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# Abnormal Findings on “T1WI or DWI or MRCP:” An Effective Boolean Interpretation Model in Discriminating Small Pancreatic Ductal Adenocarcinoma from Control Group

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## ABSTRACT

**Objectives:** The objectives of the study was to evaluate the diagnostic performance of findings on T1-weighted imaging (T1WI), T2-weighted imaging (T2WI), diffusion-weighted imaging (DWI), and magnetic resonance cholangiopancreatography (MRCP) separately and to identify an optimal Boolean interpretation model for discriminating patients with small pancreatic ductal adenocarcinoma (PDAC) from control groups in clinical practice.

**Material and Methods:** We retrospectively enrolled 30 patients with surgery confirmed small PDAC ( $\leq 20$  mm) and 302 patients without pancreatic abnormality between April 2008 and February 2020. The presence of masses was evaluated by T1WI, T2WI, and DWI. Abnormality of the main pancreatic duct (MPD) was evaluated by T2WI and MRCP. Multivariate logistic regression analysis was performed to select significant sequences for discriminating the small PDAC and control groups. Boolean operators “OR” or “AND” were used to construct sequence combinations. Diagnostic performances of these sequences and combinations were evaluated by  $X^2$  tests.

**Results:** The sensitivity of T2WI was lowest (20%) for detecting masses. For evaluating MPD abnormality, sensitivity was higher for MRCP than for T2WI (86.7% vs. 53.3%). Multivariate logistic regression analysis showed that T1WI and DWI for detecting the presence of masses and MRCP for evaluating MPD abnormality were significantly associated with differentiation between the two groups ( $P = 0.0002$ ,  $P = 0.0484$ , and  $P < 0.0001$ , respectively). Seven combinations were constructed with T1WI, DWI, and MRCP. The combination of findings on “T1WI or DWI or MRCP” achieved the highest sensitivity of 96.7% and negative predictive value of 99.6%.

**Conclusion:** The combination of findings on “T1WI or DWI or MRCP” might be an optimal interpretation model for discriminating small PDAC from control groups in clinical practice.

**Keywords:** Non-contrast magnetic resonance imaging, Pancreatic ductal adenocarcinoma, Early diagnosis, Screening, Boolean operators

## INTRODUCTION

The prognosis of pancreatic ductal adenocarcinoma (PDAC) is extremely poor because most patients are diagnosed at advanced stages and unresectable. Early stage PDAC (small PDAC) is

generally defined as a solid pancreatic lesion originating from the intraductal epithelium with the largest diameter  $\leq 20$  mm without lymph nodes or distant metastases.<sup>[1]</sup> The resectability rate and postoperative cumulative 5-year survival rate are higher for small PDAC than for PDAC ( $>20$  mm).<sup>[2,3]</sup>

Several non-genetic risk factors such as age, smoking, alcohol, diabetes, and chronic pancreatitis are associated with the development of PDAC.<sup>[4,5]</sup> Furthermore, approximately 10% of PDACs are related to an underlying familial history or genetic mutation.<sup>[6,7]</sup> Therefore, the goal for PDAC screening should include the early detection of small PDACs that are amenable to receive surgical resection and the follow-up for identified high-risk individuals.<sup>[6]</sup>

In this regard, several studies have evaluated the diagnostic performance of endoscopic ultrasound sonography (EUS), US, computed tomography (CT), and magnetic resonance imaging (MRI).<sup>[3,4,8-13]</sup> MRI has an advantage over EUS, US, and CT in its higher soft-tissue contrast.<sup>[8,14,15]</sup> T1-weighted imaging (T1WI), T2-weighted imaging (T2WI), diffusion-weighted imaging (DWI), magnetic resonance cholangiopancreatography (MRCP), and dynamic contrast-enhanced (DCE) MRI are generally used for diagnosing PDAC.<sup>[16]</sup> Park *et al.* reported the equivalent diagnostic performance of non-contrast T1WI, T2WI, and DWI set and DCE-MRI with MRCP set for detecting small PDAC.<sup>[3]</sup> Furthermore, Kulkarni *et al.* also described that DCE-MRI might not be required for the detection of PDAC or for follow-up surveillance of cystic pancreatic lesions.<sup>[6]</sup>

In clinical practice, we occasionally perform non-contrast MRI for screening or follow-up of high-risk individuals of PDAC. The presence of masses was evaluated on T1WI, T2WI, and DWI. The abnormality of main pancreatic duct (MPD) was evaluated on T2WI and MRCP.<sup>[17]</sup> These findings are intuitively evaluated; however, no studies have provided an interpretation model for detecting small PDAC by applying “logical sum, OR” or “logical product, AND” Boolean operators between the findings to our knowledge.<sup>[18]</sup> When a radiologist makes a clinical judgment, it is important to know whether to treat the patient as suspected small PDAC if positive findings are found only in one sequence or in two or more sequences.

The purpose of this study was to evaluate the diagnostic performance of findings on T1WI, T2WI, DWI, and MRCP separately and to identify an optimal Boolean interpretation model for discriminating patients with small PDAC from control groups in clinical practice.

## MATERIAL AND METHODS

### Patients

Our institutional review board approved this retrospective study and waived the requirement for informed consent. We reviewed the surgical database during April 2008 and

February 2020 at our institution. A total of 43 patients underwent surgery without any prior treatment and were histologically diagnosed as PDAC. The initial MRI evaluation was performed for all the 43 patients. Among them, patients with the longest diameter of  $>20$  mm on portal phase of DCE-MRI were excluded ( $n = 13$ ). Thus, 30 patients were enrolled as the small PDAC group. The median time interval between MRI examinations and surgery was 13 days (range, 0–61 days). For the control group, consecutive patients who underwent the abdominal MRI examination were reviewed during the same period. Initially, a total of 735 patients without any solid or cystic tumors in the pancreas were selected. Because observers might be affected by prominent positive findings in other abdominal organs, the following patients were excluded: (a) Patients with percutaneous transhepatic cholangiodrainage treatment ( $n = 33$ ); (b) patients with severe hepatobiliary dilatation or jaundice ( $n = 306$ ); (c) patients with apparent intrahepatic cholangiocarcinoma ( $n = 80$ ); (d) patients with liver metastasis ( $n = 5$ ); (e) patient with follicular lymphoma in the retro-pancreatic space ( $n = 1$ ); and (f) patients with poor image quality of MRCP ( $n = 8$ ). The control group showed no abnormal findings in the pancreas on MRI and persistently negative findings on follow-up CT or MRI for at least 2 years. Consequently, 302 patients (161 men, 141 women; age range, 14–91 years; mean age, 59 years) were enrolled as the control group.

### MRI protocols

All patients underwent MR examination of the abdomen using a 3.0-T system (MAGNETOM Trio, A Tim System, Siemens Healthcare GmbH, Erlangen Germany). Patients were imaged in the supine position with 12 coil elements. The MR imaging protocols included the following sequences: (1) A T1WI 2D dual-gradient-recalled echo sequence (in-phase and out-of-phase) (189/2.46 [repetition time in milliseconds/echo time in milliseconds]; flip angle, 80°; section thickness, 5 mm; acquisition matrix, 182 × 320; bandwidth, 400 Hz/pixel; field of view (FOV), 340 mm × 340 mm; acquisition time, 17 s); number of excitations (NEX), 2; (2) a breath-hold multi-shot T2WI sequence (2600/102 [repetition time in milliseconds/echo time in milliseconds]; flip angle, 120°; section thickness, 5 mm; acquisition matrix, 182 × 320; bandwidth, 300 Hz/pixel; FOV, 340 mm × 340 mm; acquisition time, 18 s); NEX, 2; and (3) a navigator-triggered axial DWI sequence with single-shot echo planar imaging with motion-probing gradients in three directions (1000/64 [repetition time in milliseconds/echo time in milliseconds], flip angle, 90°; section thickness, 5 mm; acquisition matrix, 90 × 128; bandwidth, 2298 Hz/pixel; FOV, 380 mm × 380 mm; acquisition time, 18 s); NEX, 1; application of motion-probing gradient pulse along the x, y, and z directions. Apparent diffusion coefficient (ADC) maps were automatically created with *b*-values of 0 s/mm<sup>2</sup>

and 800 s/mm<sup>2</sup>; (4) a navigator-triggered three-dimensional MRCP turbo spin-echo sequence (3D MRCP) with 1000/604 [repetition time in milliseconds/echo time in milliseconds]; flip angle, 180°; acquisition matrix, 369 × 384; section thickness, 0.9 mm; bandwidth, 449 Hz/pixel; FOV, 250 mm × 250 mm; acquisition time, 180–240 s. Maximum intensity projection (MIP) in an orientation analogous to that of the navigator-triggered 3D MRCP turbo spin-echo sequences was obtained. To measure the lesion size in the small PDAC group, the portal phase of DCE-MRI was used. DCE-MRI scans were performed with a 3D fat-suppressed T1WI 3D turbo field-echo sequence to obtain arterial phase (30–35 s), portal phase (65–70 s), delayed phase (3 min), and hepatobiliary phase (15 min) of gadoteric acid disodium after the injection of contrast agent (Primovist, Bayer Schering; 0.025 mmol/kg). The contrast agent was injected as a rapid bolus and immediately followed by a 30–35 mL saline flush through a power injector at a rate of 2 mL/s.

### Image analysis

Two observers (observer 1 and 2 with 2 and 12 years of experiences in abdominal imaging, respectively) independently reviewed all MR images. They were only aware that the study was performed to detect small PDAC but blinded to all other information, such as patients' clinical data, other imaging (CT or US), and histological findings. To perform the reading tests, MRI DICOM data of small PDAC group ( $n = 30$ ) and control group ( $n = 302$ ) were transferred from a commercially available workstation (HMC Viewer Ver. V1.0.0, Hitachi, Japan) to a personal computer and presented by software (RadiAnt DICOM Viewer, version 2020.1; <https://www.radiantviewer.com/>). The reading tests contained four sessions of T1WI, T2WI, DWI, and MRCP, separately. Each session contained one single sequence. Images of patients were randomly allocated without repetition under anonymized conditions. The time interval between each session was at least 2 weeks to reduce learning effects. The presence of a mass was evaluated on T1WI, T2WI, and DWI sequences [Figures 1a-c, respectively]. The signal intensity (SI) of the lesion was compared to the surrounding pancreatic parenchyma, and a mass with low SI was recorded as positive on T1WI, a mass with iso- or high SI was recorded as positive on T2WI, and a mass with high SI was recorded as positive on DWI. In case when the presence of a mass was evaluated as positive on T1WI or T2WI, we placed oval or round regions of interest (ROIs) as large as possible within the lesion and surrounding pancreatic parenchyma by consensus. The ratio of SI ( $SI_{ratio}$ ) between the lesion and surrounding pancreatic parenchyma was calculated as follows;

$$SI_{ratio} = SI_{lesion} / SI_{parenchyma}$$

For DWI, we placed an oval or round ROI as large as possible within the lesions by consensus in case when the presence of

a mass was evaluated as positive on DWI. The mean ADC values of the ROIs were recorded.

The MPD abnormality was evaluated on T2WI and MRCP [Figures 1d and e, respectively]. Dilatation of the MPD on T2WI and dilatation (maximal diameter of a MPD >3 mm) or narrowing of the MPD on MRCP was detected as positive.<sup>[3,19]</sup> The presence of a mass on T2WI was recorded as T2-mass, and MPD abnormality on T2WI was recorded as T2-MPD. Lesion size (maximum diameter in the axial plane) and location (head, uncinata, body, and tail) were evaluated based on the portal phase of DCE-MR images, because the portal phase provides good contrast of lesion to surrounding pancreatic parenchyma and anatomical information. Our purpose was to evaluate the diagnostic performance of combination of findings on non-contrast MRI sequences, and portal phase was not used for the Boolean combination. Other patients' clinical data, such as gender and age, were also recorded.

### Statistical analysis

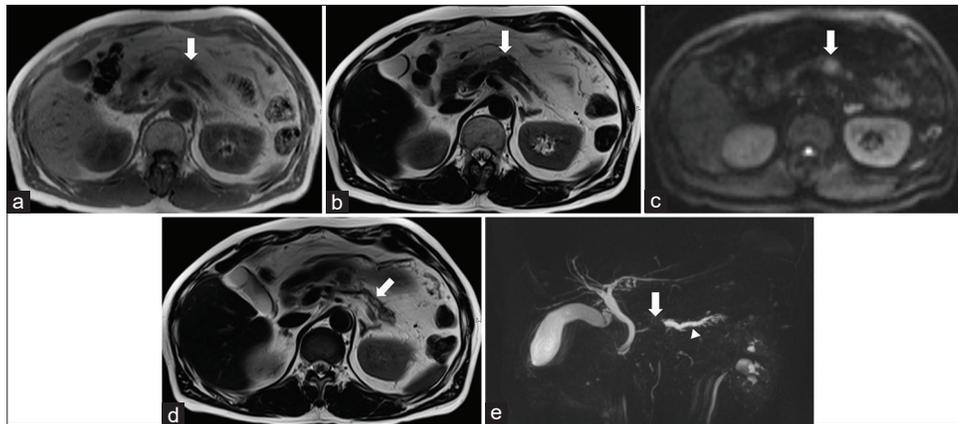
The patients' gender was compared between the two groups using Fisher's exact test. The patients' age was compared between the small PDAC and control groups using Mann-Whitney U test. Reading results (T1WI, T2-mass, DWI, T2-MPD, and MRCP) were treated as binomial variables (negative: 0, positive: 1), and the diagnostic performances of T1WI, T2-mass, DWI, T2-MPD, and MRCP were evaluated using  $X^2$  tests, and sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV) were calculated. To select the findings of imaging sequences significantly associated with differentiation between the small PDAC and control groups, multivariate logistic regression analysis was performed. From the selected sequences for separately evaluating mass and MPD abnormality, combinations were subsequently constructed by applying Boolean operators "logical sum, OR" or "logical product, AND."<sup>[18]</sup> When the operator "OR" was applied, a combination was recorded as "positive" if there was at least one positive finding from the selected sequences. None of them was recorded as "negative." When the operator "AND" was applied, a combination was recorded as "positive" if positive findings were found in every involved sequence, otherwise a combination was recorded as "negative." Diagnostic performances of the combinations were evaluated using  $X^2$  tests, and sensitivity, specificity, PPV, and NPV were calculated. The interobserver agreement between the two observers was calculated using  $\kappa$  statistics. A  $\kappa$  value of 1.0 indicated perfect agreement; 0.81–0.99, almost perfect agreement; 0.61–0.80, substantial agreement; 0.41–0.60, moderate agreement; 0.21–0.40, fair agreement; and  $\leq 0.20$ , slight agreement, respectively.<sup>[20]</sup> The  $SI_{ratio}$  on T1WI and T2WI, and the mean ADC value of a lesion were recorded.

Statistical analyses were performed on JMP Pro 15 (SAS Institute, Cary, NC).  $P < 0.05$  was considered as statistically significant.

## RESULTS

No significant difference was found in gender between the small PDAC group and control group ( $P = 0.99$ ). Age was significantly higher in the small PDAC group than in the control group ( $P = 0.0083$ ). The lesion size of the small PDAC group ranged from 8 to 20 mm (median, 17 mm). Seventeen lesions located in the pancreatic head, four in the uncinate, eight in the body, and one in the tail [Table 1]. In detecting the presence of mass, the sensitivity of T2-mass was lowest [20%, Table 2]. In detecting the presence of MPD abnormality, the sensitivity was higher for MRCP than for T2-MPD (86.7% vs. 53.3%, respectively). Multivariate logistic regression analysis showed that T1WI and DWI for detecting the presence of mass were significantly associated with the differentiation between small PDAC and control groups ( $P = 0.0002$  and  $P = 0.0484$ , respectively). The  $SI_{ratio}$  on T1WI was  $0.74 \pm 0.10$ , indicating small PDACs presented

lower SI compared to surrounding pancreatic parenchyma on T1WI. The  $SI_{ratio}$  on T2WI was  $1.22 \pm 0.39$ , indicating small PDACs presented slightly higher SI compared to surrounding pancreatic parenchyma on T2WI. The mean ADC of lesion was  $1.49 \pm 0.34 \times 10^{-3} \text{ mm}^2/\text{s}$ . MRCP for detecting MPD abnormality was also significantly associated with the differentiation between the two groups ( $P < 0.0001$ ), whereas T2-mass and T2-MPD were not ( $P = 0.6680$  and  $0.5904$ , respectively). The  $\kappa$  value for T1WI and DWI was 0.67 and 0.62, indicating substantial interobserver agreement. The  $\kappa$  value for MRCP was 0.82, indicating almost perfect interobserver agreement [Table 2]. The selected sequences were T1WI, DWI, and MRCP. The seven combinations were constructed as follows: T1WI or DWI or MRCP, (T1WI or DWI) and MRCP, (T1WI or MRCP) and DWI, T1WI and DWI and MRCP, (T1WI and DWI) or MRCP, (T1WI and MRCP) or DWI, and (DWI or MRCP) and T1WI. Among these combinations, the combination “T1WI or DWI or MRCP” showed the highest sensitivity in detecting small PDAC (96.7%). The specificity of “T1WI or DWI or MRCP” was 93.4%, lower than the other combinations. The NPV of



**Figure 1:** A 63-year-old man diagnosed with pancreatic ductal carcinoma by ultrasound-guided fine-needle aspiration. T1-weighted imaging shows a mass with low signal intensity in the pancreatic body (arrow) (a). T2-weighted imaging shows a mass in the pancreatic body (arrow) (b). Diffusion-weighted imaging (b value  $800 \text{ s}/\text{mm}^2$ ) shows a mass with high signal intensity in the pancreatic body (arrow) (c). Mild dilatation of the main pancreatic duct in the pancreatic tail (arrow) (d). The maximum intensity projection image of magnetic resonance cholangiopancreatography shows abrupt cutoff of the main pancreatic duct (arrow) with dilatation of the upstream main pancreatic duct and side branches (e).

**Table 1:** Patients and lesion background characteristics of the small pancreatic ductal adenocarcinoma and control groups.

Variables	Small PDAC group (n=30)	Control group (n=302)	P-value
Gender (Male/Female) (n (%))	16 (53)/14 (47)	161 (53)/141 (47)	0.99
Age (median [range]), (years)	64.5 (54–84)	60.5 (14–91)	0.0083 <sup>a</sup>
Lesion Size (median [range]), (mm)	17 (8–20)	N/A	N/A
Lesion location (n (%))			
Head	17 (57)	N/A	N/A
Uncinate	4 (13)	N/A	N/A
Body	8 (27)	N/A	N/A
Tail	1 (3)	N/A	N/A

<sup>a</sup>Statistically significant. N/A: Not applicable

“T1WI or DWI or MRCP” was 99.6%, higher than the other combinations [Table 3]. The  $\kappa$  value for the combination “T1WI or DWI or MRCP” was 1.0, indicating perfect interobserver agreement.

## DISCUSSION

In this study, we separately evaluated the diagnostic performance of findings on non-contrast T1WI, T2WI, DWI, and MRCP sequences in detecting small PDAC by evaluating the presence of mass and the MPD abnormality. The combination “T1WI or DWI or MRCP” showed higher sensitivity (96.7%) and NPV (99.6%) than the other combinations. The presence of at least one positive finding from the three sequences suggests the presence of a small PDAC and further clinical examination should be considered.

Independent evaluation of each sequence is not generally performed in clinical practice; however, separate reading tests for evaluating findings on each sequence could help radiologists recognize the roles and relationships of these non-contrast sequences. A few studies have reported the diagnostic performance of non-contrast MRI sequences for detecting small PDAC. Park *et al.* demonstrated that non-contrast MRI sequences comprising T1WI, T2WI, and DWI showed comparable diagnostic performance to that of DCE-MRI with MRCP.<sup>[3]</sup> Some studies suggest that gadolinium contrast may not be required for the detection of PDAC.<sup>[6]</sup> Another study by Kawakami *et al.* suggested that DWI combined with MRCP was effective for detecting

PDAC.<sup>[21]</sup> Therefore, we enrolled only non-contrast sequences for diagnostic performance evaluation.

We used the Boolean operators, “logical sum, OR” and “logical product, AND” to construct sequence combinations.<sup>[18]</sup> In this study, “logical sum, OR” means that if there is at least one positive finding in these sequences, the combination is recorded as positive; and “logical product, AND” means that only if all sequences have a positive result, the combination is recorded as positive. Our results showed that T2-mass and T2-MPD were not significantly associated with differentiation between the small PDAC and control groups; therefore, T2WI was excluded from the construction of combinations. Harrington *et al.* reported that small PDAC could be detected as a mass on T1WI or an MPD abnormality on MRCP.<sup>[22]</sup> Ichikawa *et al.* demonstrated the high sensitivity and specificity of DWI for detecting PDAC.<sup>[23]</sup> Our results were consistent with these previous reports showing the usefulness of T1WI, DWI, and MRCP. We validated the visual reading tests by quantifying the  $SI_{ratio}$  on T1WI or T2WI. When the presence of a mass was evaluated as positive on T1WI, low  $SI_{ratio}$  ( $0.74 \pm 0.10$ ) supported the lower SI of lesions compared to surrounding pancreatic parenchyma on T1WI. When the presence of a mass was evaluated as positive on T2WI, the  $SI_{ratio}$  ( $1.22 \pm 0.39$ ) indicated the slightly higher SI of lesions compared to surrounding pancreatic parenchyma on T2WI. The mean ADC of lesion was  $1.49 \pm 0.34 \times 10^{-3} \text{mm}^2/\text{s}$ , which was almost similar to the results in a previous study ( $1.46 \pm 0.18$ ).<sup>[24]</sup>

As for the combination, “T1WI or DWI or MRCP” was constructed by “logical sum, OR” and showed higher

**Table 2:** Diagnostic performance of non-contrast MRI sequences in evaluating mass and main pancreatic duct abnormality for detecting small pancreatic ductal adenocarcinoma.

	Sequences	Sensitivity	Specificity	PPV	NPV	P-value (univariate)	P-value (multivariate)	$\kappa$
Mass	T1WI	80	98.3	82.8	98	<0.0001 <sup>a</sup>	0.0002 <sup>a</sup>	0.67
	T2-mass	20	98.7	60	92.5	<0.0001 <sup>a</sup>	0.6680	0.34
	DWI	66.7	96	62.5	96.7	<0.0001 <sup>a</sup>	0.0484 <sup>a</sup>	0.62
MPD	T2-MPD	53.3	98.3	76.2	95.5	<0.0001 <sup>a</sup>	0.5904	0.76
	MRCP	86.7	99	89.7	98.7	<0.0001 <sup>a</sup>	<0.0001 <sup>a</sup>	0.82

<sup>a</sup>Statistically significant. PPV: Positive predictive value, NPV: Negative predictive value

**Table 3:** Diagnostic performance of the combinations of sequences for detecting small pancreatic ductal adenocarcinoma.

Combinations	Sensitivity	Specificity	PPV	NPV	P-value	$\kappa$
T1WI or DWI or MRCP	96.7	93.4	59.2	99.6	<0.0001 <sup>a</sup>	1.00
(T1WI or DWI) and MRCP	83.3	100	100	98.4	<0.0001 <sup>a</sup>	0.81
(T1WI or MRCP) and DWI	66.7	100	100	96.8	<0.0001 <sup>a</sup>	0.74
T1WI and DWI and MRCP	46.7	100	100	95.0	<0.0001 <sup>a</sup>	0.73
(T1WI and DWI) or MRCP	93.3	99	90.3	99.3	<0.0001 <sup>a</sup>	0.81
(T1WI and MRCP) or DWI	90	96	69.2	99.0	<0.0001 <sup>a</sup>	0.68
(DWI or MRCP) and T1WI	76.7	100	100	97.7	<0.0001 <sup>a</sup>	0.80

<sup>a</sup>Statistically significant. PPV: Positive predictive value, NPV: Negative predictive value

sensitivity (96.7%) and NPV (99.6%) but lower PPV (59.2%) than the others. These results suggest that this combination can effectively detect patients with small PDACs. When a patient was judged as negative using the “T1WI or DWI or MRCP” combination, it highly suggested that the case was normal. False positives may be due to the low PPV. To improve PPV, other biomarkers need to be incorporated into non-contrast MRI in the screening of high-risk individuals.

The diagnostic performance of the combination “T1WI or DWI or MRCP” for detecting small PDAC might be addressed from the following mechanisms and drawbacks. On T1WI, the normal pancreas generally has a moderate-to-high SI due to the influence of high protein-containing water in the acinar cells, whereas SI may be lower for lesions with damaged acinar cells than for a normal pancreas. In patients with chronic pancreatitis or atrophy, the entire pancreas might present with low SI on T1WI, making it difficult to detect small PDAC.<sup>[25,26]</sup> DWI exploits the random motion of water molecules in biological tissues. PDAC with reduced diffusion of water molecules typically shows a high SI on DWI.<sup>[27,28]</sup> However, one study reported that PDACs could not be detected as a mass with a SI higher than that of a normal pancreas because PDACs are occasionally accompanied by a variable degree of obstructive pancreatitis showing high SI on DWI.<sup>[29]</sup> Furthermore, the low spatial resolution of DWI might be another drawback. MRCP acquires heavily T2-weighted images and captures abnormalities of the pancreatic duct associated with the presence of PDAC.<sup>[17]</sup> Especially the MIP, which is reconstructed from three-dimensional MRCP, can identify the three-dimensional anatomy of pancreatic ducts with high resolution.<sup>[22]</sup> An abrupt cutoff of the MPD strongly suggests the presence of mass.<sup>[30,31]</sup> However, an abrupt cutoff of the MPD is a secondary finding, and it is difficult to detect small PDAC in patients in which the MPD is unaffected or small lesions in the tail of the pancreas. In this way, the combination “T1WI or DWI or MRCP” could compensate for the drawbacks of each sequence and increase the sensitivity to detect small PDAC.

This study had several limitations. First, this retrospective study had an uneven sample sizes and unavoidable selection bias between the small PDAC and control groups. Although the lesion location of small PDAC varied in this study, subgroup analysis according to the lesion location could not be performed due to the small sample size. Furthermore, the percentages of sensitivity and NPV in this study might be affected by the sample size of small PDAC and control groups. However, the superiority of combination “T1WI or DWI or MRCP” in diagnostic performance compared to other combinations was identified. Multi-center studies with larger sample sizes are needed. Second, patients with other histological types, such as pancreatic endocrine neoplasm, intraductal papillary mucinous neoplasm, and pancreatic

cyst were excluded in this study. The clinical management is different between small PDAC and such histological types, and further research to determine how to discriminate these histological types from control groups will be needed. Third, we selected consecutive patients who underwent the abdominal MR examination without apparent pancreatic abnormalities as the control group. PDAC screening might not be performed for the general population because of low disease frequency, and stratification of high-risk individuals with background pancreatic disease, including chronic pancreatitis, diabetes, and pancreatic cystic disease, is necessary for PDAC screening. These high-risk individuals are the differential diagnosis to small PDACs. Our control group without high-risk individuals or differential diagnosis might artificially improve the diagnostic performances of sequence combinations. Further studies to differentiate patients with small PDAC from high-risk individuals should be conducted in the future.

In conclusion, the combination of findings on “T1WI or DWI or MRCP” might be an optimal Boolean interpretation model for discriminating small PDAC from control groups in clinical practice.

#### Declaration of patient consent

Institutional Review Board (IRB) permission obtained for the study.

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#### Conflicts of interest

There are no conflicts of interest.

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