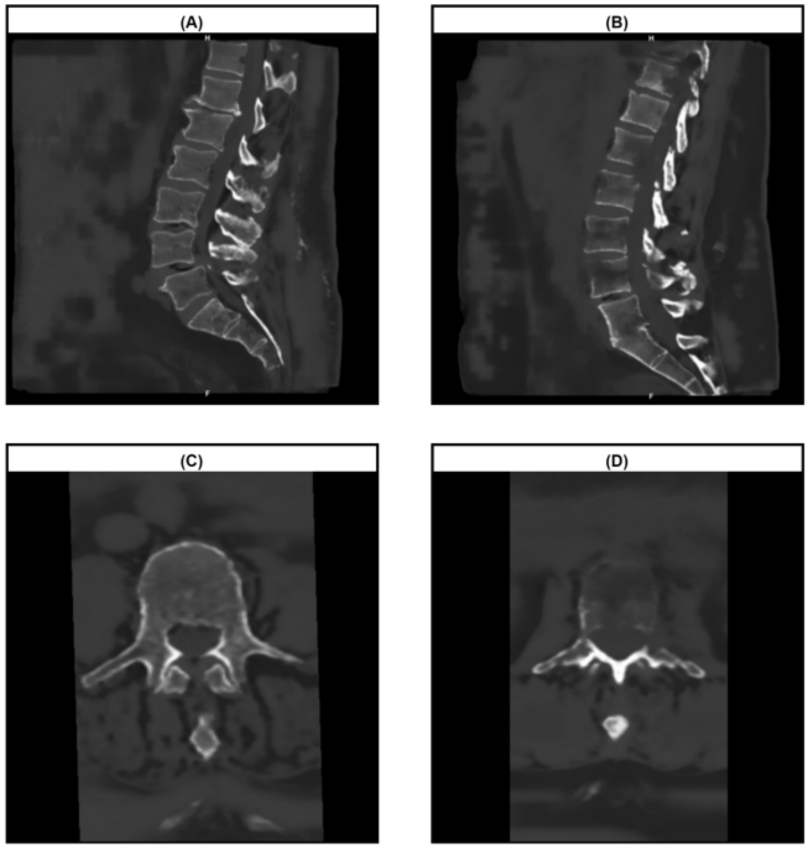

Fig. 5. Example of adequate and inaccurate visualisation of the vertebrae. (A) Sagittal view of the lumbar and sacral spine with adequate visualisation of vertebrae L1 to L4. (B) Sagittal view of the lumbar and sacral spine incorrect visualisation of vertebrae L1 to L4. (C) Axial view of an adequate visualisation of vertebra L3. (D) Axial view of an incorrect visualisation of vertebra L3.

It is worth mentioning that the observers were highly impressed by the high quality of the MR images, especially by the ability to detect and diagnose the different pathologies. Figure 5B shows an adequate representation of the Bertolotti syndrome, which consists of back pain caused by lumbosacral transitional vertebrae, the partial or complete fusion of L5 and S1 [19]. The observers scored 5 for these two vertebrae.

When looking at the individual scores provided for each vertebra per anatomical structure in Figure 3, the anterior and posterior wall has more often been scored as "agreed" on the adequate visualisation compared to the other anatomical structures. Together with the slightly higher scores on "neutral" and "(strongly) disagree", this anatomical structure was scored with a slightly wider variation. The walls also show lower ICC and higher confidence intervals when assessing the interrater reliability, therefore, having a slightly higher variability of the scores between the observers as compared to the rest. However, all the anatomical structures obtained scores equal to 4 or 5 in more than 90% of the cases, and the coefficients indicated good to excellent reliability among the observers according to the ICC interpretation defined in Koo et al. [18]. The percentages of agree and strongly agree were 97, 94 and 96, and the ICC coefficients were 0.94, 0.85 and 0.96 for the pedicles, anterior and posterior walls, and vertebral endplates, respectively. These results demonstrate that BoneMRI provides adequate visualisation of the anatomical structures of the vertebra.

Although most scores were 4 and 5 for the three anatomical structures, the correlation analysis of Table II demonstrates that BoneMRI provides the best visualisation score for the lower vertebra levels (L5 and S1). The multi-level Friedman test shows that there is a relation between the vertebra level and scores obtained, as the three tests performed were statistically significant (p-value lower than 0.05). When performing a Wilcoxon signed-rank test to assess the statistically difference between the scores in every vertebra level, significant differences were obtained between vertebrae L5-S1 and L1-L2 for the pedicles, and between L5-S1 and L1-L4 for the walls and endplates. The results indicate that L5 and S1 show better visualisation of the anatomical structures compared to L1 and L2, although the visualisation is found adequate for the entire lumbar and sacral spine, as more than 90% of the scores were 4 or 5 for every level and anatomical structure.

When evaluating the statements of part 2 on the confidence and added value provided by BoneMRI, the observers obtained a score of 4 or 5 on more than 90% of the cases for most of the questions. However, they scored "neutral" (likert score: 3) for 96% of the patients when choosing the surgical approach, indicating that the method is selected independently of the scan — surgical approach is usually defined beforehand by the surgeon, without taking the image into account. None of the statements resulted in scores equal to 1 or 2, so the isotropic 3D T1 MR scans did not perform better than BoneMRI in any of the cases studied.

The ICC for pre-operative planning and added value —Figure 4— ranged from 0.41 to 1.00, showing wide variation. The observers' agreement was approximately 0.7 for the statements on the planning of the screw with confidence for the screw length, diameter and position. An ICC of 0.9 was found when visualising landmarks and pathologies, although an ICC of 0.55 was obtained when looking at the presence of pathologies; it ranges from 0.41 to 1.00 when discussing their confidence for preoperative planning on BoneMRI; and a 0.76 and 0.83 was obtained when arguing if the observers felt better prepared for surgery and if BoneMRI provided added value for pre-operative planning, respectively. By inspecting the data, the low ICCs of 0.55 and 0.41 found for "Is pathology present" and "Confidence in screw fixation method", respectively, can be explained by a low variability among the sampled subjects or because of the small number of subjects, instead of a low degree of agreement, as explained by Koo et al. [18]. Contradictorily, an ICC of 1 was obtained for "Confidence on surgical approach" because the results are exactly the same for the three observers —the method is selected independently of the scan. The amount of variability is similar for all the statements, but it has only resulted in unclear ICCs for the questions mentioned above.

The Wilcoxon rank-sum tests, showed in Table IV, demonstrated a significant difference (p-value lower than 0.05) between the presence of pathology and the next statements: "BoneMRI provides a better visualisation of relevant osseous pathologies", "With BoneMRI I would be more confident in the choice of screw fixation method" and "I feel better prepared for surgery if I use BoneMRI for pre-operative planning". For the three questions, the observers introduced scores of 3 to 5 (94%, 90% and 97% scored 4 or 5, respectively, and 6%, 10% and 3% scored a 3, respectively), but a higher percentage of the score 5 was recorded when pathology was present. This relation could be explained straightforwardly, as the visualisation of pathologies can only be rated if there is a pathology and, with the presence of pathology, the observers felt BoneMRI more helpful in terms of screw fixation method and better prepared for surgery. The observers expressed more confidence about planning because of the great representation of pathologies that BoneMRI provided. These findings suggest that BoneMRI provides adequate visualisation of the pathologies.

As demonstrated by the high scores obtained, BoneMRI is considered a valuable tool for surgical planning and navigation of the lumbar and sacral spine.

Despite the optimal results obtained, this study has encountered some methodological considerations that are worth mentioning. Because the questions were based on the whole scans and not the screws placed, the number of subjects may play a role in the results, possibly being too low to represent the whole population (24 patients vs 110 screws). In addition, the patient variation —age, sex, gender, type of pathology, difficulty of operation, etc.— could be investigated in future analyses. There is also low variability between the observers, which results in unclear ICCs. However, this could be an effect of the high image quality of the scans or be due to the similar backgrounds of the observers, who are representatives of the potential end-users of the product. Finally, performing surgery based on the pre-operative planning performed with BoneMRI could give a deeper insight into the performance of BoneMRI for surgical planning and navigation. Statistics, like the number of screw placement plannings that needed to be modified during surgery, or the percentage of screws' misposition, could be employed to verify the feasibility of planning with BoneMRI.

V. CONCLUSION

IN conclusion, BoneMRI produces adequate qualitative image quality, providing optimal visualisation of the lumbar and S1 vertebrae. The value of BoneMRI scans for surgical planning and navigation in the spine has been demonstrated.

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