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REVIEW ARTICLE

Diffusion-weighted MRI of the abdomen

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ABSTRACT

Today, diffusion-weighted MRI is an important, complementary sequence in an MRI of the abdomen, especially in oncological questions, but also in inflammatory diseases. The following paper deals with the technical basics and shows typical indications and findings as well as the value of the method in the diagnosis of parenchymatous upper abdominal organs and the gastrointestinal tract.

Keywords: Diffusion-weighted MR Imaging; Apparent Diffusion Coefficient; Abdomen

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1. Introduction

The principle of diffusion-weighted MR imaging (DWI) was described as early as the 1950s and 1960s by Carr and Purcell and by Stejskal and Tanner and has become established in neuroradiology as a standard sequence, particularly in the diagnosis of acute stroke, since the description of the intravoxel incoherent motion technique by Le Bihan and colleagues in 1988. Because DWI is highly susceptible to artifacts, but motion artifacts hardly play a role in brain tissue, where there is also a high signal-to-noise ratio (SNR), DWI was initially limited to the diagnosis of cerebral diseases. Physiological motion artifacts, caused for example by intestinal motility, cardiac pulsations or respiration, prevented the use of DWI in wide areas of the human body for many years. Only in the recent past have technical advancements in MRI—e.g., the introduction of echoplanar imaging, the use of multichannel body coils, or the development of parallel imaging techniques—allowed the acquisition of comparatively low-artifact, high-quality, diffusion-weighted images of the abdomen.

2. Technical basics of DWI of the abdomen

2.1 Principle

DWI can be used to map the extent of intracellular and extracellular diffusion of hydrogen protons in the human body. The diffusion of hydrogen protons in tissues is inversely correlated with the cellularity and the integrity of membranous structures, which act as natural diffusion barriers both intracellularly and extracellularly. Compared to healthy tissue, for example, tumors:

In tumorous tissue, cellularity is often increased, limiting extra-

cellular diffusion.

● Tumor cells usually show high mitotic activity, i.e., they have comparatively large nuclei (high nuclear/plasma ratio) and are rich in intracellular organelles (e.g., rough endoplasmic reticulum, Golgi apparatus), which as membrane-rich structures restrict the intracellular diffusion of hydrogen protons.

In order to visualize the extent of diffusion using MR imaging, during acquisition of a T2w spin-echo sequence, 2 additional gradient pulses of equal strength oriented in the same direction are switched symmetrically before and after the 180° refocusing pulse (**Figure 1**). The first gradient leads to a dephasing of the spins. If all spins remained in the same place (no diffusion), they would be completely rephased again by the second gradient. However, if a change of location of the spins by diffusion takes place in the meantime, the rephasing is incomplete and a signal drop can be measured. Therefore, the larger this change of location, i.e., the more the hydrogen protons move, the lower the signal strength.

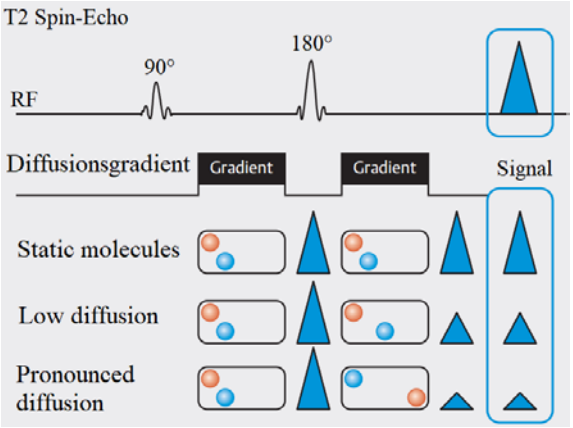

Figure 1. Schematic representation of a diffusion-weighted sequence based on a T2 TSE sequence. Symmetrically around the 180° refocusing pulse, 2 additional gradient pulses of equal strength oriented in the same direction are switched. The first gradient causes dephasing of the spins, the second gradient causes rephasing of the spins that are still within the same voxel. If all spins remained in the same place (static molecules), they would be completely rephased again by the second gradient. However, if a change of location of the spins by diffusion takes place in the meantime, the rephasing is incomplete and a signal drop can be measured. The lower the signal strength, the more the hydrogen protons move.

Amplitude, duration and distance of the two pulses are included in the diffusion weighting factor, the so-called b-value. The b-value is an adjustable sequence parameter (unit: s/mm^2). The larger the b-value is chosen, the greater the signal loss caused by a diffusion movement. For sequence acquisition with different b-values, the signal loss follows an exponential curve as the b-value increases. The "slope" of this curve or the "best exponential fit" is described by the ADC value (ADC = "apparent diffusion coefficient"), which thus allows quantification of the extent of diffusion of hydrogen protons (**Figure 2**).

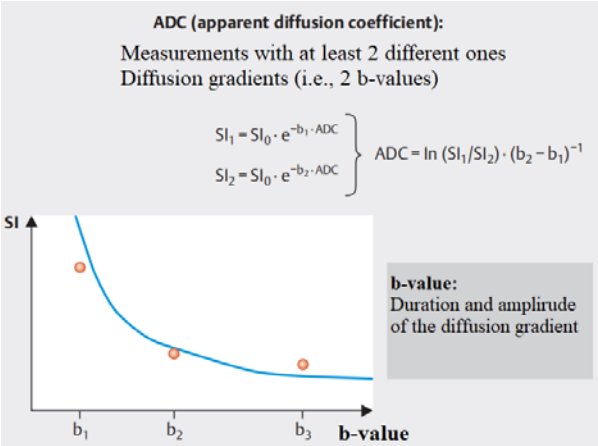

Figure 2. The larger the b-value is selected, the stronger the signal loss caused by a diffusion movement. For sequence acquisition with different b-values, the signal loss follows an exponential curve as the b-value increases. The "slope" of this curve or the "best exponential fit" is described by the ADC value, which allows quantification of the extent of diffusion of hydrogen protons.

With a high b-value, i.e., strong diffusion weighting, the contrast between tissues with different diffusion behavior increases. However, a high b-value requires a long echo time (TE), reduces the SNR and leads to stronger image distortions and less accurate ADC measurements. Thus, depending on the body region, a compromise must be found between sufficient diffusion contrast on the one hand and acceptable SNR on the other:

● With a b-value of 0 s/mm^2, the measured signal intensity does not depend on diffusion. The image contrast corresponds to that of a T2w image.

● At low b-values (<100 s/mm^2), blood flow causes suppression of the signal in vessels, the so-called "black blood effect", which can be favorable, for example, to detect tumorous changes (see below). However, since perfusion effects also play a role at low b-values and distort the calculation of the ADC value, high b-values (>500 s/mm^2) must also be acquired.

- At high b-values, perfusion effects do not play a role; a valid calculation of ADC values is therefore possible. Only structures with a high cell density (e.g., brain, lymph nodes, spleen, tumors) are displayed with high signals due to the limited diffusion here.

2.2 Technical implementation of DWI in the abdomen

Single-shot echo planar imaging (SS-EPI) sequences, which have a short acquisition time and high robustness to motion artifacts, have become established for obtaining diffusion-weighted images of the abdomen. Disadvantages of these sequences include limited spatial resolution and a pronounced susceptibility to susceptibility artifacts. Another problem of diffusion-weighted sequences is the low SNR. Strategies to increase the SNR at a given field strength are

- a shorter TE (<100 ms),
- segmental or echo-planar multishot readout, but this increases the acquisition time,
- as well as the use of a comparatively coarse matrix.

Inhomogeneities in the gradient currents, the so-called "eddy currents", can result in image distortions that can be reduced by modern, improved gradient systems and circuits.

The use of parallel imaging techniques is essential for DWI of the abdomen, whether k-space-based ("simultaneous acquisition of spatial harmonics" [SMASH], "generalized autocalibrating partially parallel acquisition" [GRAPPA]) or image-based ("sensitivity-encoded" [SENSE]). On the one hand, this reduces the measurement time and, on the other hand, in connection with shorter echo trains, distortion artifacts can be reduced, the spatial resolution can be increased and DWI sequences with several b-values can be produced.

When acquiring SS-EPI sequences, suppression of the fat signal is required. This is possible by an upstream inversion pulse (STIR use especially in diffusion-weighted whole-body MRI), spectral fat saturation, chemical shift selective fat suppression (CHESS), or water-selective techniques.

DWI sequences can be acquired in breath-holding technique or in free breathing. The achievable SNR is significantly higher for sequences in free breathing. In order to achieve high image quality, recordings in free breathing can be created either with multiple signal acquisitions or in combination with breath-hold and possibly ECG triggering.

Proven parameters for a DWI sequence of the upper abdomen at 1.5 T are:

- b-values 50, 300 and 600 s/mm^2 (alternatively: 50, 400 and 800 s/mm^2)
- TE 69 ms, TR 3,000 ms
- Echo train length 58, echo spacing 0.69 ms
- Bandwidth 1,736 Hz/pixel
- spectral fat saturation ("spectral presaturation attenuated inversion-recovery" [SPAIR])
- Field of View (FoV) 263 × 350 mm
- Matrix 144 × 192
- Layer thickness 5 mm
- iPAT factor 2 (GRAPPA)
- Breath triggering ("prospective acquisition correction" [PACE])

2.3 Image interpretation

The signal behavior of a structure, e.g., a tumor, at different b values allows conclusions to be drawn about the nature of the structure when assessed qualitatively (**Figure 3**):

Cystic lesions show high signal intensity at low b-values, lose signal at higher b-values and are correspondingly bright on the ADC parameter image.

Solid, cell-rich lesions, on the other hand, retain a high signal (low diffusion) even at a high b value and are correspondingly dark on the ADC parameter image.

However, because the signal intensity of a lesion in DWI depends not only on the extent of diffusion but also on the T2 relaxation time, lesions with very long relaxation times (e.g., cysts) may appear hyperintense even at high b-values and feign limited diffusion ("T2-shine-through" artifact). In this case, the lesion also appears hyperintense on the ADC parameter image (**Figure 3**). This illustrates that image interpretation always requires a synopsis with the standard morphological sequences.

In principle, it is possible to quantitatively characterize lesions on the basis of the ADC value.

Malignant, cell-rich lesions usually show lower ADC values (typically < 1.2–1.4 × 10^{-3} mm^2/s) than benign, cell-poor lesions. However, caution should be exercised in necrotic tumors or partially solid lesions with mucinous/cystic components. In addition, the significant overlap in ADC values of benign and malignant lesions reported in numerous studies limits the utility of quantitative characterization based on ADC value. It should also be noted that ADC values determined on different devices or in different institutions cannot usually be compared due to the still very low standardization of sequence parameters.

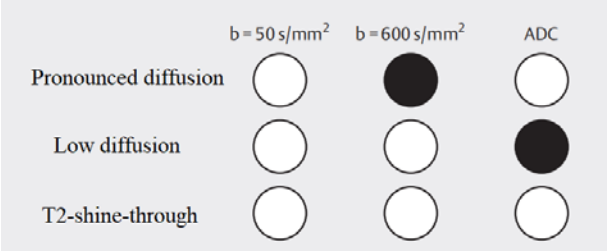

Figure 3. Lesions in which pronounced diffusion is possible, such as cysts, show high signal intensity at low b-values, lose signal at higher b-values, and are correspondingly bright on the ADC parameter image. Solid, cell-rich lesions with limited diffusion retain high signal even at high b-values and are correspondingly dark on the ADC parameter image. Lesions with a very long T2 relaxation time (e.g., cysts) may appear hyperintense even at high b-values, mimicking restricted diffusion ("T2-shine-through" artifact). In this case, however, the lesion also appears hyperintense on the ADC parameter image.

3. Diffusion imaging of the parenchymatous upper abdominal organs

3.1 Liver

3.1.1 Detection of focal liver lesions

According to numerous studies in recent years, focal liver lesions can be detected significantly better with DWI than with standard morphological sequences. While the latter are usually sufficient to reliably detect lesions with a diameter >10 mm, DWI is particularly useful for small, focal lesions (diameter ≤10 mm). In particular, on images at low b value (e.g., b = 50 s/mm^2), most focal liver lesions show a high SNR and, because blood vessels do not give a signal ("black blood effect"), are clearly hyperintense compared with the surrounding liver parenchyma (**Figure 4**). Small and minute lesions, which are often difficult to delineate on T2w sequences, are not a problem with signal-free vessels on DWI. Here, DWI is superior to T2w sequences and, as a method without the use of a contrast agent, is equivalent to contrast-enhanced MRI after application of the hepatocyte-specific contrast agent Gd-EOB-DTPA. The combination of DWI and Gd-EOB-DTPA-enhanced MRI can significantly increase the sensitivity for detecting lesions smaller than 10 mm[1]. However, a disadvantage of assessing diffusion-weighted low b-value images is that differentiation of focal lesions is not possible, as approximately all different lesions present hyperintense.

3.1.2 Characterization of focal liver lesions

In addition to detection, DWI also allows qualitative and quantitative characterization of focal liver lesions. Of particular importance here are images acquired at higher b-values (e.g., 600 or 800 s/mm^2):

- *Qualitatively*, cystic and solid liver lesions can be differentiated. Whereas cysts lose signal at higher b-values, solid lesions remain hyperintense (caution: exception in "T2-shine-through" artifact, **Figure 5**). However, if the lesion is solid, purely qualitative visual analysis does not distinguish between benign (e.g., focal nodular hyperplasia [FNH], hepatocellular adenoma) and malignant lesions, as both are hyperintense at high b-values.
- *Quantitatively*, characterization of focal liver lesions is possible by measuring ADC values. Benign liver lesions show higher ADC values than malignant lesions. Problematically, ADC values of benign and malignant lesions overlap significantly, so this classification should also never be based on DWI alone. Various ADC thresholds (1.4–1.6 × 10^{-3} mm^2/s), with specificities between 77 and 100% and sensitivities between 74 and 100%, are reported in the literature[2].

As in other organs, abscesses in the liver show diffusion restriction, thus they are hyperintense with a high b value and have a low ADC value.

Practical tip:

- DWI is an excellent method to detect focal liver lesions. It shows high sensitivity especially in detecting small lesions (≤10 mm) and should therefore be an integral part of every liver MRI protocol.
- Characterization of focal liver lesions by DWI is possible with only moderate reliability. In the

differential diagnostic classification of a liver lesion, DWI can at best serve as a supplementary component to the morphologic sequences.

3.1.3 Assessment of the response to therapy

As a functional method, DWI could play a role in assessing the response of malignant tumors to therapy. The initially low ADC value of a vital, cell-rich tumor should increase significantly after the start of an effective therapy - after a short, passive drop (approx. 24–48 h after the start of therapy), possibly due to cell swelling—as soon as necrosis occurs in the tumor tissue. This has been shown in numerous studies—both under systemic chemotherapy and after transarterial chemoembolization of HCC foci. However, to date, there are neither reliable thresholds nor sufficient standardization of the use of DWI to assess treatment response (e.g., sequence parameters, timing of examination). Thus, the procedure currently has no assured value in clinical routine in this regard.

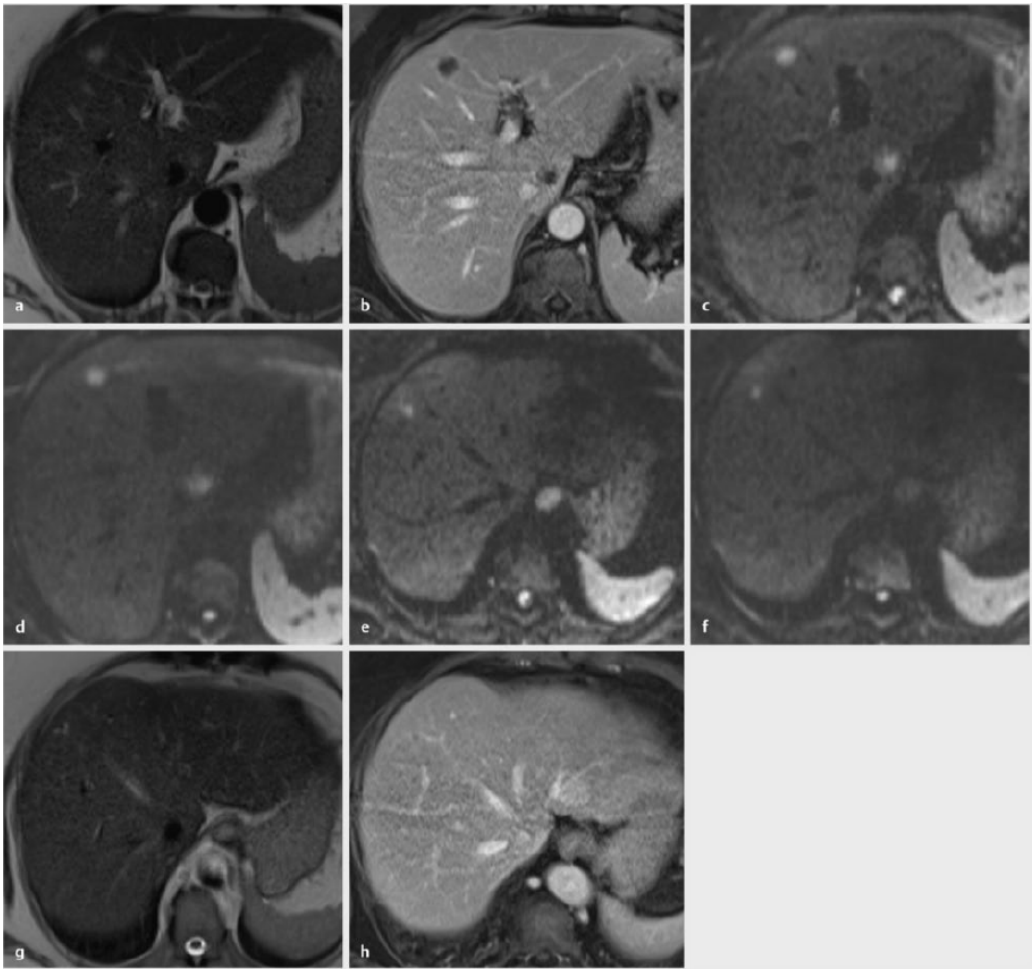

Figure 4. 53-year-old patient with hepatic metastases from colon carcinoma before planned partial liver resection. **a:** in the axial T2-HASTE sequence, flat hyperintense lesions are seen in S4a and S1; **b:** the lesions present centrally hypointense with annular peripheral enhancement in the portal venous phase after contrast administration (ax T1-VIBE); **c:** in DWI, both lesions are hyperintense at b = 50 s/mm^2; **d:** even at b = 600 s/mm^2, both lesions are hyperintense, indicating restricted diffusion; **e:** in DWI, another smallest lesion is detectable in S8, which is hyperintense at b = 50 s/mm^2; **f:** detection of hyperintense lesion in S8 at b = 600 s/mm^2; **g:** the lesion cannot be reliably delineated in T2 weighting; **h:** the lesion cannot be reliably demarcated even after contrast administration.

3.1.4 Assessment in diffuse liver disease

Standard sequences do not reliably diagnose or grade liver fibrosis/cirrhosis. In studies, fibrotic/cirrhotic changes of the liver tissue could be detected and quantified by a decrease of the ADC value in the DWI. The extent to which the ADC value decreases appears to correlate with the extent of liver fibrosis. This is presumably due to an increase in fiber-rich connective tissue detectable in liver fibrosis/cirrhosis

and the resulting decreased diffusion in the liver parenchyma. However, there are currently no reliable reference values for the use of DWI in the detection or quantitative estimation of liver fibrosis/cirrhosis in clinical routine.

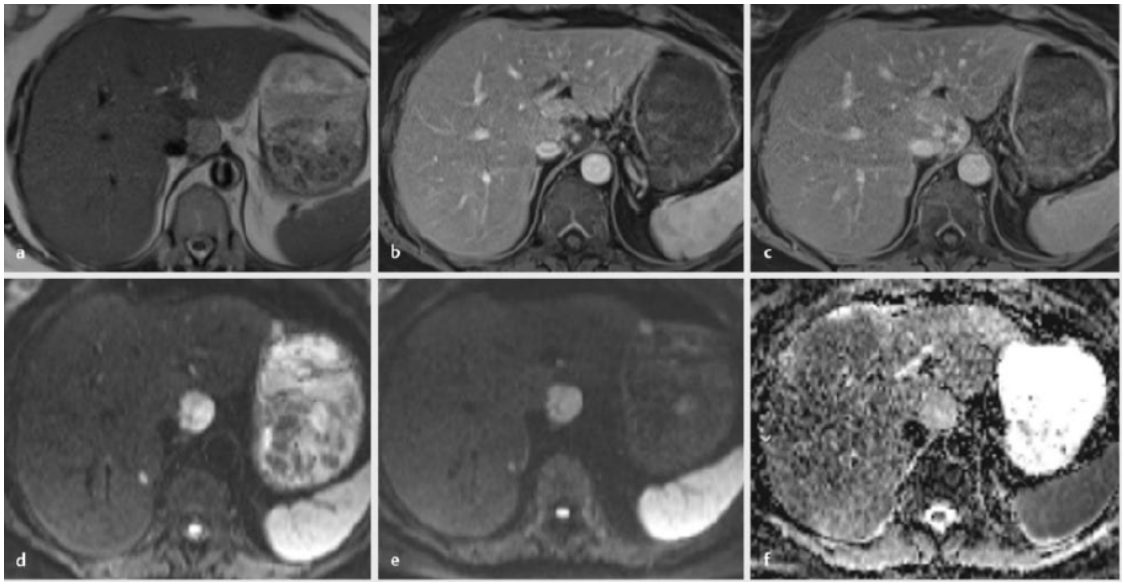

Figure 5. 62-year-old female patient with breast carcinoma who was suspected of having a liver metastasis in S1 on staging CT. **a:** axial T2-HASTE sequence shows a clearly hyperintense lesion; **b, c:** in contrast dynamics, there is peripheral nodular centripetal enhancement, typical of a cavernous hemangioma; **d:** in DWI, the lesion is hyperintense at b = 50 s/mm^2; **e:** hyperintense visualization of the lesion even at b = 600 s/mm^2; **f:** however, the lesion also appears relatively hyperintense on the ADC parameter image; This is a typical finding of a "T2-shine-through" artifact.

The finding should not be described as a suspicious diffusion restriction; in addition to considering the ADC parameter image, the signal behavior of the lesion in the standard morphological sequences is crucial.

3.2 Pancreas

The role of DWI in the evaluation of pathologic processes of the pancreas is less established than for those of the liver. However, because a pancreatic MRI protocol should allow adequate assessment of the presence of liver metastases in oncologic questions, it is recommended that a diffusion-weighted sequence be acquired as part of an MRI scan of the pancreas. Studies have evaluated DWI for its ability to detect and characterize adenocarcinomas of the pancreas, neuroendocrine tumors, and cystic lesions, or to differentiate neoplastic from inflammatory processes. Adenocarcinomas of the pancreas typically present hyperintense with low and high ADC values. This is caused by restricted diffusion due to fibrotic changes resulting from the desmoplastic environmental reaction typical of this tumor entity (**Figure 6**). Especially in small tumors, DWI can be helpful in detecting peritumoral lymph nodes as well as possible liver metastases[3].

The differentiation of an adenocarcinoma from a focal, tumefactive pancreatitis, which is often problematic even with other sequences, is also not achieved with sufficient reliability using DWI (**Figure 7**). Also, differentiation of cystic pancreatic lesions by DWI is not possible with sufficient certainty. Neuroendocrine tumors of the pancreas can usually be well differentiated by DWI because they have restricted diffusion and thus present hyperintense at high b-value and show low ADC.

3.3 Spleen

Due to its high cellularity and consecutively restricted diffusion, the spleen is clearly hyperintense on diffusion-weighted images with a high b value and shows a low ADC value.

Infiltration of the spleen in the setting of Gaucher disease is associated with a decrease in ADC levels, which, according to one study, also appears to correlate with disease severity[4].

There are only isolated case reports on the value of DWI in the evaluation of focal splenic lesions,

such as sclerosing angiomatous nodular transformation (SANT). DWI currently plays no role in clinical routine in this regard.

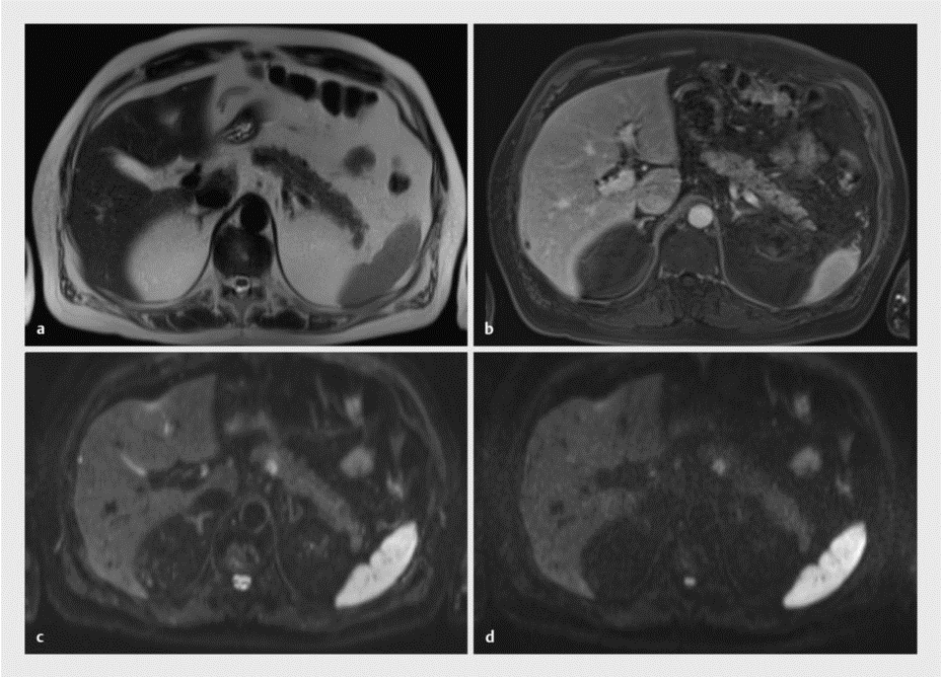

Figure 6. 76-year-old female patient with elevated CA 19-9, CT scan of the upper abdomen was unremarkable, as was endosonography.
a: in the axial T2w sequence, no lesion is detectable in the pancreatic region; **b:** there is also no evidence of a lesion in the contrast dynamic range; **c:** DWI shows circumscribed hyperintensity in the corpus of the pancreas at b = 50 s/mm^2; **d:** this hyperintensity is also found at b = 600 s/mm^2; Histopathologic evaluation of the pancreatic left pancreas resection revealed a ductal adenocarcinoma.

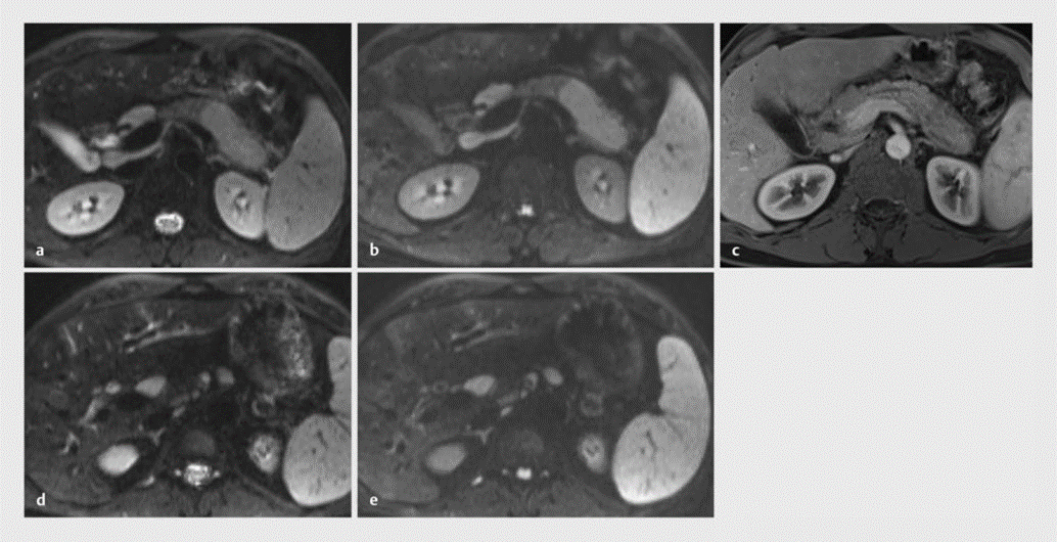

Figure 7. 34-year-old female patient with upper abdominal pain.
a: diffusion weighting shows a clear signal enhancement in the pancreatic tail at b = 50 s/mm^2 (**a**) and (**b**); **b:** hyperintensity in the pancreatic tail is also detectable at b = 600 s/mm^2; **c:** the tail of the pancreas is clearly distended; After contrast administration, a typical halo around the pancreas tail is detectable; Autoimmune pancreatitis, already suspected on the basis of imaging, was confirmed histologically; **d:** increased as well as partially enlarged, reactive, peripancreatic lymph nodes are easily delineated by DWI at b = 50 s/mm^2; **e:** peripancreatic lymph nodes are well delineated even at b = 600 s/mm^2.

3.4 Kidneys

In the evaluation of renal lesions, it is crucial to differentiate cystic and solid lesions, to detect intralesional fat and, if necessary, to document enhancement in the sequences after contrast

administration. DWI has played a minor role in this regard to date. In renal cell carcinoma, it may be helpful in differentiating tumor thrombi, for example. In contrast, DWI cannot make a decisive contribution to the differentiation of solid renal processes. Although oncocytomas show slightly higher ADC values on average than renal cell carcinomas, the overlap of ADC values is too pronounced to dispense with surgical or interventional ablative procedures in individual cases. Due to their lipid content, angiomyolipomas show low ADC values similar to those of renal cell carcinomas. In this case, a differential diagnosis can be made on the basis of standard morphological sequences.

The value of DWI in the diagnosis of non-tumorous diseases of the kidney, such as inflammatory diseases, renal artery stenosis, non-vascular diseases and after kidney transplantation are the subject of scientific investigations.

A recommended sequencing protocol was recently published to standardize DWI in the evaluation of renal pathologic processes[5].

5. Diffusion imaging of intra-abdominal lymph nodes

Accurate lymph node staging is often of high prognostic and therapeutic relevance in malignant tumors. Both CT and MRI currently rely primarily on morphological criteria: A diameter >10 mm in the short axis, rounding, local clustering, growth beyond the capsule, or the presence of central necrosis are considered indicative of lymph node metastasis or malignant lymph node. However, since enlarged lymph nodes need not be metastatically affected and, conversely, infiltration of tumor cells may already be pathologically detectable in non-enlarged lymph nodes (micrometastases), the accuracy of both methods in determining the N stage is rather low.

Lymph nodes can generally be detected well by DWI because, as cell-rich structures, they exhibit limited diffusion and are thus hyperintense to visualize at high b values (**Figure 7d**, **Figure 7e**). DWI can be helpful in differentiating between lymph node metastases and benign lymph nodes.

False positive results may occur in some inflammatory diseases such as mycobacterioses, sarcoidosis or infections with Bartonella henselae (cat scratch disease). False negative results are observed when ADC levels are measured in necrotic areas of lymph node metastasis. Low ADC values are also observed, in particular, in infested lymph nodes in the context of malignant lymphoma. In the future, DWI could play a role in diagnostics, especially in the follow-up of pediatric patients, due to the lack of radiation exposure.

6. Diffusion imaging in the gastrointestinal tract

In contrast to diffusion imaging in parenchymal abdominal organs, the problem with the gastrointestinal tract is that regular bowel wall thickness of 3 to 5 mm with adjacent air within the bowel often results in artifacts and thus diffusion imaging, especially due to bowel motion with ADC images calculated from it, is often not adequately diagnostic.

Questions are:

Primarily acute inflammatory changes of the gastrointestinal tract, e.g., acute inflammatory changes in chronic inflammatory bowel disease (IBD, **Figure 8**), but also the diagnosis of appendicitis or diverticulitis

Chronic changes with increased fibrosis, if applicable, such as in burnt-out colitis or chronic diverticulitis.

Possible fibrosis in the intestine, which is a frequent surgical indication in patients with inflammatory bowel disease.

In oncologic imaging, the search for primary tumors in the esophagus, stomach, colon, and rectum; DWI may also be helpful in evaluating potential peritoneal carcinomatosis, if applicable.

The following is a review of the current literature and clinical applications of diffusion imaging in the gastrointestinal tract topographically from cranial (esophagus) to caudal (rectum).

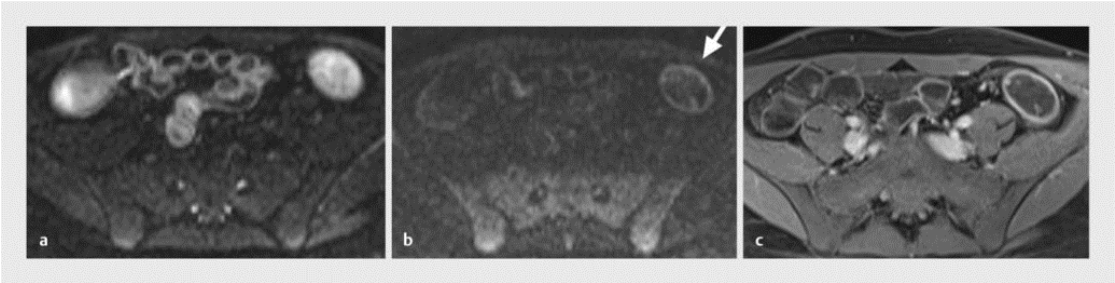

Figure 8. 28-year-old patient with suspected segmental involvement in the region of the descendosigmoid transition in known Crohn's disease.
a: in DWI, the bowel wall is not assessable at b = 50 s/mm^2 due to intraluminal fluid; **b:** at b = 600 s/mm^2 there is a clear signal enhancement of the intestinal wall at the descendosigmoidal junction (arrow) compared to the intestinal wall of the other recorded intestinal segments; **c:** after contrast administration, increased contrast uptake is seen at the appropriate site with moderate bowel wall thickening.

6.1 Esophagus and stomach

Here, only isolated publications exist in the sense of feasibility studies. In principle, MRI imaging with DWI in the esophagus and stomach is very difficult because these regions are very susceptible to artifacts due to the proximity of the beating heart and due to the partial respiratory dependence of the organs, which is exacerbated in diffusion imaging due to the method.

Omur *et al.* performed DWI with determination of ADC value in 94 patients with wall thickening of the stomach diagnosed on CT[6]. In this small group, there was a significant difference between benign masses with ADC values of 2.95 ± 0.59 (×10^{-3} mm^2/s) and malignant tumors in 44% with ADC values of 1.62 ± 0.57 (×10^{-3} mm^2/s). The paper concludes that the ADC value may be useful to evaluate thickening of the gastric wall for differential diagnosis.

Further work on smaller groups of patients investigated the influence of the ADC value with regard to the potential response to chemotherapy or radiotherapy with the result that no significant correlation of the ADC value with the response to therapy can be achieved before therapy[7]. Another paper investigated the correlation of ADC value and TNM staging with the result that ADC value largely correlates with postoperative TNM[8]. Again, there is less immediate clinical benefit to be derived from the work for routine use, so that the ADC value for differential diagnosis or prospective evaluation of treatment response of tumors of the esophagus and stomach could certainly achieve scientific potential in the context of radiomics diagnostics, but currently has no place in routine clinical practice.

6.2 Small intestine

Since tumors in the small intestine are relatively rare, most publications on the topic of diffusion imaging in the small intestine deal with inflammatory changes, as they occur mainly in chronic inflammatory bowel diseases (IBD) and in particular in Crohn's disease.

The first publications on this topic originated in pediatrics with the aim of being able to dispense with intravenous contrasting in MR enterography if necessary. In 2013, Neubauer and colleagues examined 33 children with Crohn's disease, in whom they were able to detect all 22 lesions and complications with DWI in the same way as with the contrast-guided method[9]. False positives were 2 lesions each on DWI and one lesion each on contrast-enhanced MR enterography, which was mainly due to collapsed bowel. In this study, diffusion imaging was equivalent to contrast-enhanced MR enterography in 71% and even superior to contrast-enhanced examination in 27%.

In adult patients, a 2013 publication by Buisson in 31 patients compared with contrast-enhanced MR enterography showed that qualitative assessment of DWI sequence-without quantitative consideration of ADC results-has a sensitivity of 100% and a specificity of 93%, whereas quantitative evaluation of ADC values with a cut-off value of 1.6 (×10^{-3} mm^2/s) achieves a sensitivity of 82% with a specificity of 100%[10].

The study by Seo *et al.* on 50 patients published in 2016 is designed as a "non-inferiority study" and

compares T2 imaging together with diffusion imaging against T2 imaging together with contrast-enhanced imaging and T1w sequences[11]. An agreement of 91.8% is achieved with a correlation ratio of 0.937. Both DWI and contrast-enhanced examinations achieve a sensitivity of 93% and a specificity of 67% each with an equally identical accuracy of 87%. In the study, only one abscess was misinterpreted as phlegmon with the DWI study.

A study by Oussalah *et al.* investigated whether MRI with diffusion imaging is sufficient for colon imaging in patients with inflammatory bowel disease even without oral or rectal contrast and distension[12]. Here, 96 patients were studied, 35% of whom had ulcerative colitis and 61% of whom had Crohn's disease. Here, especially in the patients with ulcerative colitis, the result was surprisingly good with a sensitivity of 89.5% (specificity 86.7%), while the sensitivity for Crohn's disease in the study was only 58%.

6.3 Colon

Again, there is a publication that investigated diffusion imaging to differentiate diffuse wall thickening in 41 patients[13]. Endoscopic imaging correlation was used to differentiate into benign and malignant at an ADC cutoff of 1.21 ($\times 10^{-3}$ mm^2/s), which was achieved with a sensitivity of 100% and a specificity of 87% with an accuracy of 89%. In no case was a malignant lesion falsely judged as benign in this study.

6.4 Rectum

Here, publications exist on smaller patient groups to assess tumor detection or tumor grading. Hosonuma *et al.* investigated the detection rate of rectal cancer in 15 patients with rectal cancer at a b value of 800 with a sensitivity of 100% and a specificity of 65%[14].

Akashi *et al.* used diffusion imaging to investigate the aggressiveness of rectal cancer in 40 patients in correlation with staging and grading[15]. The results of this study showed principally low ADC values in poorly differentiated tumors, although accurate differentiation by ADC values alone was not statistically significant in all cases due to a high overlap of results.

6.5 Peritoneal carcinomatosis

6.5.1 Nuclear Statements

The diffusion of hydrogen protons in tissues depends on cellularity and the integrity of membranous structures that act as natural diffusion barriers. DWI can be used to show differences in the extent of diffusion of hydrogen protons between tumors and healthy tissue, for example.

For the acquisition of high-quality, diffusion-weighted images of the abdomen, fat-suppressed SS-EPI sequences are generally used, in the region of the upper abdomen ideally in free respiration in combination with respiratory triggering.

One domain of DWI is the detection of focal liver lesions. The combination of DWI with contrast-enhanced sequences significantly increases the sensitivity of MRI in detecting small (≤10 mm) focal liver lesions. In the characterization of focal liver lesions, DWI can at best be regarded as an additional tool; in this regard, the established morphologic standard sequences are authoritative.

The role of DWI in the diagnosis of the remaining parenchymal upper abdominal organs is less well studied. Particularly in the kidneys, the procedure could also provide valuable information in the future for non-oncological questions.

Diagnosis of the gastrointestinal tract poses particular challenges for diffusion-weighted sequences, which are susceptible to artifacts. In addition to the diagnosis of the primary tumor, this method is particularly useful for the evaluation of peritoneal carcinomatosis and the diagnosis of chronic inflammatory bowel diseases.

In 30 patients, Soussan *et al.* studied diffusion imaging with PET/CT, with 18 patients subsequently undergoing surgery and 12 patients having follow-up[16]. Overall, 19 of the 30 patients had peritoneal carcinomatosis, which was seen with PET/CT with a sensitivity of 84% and specificity of 73%, with a positive predictive value (PPV) of 84% and a negative predictive value (NPV) of 73%. DWI achieved similarly good values with sensitivities of 84%, specificities of 82%, PPV 89%, and NPV of 75%. Especially supramesocolic, diffusion imaging was superior to PET/CT. For tumors <1 cm, PET/CT achieved a sensitivity of 42%, and DWI imaging achieved a

sensitivity of 50%.

In summary, diffusion imaging is a radiological tool with high potential for detecting infections and tumors in the gastrointestinal tract. However, with the exception of the assessment of the small bowel in Crohn's disease, the study situation is not good enough to consider the method as a clinical routine.

Conflict of interest

The authors declare that they have no conflict of interest.

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