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The Efficacy of Color-Mapped Diffusion-Weighted Images Combined With CT in the Diagnosis and Treatment of Cholesteatoma Using Transcanal Endoscopic Ear Surgery

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Objective: To assess the efficacy of a color-mapped diffusion-weighted image combined with a computed tomography scan (CMDWI-CT) in preoperatively evaluating the anatomical location of cholesteatomas and determining whether a patient is indicated for transcanal endoscopic ear surgery (TEES) to reduce intraoperative switching to microscopic ear surgery (MES).
Study Design: Prospective case study.
Setting: A single university hospital.
Patients: Fifty-five patients scheduled for middle ear cholesteatoma surgery.
Intervention: The CMDWI-CT is produced in a multistep process. A color-mapped fusion image (CMFI) is created by performing MR cisternography on a 1-mm thin-slice nonecho planar diffusion-weighted imaging (non-EPI DWI) and then by performing color mapping on the resulting image to enhance cholesteatoma visualization. False positives are reduced by taking a T1-weighted image (T1WI), whereas false negatives are further reduced by preoperative endoscopic examination. As cholesteatomas are difficult to locate on a CMFI in the temporal bone region, we stripped out the MR cisternography data from the CMFI and then fused the CMFI to the initial computer tomography (CT) scan to create a CMDWI-CT. This CMDWI-CT better clarifies the cholesteatoma position within temporal bone.
Main Outcome Measure(s): CMDWI-CT preoperative findings were compared with intraoperative findings. The positive predictive value and negative predictive value were also evaluated depending on the cholesteatoma location.
Results: CMDWI-CT facilitated accurate detection of the cholesteatoma anatomical location in the temporal bone region which was reflected in positive predictive and negative predictive values of over 90% for all areas of the middle ear.
Conclusion: CMDWI-CT is a reliable diagnostic modality for evaluating the anatomical location of cholesteatomas that seem as high-signal regions on a CMFI and for determining whether TEES is indicated for treatment in such patients.
Key Words: Cholesteatoma—Color-mapped diffusion-weighted images combined with CT scan—Color-mapped fusion image—T1-weighted image—Transcanal endoscopic ear surgery.

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Transcanal endoscopic ear surgery (TEES) is an extremely effective procedure for the removal of cholesteatomas (1–3). TEES can be further combined with powered instruments to treat cholesteatomas extending up to and including the antrum (4). However, when a cholesteatoma extends into the central mastoid as defined by Tos (5), we employ a dual approach using both TEES and microscopic ear surgery (MES). Unfortunately, diagnostic imaging technology has not, up until now, been able to provide surgeons with 100% accurate information on the location of each cholesteatoma because of the presence of temporal bone. Thus, preoperative planning always contains a higher level of uncertainty than desired. Subsequently, surgeons may discover during the actual surgery that a cholesteatoma is located deeper in the middle ear than indicated by preoperative planning and have to switch from an exclusive TEES approach to a dual TEES/MES approach. This situation is far from ideal for not only surgeons, but also patients because switching approaches during surgery obviously extends the length of the surgical procedure.

We have been working to improve the preoperative planning stage and eliminate the need to switch from a TEES-alone approach to a dual approach by improving our imaging diagnostic methods. Our efforts have extended over a 2-year period and resulted in a series of three incremental improvements resulting in more accurate images of cholesteatomas. Our first step was to use a 3-mm slice nonecho planar diffusion-weighted

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imaging (non-EPI DWI) for the detection of cholesteatomas. However, the anatomical location is relatively difficult to identify with such images because of low image resolution and an inability to identify most of the intracranial structures.

The second step involved combining a 1-mm slice non-EPI DWI with MR cisternography (MRC) to further clarify the anatomical location of the cholesteatomas. We also performed color mapping on the resulting image to create a color-mapped fusion image (CMFI) to even further enhance the visualization of the cholesteatoma. This CMFI has proven very useful in the accurate detection of cholesteatomas and in the determination of whether or not a patient is indicated for TEES for the treatment of such cholesteatomas. The incorporation of the CMFI into the diagnostic process also provided us with enough information to justify a preoperative endoscopic examination to confirm the location of a cholesteatoma. This step also helps to reduce the number of false negatives.

The third step was designed to decrease the number of false positives by taking a T1-weighted image (T1WI). We recently reported on the end result of all these imaging steps, which has greatly improved our overall diagnostic accuracy for cholesteatomas (6).

However, problems still remained because a CMFI does not accurately visualize bone. Thus although cholesteatomas will seem as a high-signal region in the temporal bone region, the precise location of the cholesteatoma is still difficult to determine. Thus, our latest step in improving the accuracy of our diagnostic imaging process was to further process any CMFIs that had a high-signal region in the temporal bone. This additional processing involved first stripping out the MRC from the original CMFI and instead using imaging data from the initial diagnostic computed tomography (CT) scan. We have named the resulting image a ''color-mapped diffusion-weighted image combined with a CT scan'' or CMDWI-CT.

The aim of this study was to assess the efficacy of a CMDWI-CT in preoperatively evaluating the anatomical location of a cholesteatoma in the temporal bone area. Our research ultimately showed that CMDWI-CTs do provide more accurate diagnostic imaging information that can be used in determining whether a given patient is indicated for TEES or a dual TEES/MES approach.

PATIENTS AND METHODS

Fifty-five patients were included in this study who were treated at our department from September 2013 to May 2014. The mean age of the patient population was 49.2 years (range from 3 to 77 yr old) with a sex ratio of 33 males and 22 females. The initial CT scans revealed that all 55 patients had a soft tissue mass in one or more areas of the middle ear with 36 out of the 55 patients having a soft tissue mass in the tympanic cavity; 44 out of the 55 patients in the attic; 39 out of the 55 patients in the antrum; and 40 out of the 55 patients in the central mastoid.

A CMFI was then created for each patient using a 3.0-T MR unit (Intera Achieva, Royal Philips Electronics Inc., Amsterdam, The Netherlands) in which a 1-mm thin slice non-EPI DWI was processed with MRC after which color mapping was performed. Table 1 shows the parameters for the non-EPI DWI and MRC. The non-EPI DWI and MRC were fused by radiologists using a three-dimensional workstation (Aquarius Net, TeraRecon, Inc., San Mateo, California) which is part of the MRI to provide anatomical information. Color mapping was also performed under the same conditions with each color automatically assigned on the basis of the degree of the signal intensity in the DWI. The highest intensity area was displayed as red. This CMFI shows how the anatomical location of the soft tissue mass is further clarified and the visualization of the cholesteatoma is enhanced (Fig. 1).

The next objective was to create a CMDWI-CT by stripping out the MRC data from the original CMFI and then by adding data from the original diagnostic CT scan to the same CMFI (Fig. 2). The first step was to fuse the original CMFI with the CT scan using a standalone three-dimensional workstation (Ziostation2, Ziosoft, Inc., Tokyo, Japan). Anatomical structures were used as fusion guideposts including the internal auditory canal, cochlear, and semicircular canal. The second step was to strip out the MRC data from the fused image to create a CMDWI-CT. It should be noted that even though the MRC data are stripped out of the CMFI in the second step, the MRC anatomical information is crucial for fusing the original CMFI and CT scan in the first step. Our objective was to visual the relationship via the CMDWI-CT between a cholesteatoma and the surrounding bone which cannot be clearly distinguished by a CMFI alone.

We confirmed the efficacy of CMDWI-CT by preoperatively determining the anatomical location of the cholesteatomas based on a CMDWI-CT and by comparing these preoperative findings to the actual intraoperative anatomical location findings. Our findings were further strengthened by a preoperative endoscopic and discrete T1WI examination separate from any CMFI evaluation to minimize false positives and false negatives. This process ensured good positive predictive values (PPV) and negative predictive values (NPV) for our patient group.

The CMDWI-CT images were evaluated by an experienced radiologist, who was not informed of the otoscopic findings before evaluating the CMDWI-CT. Although a CMDWI-CT was analyzed for each patient, some data were not included for specific regions of the middle ear in 14 of the 55 patients either because a direct endoscopic examination by an otolaryngologist revealed a cholesteatoma without debris (5 of 36 patients with a cholesteatoma in the tympanic cavity, 9 of the 44 patients in the

TABLE 1. *Non-EPI DWI and MRC parameters*

Parameter	Non-EPI DWI	MRC
Field of view (mm)	240	150
Matrix scan	128×128	256×512
Number of sections	32	60
Slice thickness (mm)	1	0.5
B-factor (s/mm^2)	800	—
Echo time (ms)	84	200
Repetition time (ms)	6248	2000
Flip angle (degrees)	90	90
Total scan time (s)	487	218

MRC indicates MR cisternography; Non-EPI DWI, nonecho planar diffusion-weighted imaging.

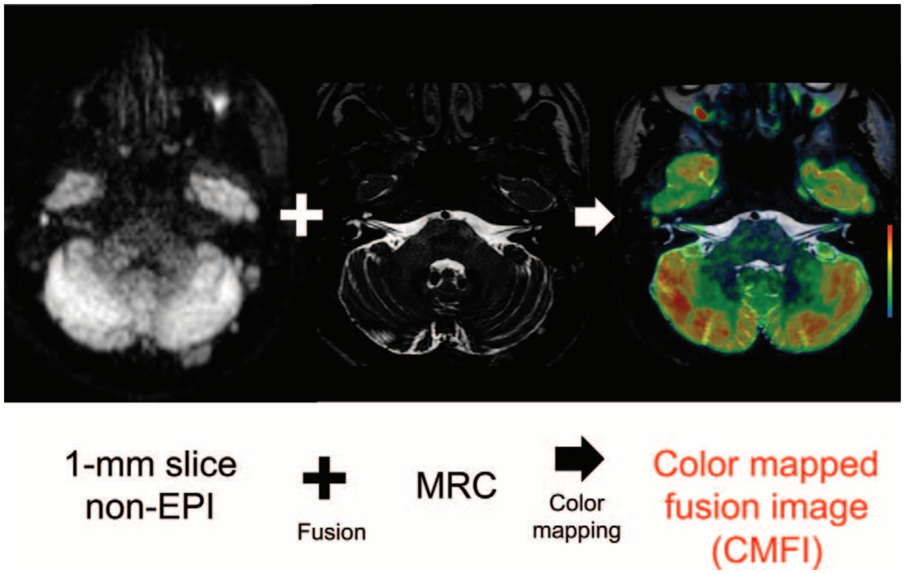

FIG. 1. CMFI processing. We combined a 1-mm slice non-EPI DWI with MRC. We also performed color mapping to enhance the visualization of the cholesteatoma. MRC indicates MR cisternography.

attic, and 2 of the 39 patients in the antrum) or because a high-intensity region was observed on both the CMFI and the T1WI, which strongly suggests that the high-intensity region is a cholesterol granuloma (1 of 39 patients in the antrum and 3 of 40 patients in the central mastoid). All data were used for the remaining 41 patients.

RESULTS

Although a CMFI provides valuable data on high-intensity signal regions indicative of a cholesteatoma, a CMDWI-CT yields data that allow for more accurate localization of cholesteatomas within temporal bone as can be observed in Figures 3 and 4. Specifically, the axial and coronal CMFIs shown in Figure 3A and C from a representative patient only narrow down the location of the cholesteatoma to the tympanic cavity, whereas the axial and coronal CMDWI-CTs shown in Figure 3B and D for the same patient revealed that the cholesteatoma is located around the stapes. Moreover, although the axial and coronal CMFIs shown in Figure 4A and C of a second patient only narrow down the location of the cholesteatoma to the antrum and central mastoid, the axial and coronal CMDWI-CTs shown in Figure 4B and D for the same patient revealed that the cholesteatoma is located around the septal bony wall in the mastoid.

Table 2 shows a comparison between preoperative evaluations of cholesteatomas by CMDWI-CT and intraoperative findings in the tympanic cavity, attic, antrum, and central mastoid. Both the PPV and NPV are extremely high in all areas of the middle ear. The PPV were 100% in both the tympanic cavity and the attic,

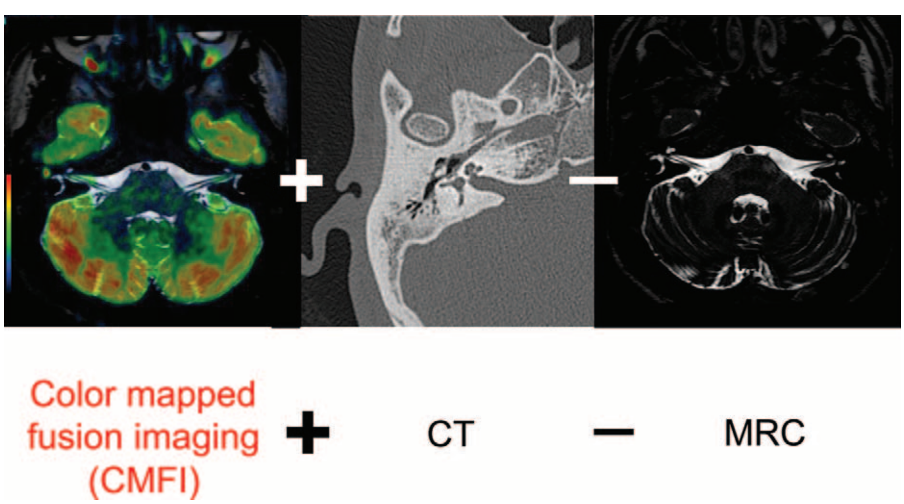

FIG. 2. CMDWI-CT processing. The MRC data is stripped out from the original CMFI and imaging data from the original CT scan is incorporated to create a CMDWI-CT.

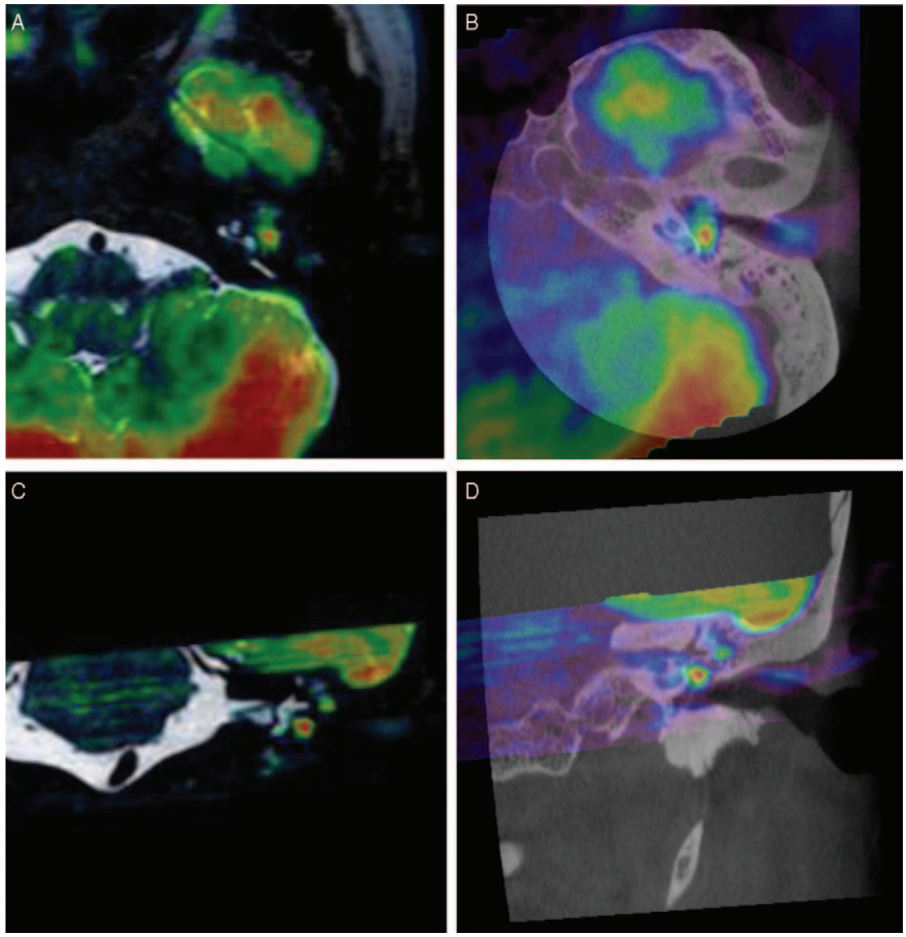

FIG. 3. *A,* CMFI (axial section), *B,* CMDWI-CT (axial section), *C,* CMFI (coronal section), and *D,* CMDWI-CT (coronal section) of a cholesteatoma for the same patient. The CMDWI-CT shows that the cholesteatoma is located around the stapes much more clearly than the CMFI.

whereas the NPV was 90% in the tympanic cavity and was 100% in the attic. The PPV was 95.2% in the antrum and was 92.3% in the central mastoid, whereas the NPV were 100% in both the antrum and the central mastoid.

Of particular concern were the two false negatives associated with cholesteatomas in the tympanic cavity. In addition, one false positive was associated with a cholesteatoma detected in the antrum and one false positive was associated with a cholesterol granuloma in the central mastoid. However, we are confident that such misdiagnoses will be even further reduced with future improvements in diagnostic imaging technology.

DISCUSSION

A CMDWI-CT is a useful diagnostic image for more accurately assessing soft tissue masses initially found on a CT scan than the CMFI that we have used up until now. A CMDWI-CT offers two clear advantages over a CMFI alone: improved imaging diagnostics and better elucidation of the spatial relationship between cholesteatomas and bony areas. First, the CMDWI-CT is a reliable diagnostic tool for evaluating preoperatively the anatomical location of a cholesteatoma and for determining whether a given patient is indicated for TEES. Figure 3 shows the typical image for a potentially recurrent cholesteatoma. This cholesteatoma can be clearly identified as near the stapes in the CMDWI-CT. Thus, a CMDWI-CT allows us to determine in such patients not only whether TEES is indicated for the removal of the cholesteatoma, but also how much of the bony structure needs to be removed to prevent a recurrent cholesteatoma.

Second, a CMDWI-CT can reveal the relationship between the cholesteatoma and surrounding bone. If the cholesteatoma goes no further than the antrum, it can usually be removed by TEES. However, if such cholesteatomas in the antrum are located behind the bony hard structure as shown in Figure 4, they cannot be removed using TEES because of the bony obstruction. Thus, another major advantage of CMDWI-CT is that any doubts can be eliminated about the proper procedure to employ in the removal of such cholesteatomas at the preoperative stage. The cholesteatoma shown in Figure 4 was completely removed employing a dual TEES/MES approach.

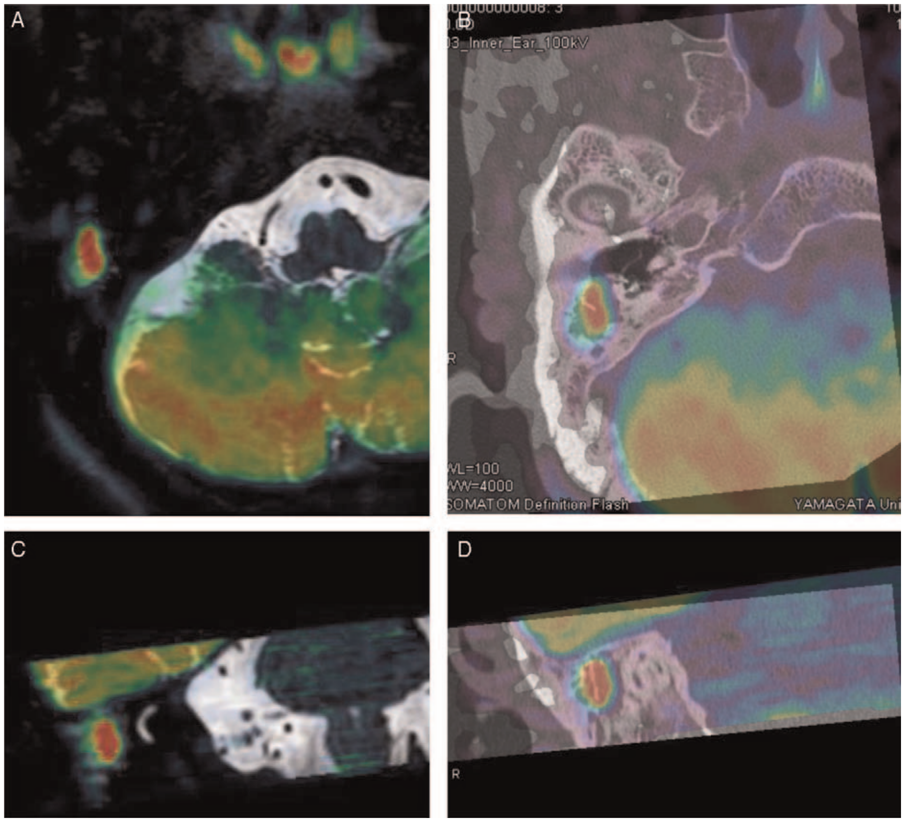

FIG. 4. *A,* CMFI (axial section), *B,* CMDWI-CT (axial section), *C,* CMFI (coronal section), and *D,* CMDWI-CT (coronal section) of a cholesteatoma for the same patient. The CMDWI-CT shows that the cholesteatoma is located around the septal bony wall in the mastoid much more clearly than the CMFI.

Two limitations still remain in the preoperative assessment of cholesteatomas, even when all diagnostic imaging steps of CT scan, CMFI, T1WI, and CMDWI-CT are performed as described herein: misdiagnoses of cholesteatomas and the inability to detect small cholesteatomas. We experienced a number of misdiagnoses in our study population of 55 with two false positives and two false negatives. The two false positives were both ultimately determined to be cholesterol granulomas with one in the antrum and the other in the mastoid. Both cholesterol granulomas showed up as low-intensity regions on the T1WI instead of the usual high-intensity region (4). Thus, we need to always keep in mind the possibility that a cholesterol granuloma will not show up as a high-

TABLE 2. *Comparison of preoperative evaluation of cholesteatomas by CMDWI-CT and T1WI versus the intraoperative findings*

Variable	Preoperative Evaluation	Intraoperative Findings		
Tympanic cavity		+	−	
CMDWI-CT high (red)	+	11	0	PPV: 100%
and T1WI low	−	2	18	NPV: 90%
Attic		+	−	
CMDWI-CT high (red)	+	28	0	PPV: 100%
and T1WI low	−	0	7	NPV: 100%
Antrum		+	−	
CMDWI-CT high (red)	+	20	1	PPV: 95.2%
and T1WI low	−	0	15	NPV: 100%
Central mastoid		+	−	
CMDWI-CT high (red)	+	12	1	PPV: 92.3%
and T1WI low	−	0	24	NPV: 100%

CMDWI-CT indicates color-mapped diffusion-weighted image combined with a CT scan; NPV, negative predictive value; PPV, positive predictive value.

intensity region on a T1WI. Our two false negatives were both open-type cholesteatomas in the tympanic cavity. These false negatives may be attributable to the particular anatomical characteristics of the tympanic cavity which can cause imaging problems. Although Jindal et al. (7) have reported that non-EPI DWI seems to be less susceptible to magnetic interface artifacts than EPI DWI especially in the middle ear, a small number of magnetic interface artifacts may have occurred in the non-EPI DWI in our study. Such artifacts would be most likely to occur in hollow spaces surrounded by bone such as the tympanic cavity. Therefore, we need to be mindful of the increased possibility of false negatives occurring in the tympanic cavity such as we encountered in our study population.

The second limitation is that we have only been able to detect cholesteatomas of 3 mm or larger using either CMFI or CMDWI-CT, a finding that agrees with the findings of other researchers (8–13). Thus, patients may have to wait until a cholesteatoma grows to a size of 3 mm or larger before its presence can be detected.

Yet despite these limitations, CMDWI-CT is an extremely useful additional tool in the diagnostic imaging process of the vast majority of cholesteatomas. CMDWI-CT greatly improves the reliability of preoperative evaluation of the anatomical location of cholesteatomas.

CONCLUSION

CMDWI-CT is useful for the accurate determination of the anatomical location of cholesteatomas in the temporal bone surrounding the middle ear, and in determining whether or not a patient is indicated for TEES for the treatment of a cholesteatoma.

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