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Autopsy Validation of the Diagnostic Accuracy of ^{123}I-Metaiodobenzylguanidine Myocardial Scintigraphy for Lewy Body Disease

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Abstract

Background and Objectives

^{123}I-meta-iodobenzyl-guanidine (^{123}I-MIBG) myocardial scintigraphy is used as a diagnostic imaging test to differentiate Lewy body diseases (LBDs), including Parkinson disease and dementia with Lewy bodies, from other similar diseases. However, this imaging test lacks validation of its diagnostic accuracy against the gold standard. Our aim was to validate the diagnostic accuracy of ^{123}I-MIBG myocardial scintigraphy for LBD against autopsy, the gold standard.

Methods

This retrospective, cross-sectional study included consecutive autopsy patients from the Brain Bank for Aging Research who had undergone ^{123}I-MIBG myocardial scintigraphy. We compared the ^{123}I-MIBG myocardial scintigraphy findings with autopsy findings. Furthermore, the proportion of residual tyrosine hydroxylase (TH)–immunoreactive sympathetic fibers in the anterior wall of the left ventricle was investigated to assess the condition of the cardiac sympathetic nerves assumed to cause reduced ^{123}I-MIBG uptake in LBDs.

Results

We analyzed the data of 56 patients (30 with pathologically confirmed LBDs and 26 without LBD pathology). Compared with the neuropathologic diagnosis, the early heart-to-mediastinum (H/M) ratio had a sensitivity and specificity of 70.0% (95% CI 50.6%–85.3%) and 96.2% (95% CI 80.4%–99.9%), respectively. The delayed H/M ratio had a sensitivity and specificity of 80.0% (95% CI 61.4%–92.3%) and 92.3% (95% CI 74.9%–99.1%), respectively. The washout rate had a sensitivity and specificity of 80.0% (95% CI 61.4%–92.3%) and 84.6% (95% CI 65.1%–95.6%), respectively. The proportion of residual TH-immunoreactive cardiac sympathetic fibers strongly correlated with the amount of cardiac ^{123}I-MIBG uptake when assessed with early and delayed H/M ratio values (correlation coefficient 0.75 and 0.81, respectively; $p < 0.001$).

Discussion

This clinicopathologic validation study revealed that ^{123}I-MIBG myocardial scintigraphy could robustly differentiate LBDs from similar diseases. Abnormal ^{123}I-MIBG myocardial scintigraphy findings strongly support the presence of LBD and cardiac sympathetic denervation. However, LBD pathology should not necessarily be excluded by normal myocardial scintigraphy results, especially when other biomarkers suggest the presence of comorbid Alzheimer disease pathology.

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Class of Evidence
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Glossary

AD = Alzheimer disease; **AGD** = argyrophilic grain disease; **AUC** = area under the ROC curve; **BBAR** = Brain Bank for Aging Research; **DLB** = dementia with Lewy bodies; **FTLD=TDP** = frontotemporal lobar degeneration with TDP-43 proteinopathy; **H/M** = heart-to-mediastinum; **^{123}I-MIBG** = ^{123}I-meta-iodobenzyl-guanidine; **LBD** = Lewy body disease; **MSA** = multiple system atrophy; **PD** = Parkinson disease; **PNS** = peripheral nervous system; **PSP** = progressive supranuclear palsy; **ROC** = receiver operating characteristic; **TDP-43** = TAR DNA-binding protein 43; **TH** = tyrosine hydroxylase.

Classification of Evidence

This study provides Class II evidence that ^{123}I-MIBG myocardial scintigraphy accurately identifies patients with LBD.

Lewy body disease (LBD) is characterized by the presence of Lewy bodies, composed of α-synuclein, and it encompasses a diagnostic spectrum, including Parkinson disease (PD) and dementia with Lewy bodies (DLB).[1,2] Accurately diagnosing LBDs and differentiating them from other similar diseases are critical for both patient care and research. To date, various clinical tools have been developed to aid LBD diagnosis. The detection of reduced cardiac uptake of ^{123}I-meta-iodobenzyl-guanidine (^{123}I-MIBG), a physiologic analog of norepinephrine,[3] has been used as a diagnostic imaging tool (specifically in ^{123}I-MIBG myocardial scintigraphy) to differentiate LBDs from other similar diseases.[1,4] This test is based on the fact that LBD pathology accompanied by denervation is observed not only in the CNS but also in the peripheral nervous system (PNS), including the cardiac sympathetic nerves.[5-11]

Several studies have evaluated the diagnostic accuracy of ^{123}I-MIBG myocardial scintigraphy for LBDs.[12-16] Those studies, however, used the clinical diagnosis as a reference standard for the evaluation of the diagnostic accuracy. Despite the current development of diagnostic biomarkers, neuropathologic confirmation remains the gold standard for LBD diagnosis. Several pathologic investigations have highlighted the discrepancy between clinical diagnoses and postmortem pathologic diagnoses in LBDs and similar neurodegenerative diseases.[17-24] Therefore, validation of the diagnostic accuracy of ^{123}I-MIBG myocardial scintigraphy against the gold standard is required.[12,14]

Here, using a large autopsy series, we determined the diagnostic accuracy of ^{123}I-MIBG myocardial scintigraphy in differentiating LBDs from similar conditions. Furthermore, we performed a neuropathologic investigation to examine the factors contributing to false-positive or false-negative ^{123}I-MIBG myocardial scintigraphy results.

Methods

Standard Protocol Approvals, Registrations, and Patient Consent

Our study was approved by the local institutional ethics committee (approval No. R20-022). Written informed consent was obtained from the patients' families before the autopsy. This study was performed in accordance with the principles of the Declaration of Helsinki, and the manuscript was structured according to the 2015 Standards for Reporting of Diagnostic Accuracy statement.[e1]

Study Design

We performed a retrospective, cross-sectional study to evaluate the diagnostic accuracy of ^{123}I-MIBG myocardial scintigraphy for the differential diagnosis of LBD and similar diseases against the gold standard of neuropathologic examination.

Participants and Settings

The study included consecutive patients autopsied at the Tokyo Metropolitan Geriatric Hospital and Institute of Gerontology between January 2006 and February 2021. The hospital is located in a suburban area of Tokyo, Japan, and provides community-based general and emergency services for the elderly population, including patients with dementia or neurodegenerative diseases.

We included patients who underwent ^{123}I-MIBG myocardial scintigraphy and applied the following exclusion criteria: (1) undergoing ^{123}I-MIBG myocardial scintigraphy for prognosis prediction of heart failure,[25,26] (2) using medications that strongly affect ^{123}I-MIBG myocardial scintigraphy results (tricyclic antidepressants, serotonin noradrenaline reuptake inhibitor, labetalol, reserpine, and phenylephrine),[27] and (3) no consent for craniotomy or registration to the Brain Bank for Aging Research (BBAR).

^{123}I-MIBG Myocardial Scintigraphy

After injection of 111 MBq ^{123}I-MIBG (FUJIFILM Toyama Chemical, Co, Ltd, Tokyo, Japan), early and delayed images were obtained with delays of 15 to 30 minutes and 3 to 4 hours, respectively. The scintigraphy findings were interpreted immediately and recorded; thus, these data were interpreted independently of the results of the autopsies. The heart-to-mediastinum (H/M) ratio was calculated with a standard method,[28] dividing the average count per pixel in the circular region of interest on the heart by the average count per pixel in the rectangular region of interest on the upper mediastinum. The participants underwent ^{123}I-MIBG

myocardial scintigraphy at different periods or facilities; thus, the collimator differences were standardized with a calibration phantom or conversion coefficients established by a previous study.[29] Accordingly, all H/M ratios were converted to a value comparable to a medium-energy–type collimator. The cutoff value used for the H/M ratios was 2.20, which is widely used.[26,30]

The washout rate was calculated from early and late heart counts (H_E and H_L, respectively) and mediastinal counts (M_E and M_L, respectively), using the following formula with background (mediastinal counts) and decay corrections: $([(H_E - M_E) - (H_L - M_L)/DCF]/(H_E - M_E) \times 100(\%)$,where DCF is a decay correction factor, calculated as 0.5^(time in hours between early and late images/^{123}I half-life in hours). The washout rate values were not standardized. The cutoff value used for the washout rate was 34%, which is widely used.[26,30]

Neuropathologic Analysis and Diagnosis

The neuropathologic analysis of both CNS and PNS was performed as previously reported.[10,31] Briefly, during autopsy, the brain was divided into halves; from 1 half, some representative parts were sampled for diagnosis and fixed with 4% paraformaldehyde for 48 hours, and the remaining parts were frozen. In addition, tissue samples were obtained from the spinal cord and PNS, including the paravertebral sympathetic ganglia (stellate or upper thoracic ganglia) and anterior wall of the heart left ventricle, and then fixed. The other half of the brain was fixed in 20% buffered formalin for 1 to 2 weeks. Representative anatomic areas were sampled and embedded in paraffin, and 6-μm-thick sections were stained with hematoxylin & eosin and Klüver-Barrera and by Gallyas-Braak silver impregnation. Subsequently, immunoreaction product deposits on immunohistochemically stained sections were visualized with a Ventana BenchMark GX autostainer (Ventana Medical Systems, Tucson, AZ) and an I-View Universal DAB Detection Kit (Roche, Basel, Switzerland), and primary antibodies against phosphorylated α-synuclein (pSyn#64; dilution 1:20,000 with formic acid for antigen retrieval; a gift from T. Iwatsubo, Japan; now available for purchase from FUJIFILM Wako Pure Chemical Corp, Osaka, Japan), nonphosphorylated α-synuclein (LB509; dilution 1:100 with protease K as pretreatment; a gift from T. Iwatsubo, Japan; now available for purchase from BioLegend, San Diego, CA, and others), phosphorylated tau (AT8; dilution 1:1,000; Innogenetics, Ghent, Belgium), human β-amyloid (12B2; dilution 1:50 with formic acid for antigen retrieval; IBL, Gunma, Japan), phosphorylated TAR DNA-binding protein 43 (TDP-43) (pSer409/410; dilution 1:10,000 with microwave in Dako target retrieval solution [pH 6.0] for antigen retrieval; a gift from M. Hasegawa, Japan; now available for purchase from Cosmo Bio, Tokyo, Japan), and tyrosine hydroxylase (TH; dilution 1:4,000 with microwave in Dako target retrieval solution [pH 6.0] for antigen retrieval; Sigma-Aldrich, St. Louis, MO).

The cases were neuropathologically assessed in this study by 2 neuropathologists (T.M. and Y.S.) blinded to the clinical data and ^{123}I-MIBG myocardial scintigraphy results. Neuropathologic diagnoses were also assigned by using the internationally accepted neuropathologic criteria for the diagnosis of LBD,[1,31,32] Alzheimer disease (AD),[33] progressive supranuclear palsy (PSP),[34] multiple system atrophy (MSA),[35] corticobasal degeneration,[36] frontotemporal lobar degeneration with TDP-43 proteinopathy (FTLD-TDP),[37] and argyrophilic grain disease (AGD).[38] Because the main aim of this study was to evaluate the diagnostic accuracy of ^{123}I-MIBG myocardial scintigraphy for detecting LBDs, all patients with Lewy body α-synuclein pathology, including incidental focal Lewy body α-synuclein pathology, were regarded as having LBDs.

Quantitative Analysis of the Cardiac Sympathetic Nerve

To assess the condition of the cardiac sympathetic nerves assumed to cause reduced uptake of ^{123}I-MIBG in LBDs,[7,11] we investigated the sympathetic nerve in the anterior wall of the left ventricle, where cardiac ^{123}I-MIBG uptake is mainly observed. The residual cardiac sympathetic nerve fiber area was determined with reference to previously described methods.[9,11,39] Briefly, short-axis sliced nerve fascicles in the epicardium, with diameters ≥50 μm and maximum diameter/minimum diameter <2, were photographed for at least 5 fascicles per case with a digital camera (DS-Ri2, Nikon, Tokyo, Japan) connected to a microscope (Eclipse Ni, Nikon) with a 40× objective lens. These hematoxylin- and DAB-stained images were processed with Image J/Fiji software (NIH, Bethesda, MD),[40,e2] and areas of hematoxylin and DAB staining were divided with the color deconvolution function.[41] After binarizing of the images with the threshold function, the proportion of residual TH-immunoreactive sympathetic fibers was calculated as the TH-immunoreactive area/total endoneurium area (fascicle area).

Statistical Analysis

Analyses were performed with Stata/IC 16 (Stata Corp LP, College Station, TX) and JMP Pro 15 (SAS Institute Inc, Cary, NC). The normality of data was assessed with the Shapiro-Wilk and Kolmogorov-Smirnov tests. Subsequently, comparisons were performed with the *t* test for normally distributed continuous variables, the Mann-Whitney *U* test for nonnormally distributed continuous variables, and the χ^2 test for categorical variables. The sensitivity, specificity, positive predictive values, and negative predictive values were estimated with the 95% Clopper-Pearson exact CIs assuming binomial distribution. To evaluate optimal cutoff values, we performed receiver operating characteristic (ROC) curve analysis and measured the area under the ROC curve (AUC) with 95% CI. The optimal cutoff values of the H/M ratios and washout rate for differentiating LBDs from non-LBDs were determined from the values that maximized sensitivity with the lower limit of the 95% CI for a specificity being set at ≥0.80. The correlations between the H/M ratios and the proportion of residual TH-immunoreactive sympathetic fibers were evaluated with the Spearman rank correlation coefficient. All statistical tests were 2 sided, and the significance level was set at 0.05. The results are expressed as mean ± SD.

Sample Size Estimation

The H/M ratios of ^{123}I-MIBG myocardial scintigraphy have an estimated specificity of ≥0.90 according to previous studies.[12-16] Furthermore, diagnostic biomarkers for LBDs require a specificity of ≥0.80.[4] A sample size of 26 patients with non-LBD produces a 2-sided 95% CI with a width equal to 0.15 when the sample specificity is assumed to be ≥0.90.

Data Availability

The datasets and full protocol of the present study are available from the corresponding author on reasonable request.

Classification of Evidence

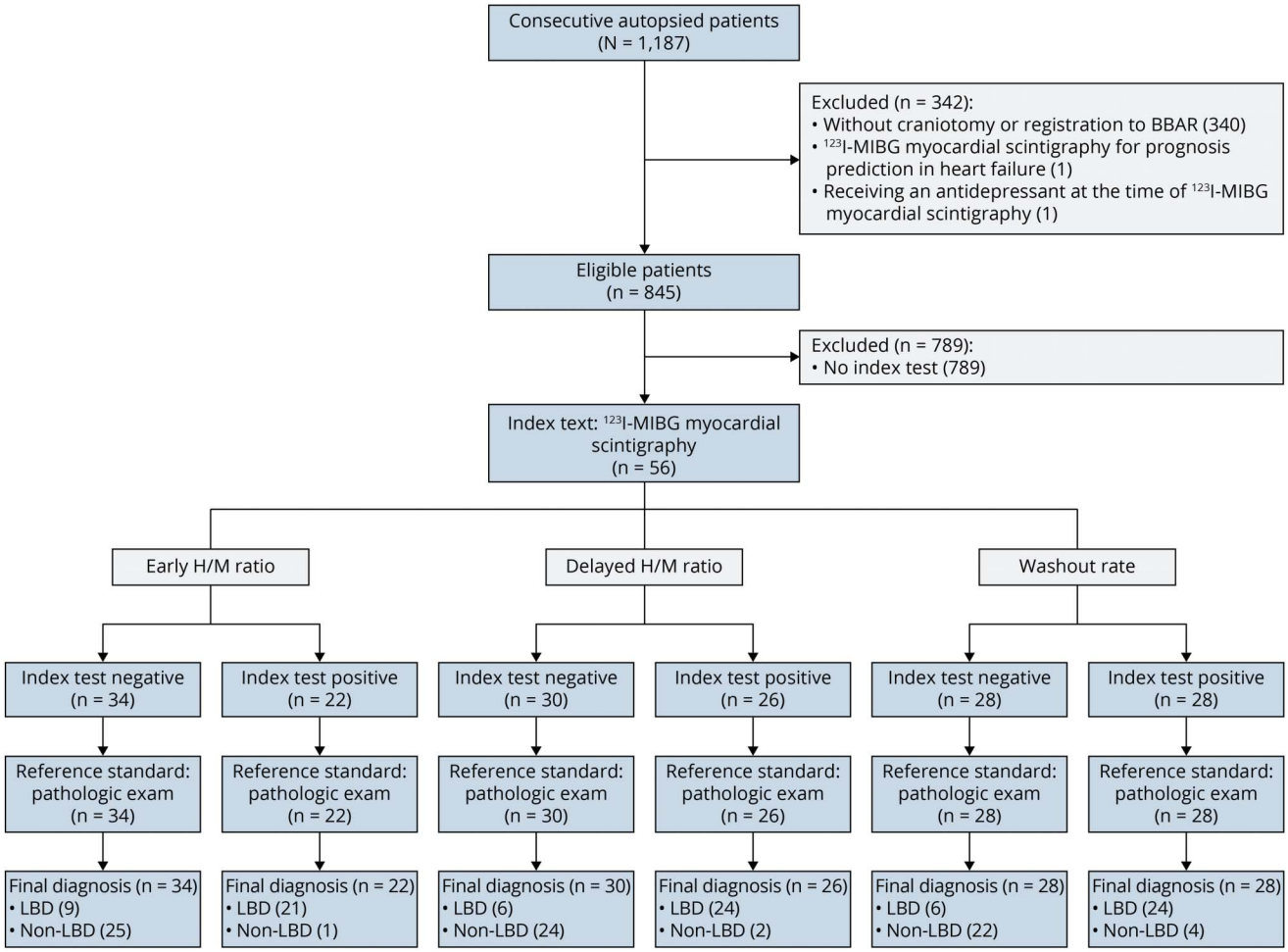
The primary research question was to determine the diagnostic accuracy of ^{123}I-MIBG myocardial scintigraphy (in particular, the specificity) on the basis of neuropathologic examination. This study provides Class II evidence for distinguishing patients with and without LBD pathology using ^{123}I-MIBG myocardial scintigraphy.

Results

Baseline Characteristics

Autopsies were performed on 1,187 consecutive patients. We excluded 340 patients owing to the lack of consent for craniotomy and registration to BBAR, 1 with ^{123}I-MIBG myocardial scintigraphy for prognosis prediction in heart failure, 1 receiving an antidepressant at the time of ^{123}I-MIBG myocardial scintigraphy, and 789 who did not undergo ^{123}I-MIBG myocardial scintigraphy (the index test). We examined 56 patients who underwent the index test to diagnose LBDs (Figure 1). The mean age of the patients at death was 82.2 ± 9.3 years (range 41–99 years); 51.8% (n = 29) were male, and 48.2% (n = 27) were female. The patients' characteristics are summarized in Table 1. The mean disease duration, interval from symptom onset to index test, and interval from index test to autopsy (reference standard) were 5.0 ± 4.2 years (range 0.1–16.2 years), 3.9 ± 3.0 years (range 0.1–12.8 years), and 8.9 ± 4.8 years (range 0.5–19.0 years), respectively. Twenty-eight patients were clinically suspected of having LBD, and the remaining 28 were suspected of having non-LBD. No adverse events were reported since performing the index test.

Figure 1 Flowchart of Participant Selection



BBAR = Brain Bank for Aging Research; H/M = heart-to-mediastinum ratio; ^{123}I-MIBG = ^{123}I-meta-iodobenzyl-guanidine; LBD = Lewy body disease.

Table 1 Baseline Demographic and Clinical Characteristics of Participants

	All (n = 56)	LBD (n = 30)	Non-LBD (n = 26)
Sex, M:F, n	29:27	17:13	12:14
Age at death, mean (SD) [range], y	82.2 (9.3) [41–99]	84.9 (7.5) [68–99]	79.0 (10.2) [41–91]
Interval between onset and ^{123}I-MIBG scintigraphy, mean (SD) [range], y	5.0 (4.2) [0.1–16.2]	5.0 (4.7) [0.2–16.2]	5.0 (3.6) [0.1–12.3]
Interval between ^{123}I-MIBG scintigraphy and death, mean (SD) [range], y	3.9 (3.0) [0.1–12.8]	4.1 (3.2) [0.1–12.8]	3.8 (2.8) [0.3–8.6]
Disease duration, mean (SD) [range], y	8.9 (4.8) [0.5–19.0]	9.1 (5.0) [2.4–19.0]	8.8 (4.6) [0.5–18.5]
Initial symptom, n (%)			
Motor symptoms	37 (66.1)	18 (60.0)	19 (73.1)
Dementia	17 (30.4)	10 (33.3)	7 (26.9)
Autonomic failure	2 (3.6)	2 (6.7)	0 (0)
Comorbid conditions, n (%)			
Diabetes	10 (17.9)	4 (13.3)	6 (23.1)
Hypertension	23 (41.1)	13 (43.3)	10 (38.5)
Heart failure	0 (0)	0 (0)	0 (0)
Ischemic heart disease before ^{123}I-MIBG scintigraphy, n (%)	1 (1.8)	0 (0)	1 (3.9)
Renal failure (eGFR <15 mL/min/1.73 m^2) or hemodialysis, n (%)	1 (1.8)	0 (0)	1 (3.9)
Peripheral neuropathy other than diabetic polyneuropathy, n (%)	0 (0)	0 (0)	0 (0)
Medication use at the time of ^{123}I-MIBG scintigraphy, n (%)			
β-Blocker other than labetalol	5 (8.9)	1 (3.3)	4 (15.4)
Calcium channel blocker	11 (19.6)	7 (23.3)	4 (15.4)

Abbreviations: eGFR = estimated glomerular filtration rate; ^{123}I-MIBG = ^{123}I-meta-iodobenzyl-guanidine; LBD = Lewy body disease.

Neuropathologic Diagnosis

The neuropathologists were in complete agreement regarding the neuropathologic diagnoses of the patients included in this study. Among the 56 patients examined in this study, 30 were classified as having LBD and 26 as having non-LBD. The 30 patients with LBD were diagnosed as having PD (n = 19), DLB (n = 9; including DLB + AD n = 5), and incidental LBD (n = 2). The BBAR Lewy body stages were 0.5 (n = 2), 2 (n = 1), 3 (n = 6), 4 (n = 13), and 5 (n = 8). To assess the validity of ^{123}I-MIBG myocardial scintigraphy for detecting LBDs, all patients with either pure LBD or mixed LBD were regarded as having proven LBD, and all other patients were classified as having non-LBD (n = 26: 10 with PSP, 3 with AD, 3 with MSA, 2 with FTLD-TDP, 2 with AGD, 1 with corticobasal degeneration, 1 with spinocerebellar degeneration, 1 with cerebrovascular disease, 1 with hydrocephalus, 1 with brain tumor, and 1 with minimal pathologic change).

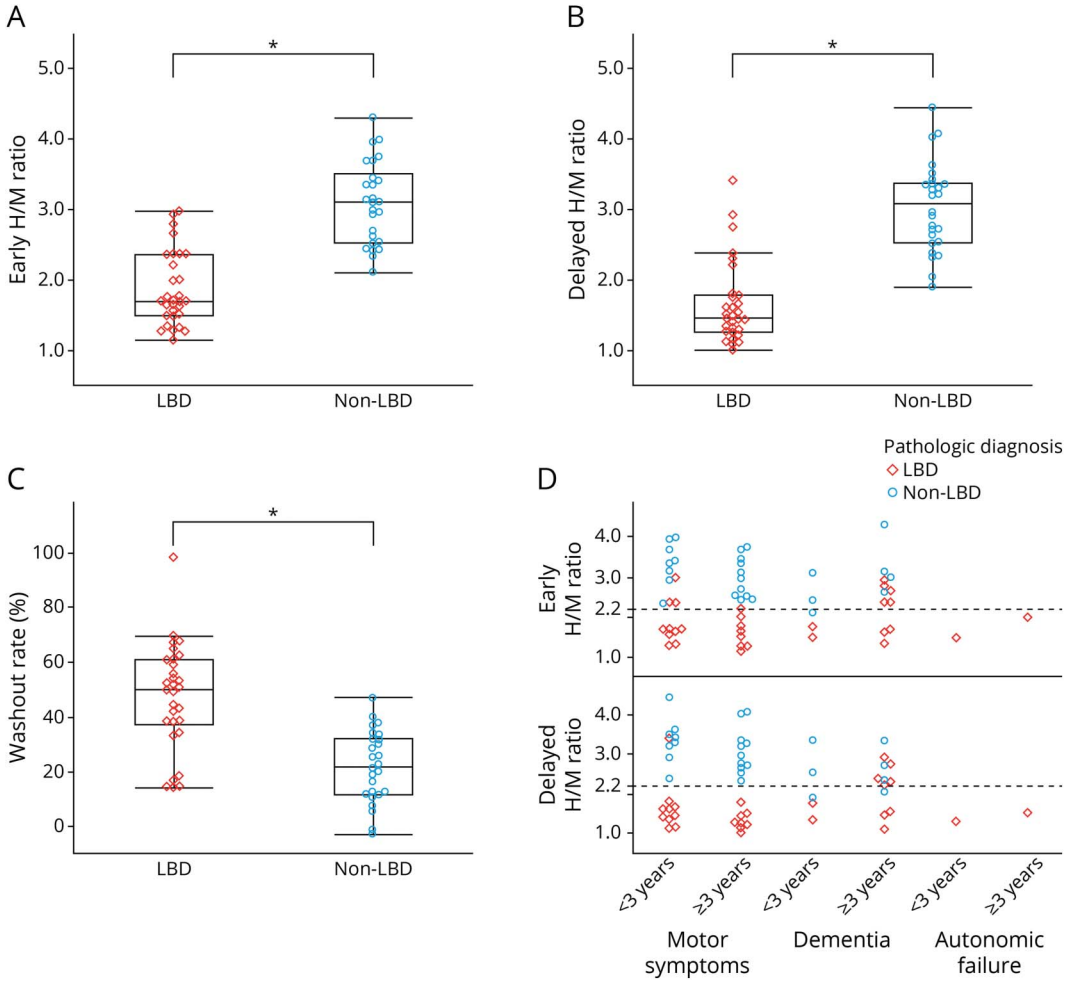
When the ^{123}I-MIBG myocardial scintigraphy results were considered together with the pathologic diagnoses, 24 patients with LBD had abnormal results for 1 or both of the H/M ratios; 24 patients without LBD had normal results for both of the H/M ratios; 6 patients with LBD, including 1 with PD, 3 with DLB + AD, and 2 with incidental LBD, had normal results for both of the H/M ratios; and 2 patients without LBD, including 1 with FTLD-TDP and 1 with AGD, had abnormal results for 1 or both of the H/M ratios.

Diagnostic Accuracy of ^{123}I-MIBG Myocardial Scintigraphy

The H/M ratio was lower in the LBD group (early 1.86 ± 0.52, delayed 1.65 ± 0.59) than in the non-LBD group (early 3.09 ± 0.58, $p < 0.001$; delayed 3.04 ± 0.63, $p < 0.001$; Figure 2, A and B). The washout rate was higher in the LBD group (47.2 ± 19.4%) than in the non-LBD group (21.8 ± 13.0%, $p < 0.001$; Figure 2C).

The cross-tabulation of the test results and data on the diagnostic accuracy of ^{123}I-MIBG myocardial scintigraphy for discriminating LBDs from non-LBDs are summarized in Table 2. Briefly, when we applied the cutoff value of 2.20 to the early H/M ratio (refer to the Methods section for details), the sensitivity and specificity were 70.0% (95% CI 50.6%–85.3%) and 96.2% (95% CI 80.4%–99.9%), respectively. When we applied the cutoff value of 2.20 to the

Figure 2 Individual Values for H/M Ratio and Washout Rate of ^{123}I-MIBG Uptake in the Pathologically Diagnosed LBD and Non-LBD Groups



Early (A) and delayed (B) heart-to-mediastinum (H/M) ratios of ^{123}I-meta-iodobenzyl-guanidine (^{123}I-MIBG) uptake show significant reductions in the Lewy body disease (LBD) group. Washout rate (C) shows a significant increase in the LBD group. Boxplot indicates the median and 25% and 75% quartiles, with whiskers representing 1.5 times the interquartile range. Early and delayed H/M ratios of ^{123}I-MIBG uptake (D) are shown for each of the following subgroups: motor symptoms, dementia, or autonomic failure, according to their initial complaints, further divided into 2 subgroups based on the time from symptom onset to scintigraphy (<3 or ≥3 years). *p < 0.001.

delayed H/M ratio, the sensitivity and specificity were 80.0% (95% CI 61.4%–92.3%) and 92.3% (95% CI 74.9%–99.1%), respectively. When we applied the cutoff value of 34% to the washout rate (refer to the Methods section for details), the sensitivity and specificity were 80.0% (95% CI 61.4%–92.3%) and 84.6% (95% CI 65.1%–95.6%), respectively.

Sensitivity Analysis

The ROC curve was used to calculate the optimal cutoff value of the ^{123}I-MIBG myocardial scintigraphy. The AUCs of the early and delayed H/M ratios and washout rate were 0.94 (95% CI 0.85–0.99), 0.93 (95% CI 0.83–0.98), and 0.87 (95% CI 0.76–0.95), respectively (Figure 3, A–D).

The optimal cutoff values to maximize the sensitivity, with the lower limit of the CI for a specificity of ≥0.80, were calculated. When we applied the cutoff value of 2.22 to the early H/M ratio, the sensitivity and specificity were 73.3% (95% CI 54.1%–87.7%) and 96.2% (95% CI 80.4%–99.9%), respectively (Figure 3B). When we applied the cutoff value of 1.81 to the delayed H/M ratio, the sensitivity and specificity were 80.0% (95% CI 61.4%–92.3%) and 100% (95% CI 86.8%–100%), respectively (Figure 3C). When we applied the cutoff value of 41% to the washout rate, the sensitivity and specificity were 66.7% (95% CI 47.2%–82.7%) and 96.2% (95% CI 80.4%–99.9%), respectively (Figure 3D).

Relationship Between Cardiac ^{123}I-MIBG Uptake and Cardiac Sympathetic Denervation

The cardiac TH-immunoreactive sympathetic fiber area was measured in 55 of the 56 (98.2%) patients; in 1 patient, the left ventricular anterior wall was not sampled. The TH-immunoreactive sympathetic fiber area was measured in at least 5 fascicles per patient (mean 8.9 fascicles), and the mean proportion of residual TH-immunoreactive sympathetic fibers was calculated.

Table 2 Diagnostic Accuracy of ^{123}I-MIBG Myocardial Scintigraphy

	Patients, n (%)				Diagnostic accuracy (95% CI), %				LR (95% CI)	
^{123}I-MIBG myocardial scintigraphy	TP	FN	FP	TN	Sensitivity	Specificity	PPV	NPV	Positive LR	Negative LR
Early H/M ratio (cutoff 2.20)	21	9	1	25	70.0 (50.6–85.3)	96.2 (80.4–99.9)	95.5 (77.2–99.9)	73.5 (55.6–87.1)	18.2 (2.6–126.2)	0.31 (0.18–0.54)
Delayed H/M ratio (cutoff 2.20)	24	6	2	24	80.0 (61.4–92.3)	92.3 (74.9–99.1)	92.3 (74.9–99.1)	80.0 (61.4–92.3)	10.4 (2.7–39.9)	0.22 (0.11–0.45)
Delayed H/M ratio (cutoff 1.81)	24	6	0	26	80.0 (61.4–92.3)	100.0 (86.8–100.0)	100.0 (85.8–100.0)	81.2 (63.6–92.8)	—	0.20 (0.10–0.41)
Washout rate (cutoff 34%)	24	6	4	22	80.0 (61.4–92.3)	84.6 (65.1–95.6)	85.7 (67.3–96.0)	78.6 (59.0–91.7)	5.2 (2.1–13.0)	0.24 (0.11–0.49)
Any (early H/M ratio, delayed H/M ratio, or washout rate)	25	5	5	21	83.3 (65.3–94.4)	80.8 (60.6–93.4)	83.3 (65.3–94.4)	80.8 (60.6–93.4)	4.3 (1.9–9.7)	0.21 (0.09–0.47)
All (early H/M ratio, delayed H/M ratio, and washout rate)	20	10	0	26	66.7 (47.2–82.7)	100.0 (86.8–100.0)	100.0 (83.2–100.0)	72.2 (54.8–85.8)	—	0.33 (0.20–0.55)

Abbreviations: FN = false-negative; FP = false-positive; H/M = heart/mediastinum; ^{123}I-MIBG = ^{123}I-meta-iodobenzyl-guanidine; LR = likelihood ratio; NPV = negative predictive value; PPV = positive predictive value; TN = true-negative; TP = true-positive.

A marked loss of TH-immunoreactive sympathetic fibers was noted in patients with LBD compared with those without LBD ($p < 0.001$); the LBD and non-LBD groups showed a mean proportion of residual TH-immunoreactive sympathetic fibers of 0.15 ± 0.24 (range 0.0021–0.72) and 0.55 ± 0.14 (range 0.24–0.83), respectively. The proportion of residual TH-immunoreactive sympathetic fibers correlated with the amount of cardiac ^{123}I-MIBG uptake in the early H/M ratio (correlation coefficient [r] = 0.75, $p < 0.001$; Figure 4A) and in the delayed H/M ratio ($r = 0.81$, $p < 0.001$; Figure 4B). Typical microscopic images of true-positive, false-positive, and false-negative cases are shown in Figure 5.

Subgroup Analysis

The patients were divided into 3 subgroups (motor symptoms, dementia, or autonomic failure) according to their initial complaints to assess the validity of ^{123}I-MIBG myocardial scintigraphy for detecting LBDs in the context of movement disorders or dementia. In addition, the patients were divided into 2 subgroups to verify whether the interval between onset and ^{123}I-MIBG myocardial scintigraphy (<3 or ≥3 years) affected the diagnostic accuracy. The distribution of H/M ratios in these subgroups is shown in Figure 2D. In the motor symptom–onset subgroup (n = 37), 18 patients had LBD; among these, 14 and 17 patients had abnormal early and delayed H/M ratios, respectively. Among the remaining 19 patients with non-LBD, none had abnormal early or delayed H/M ratios. In the dementia-onset subgroup (n = 17), 10 patients had LBD, and 5 of these patients had abnormal early and delayed H/M ratios. Among the remaining 7 patients with non-LBD, 1 and 2 had abnormal early and delayed H/M ratios, respectively. In the motor symptom–onset subgroup, 3 of the 4 patients with false-negative results in the early H/M ratio and 1 patient with false-negative results in the delayed H/M ratio were in the subgroup tested within 3 years after onset. In the dementia-onset group, all 5 patients with false-negative results for both the early and delayed H/M ratios were in the subgroup tested >3 years after onset; furthermore, 4 of the 5 patients had both LBD and AD pathologic findings.

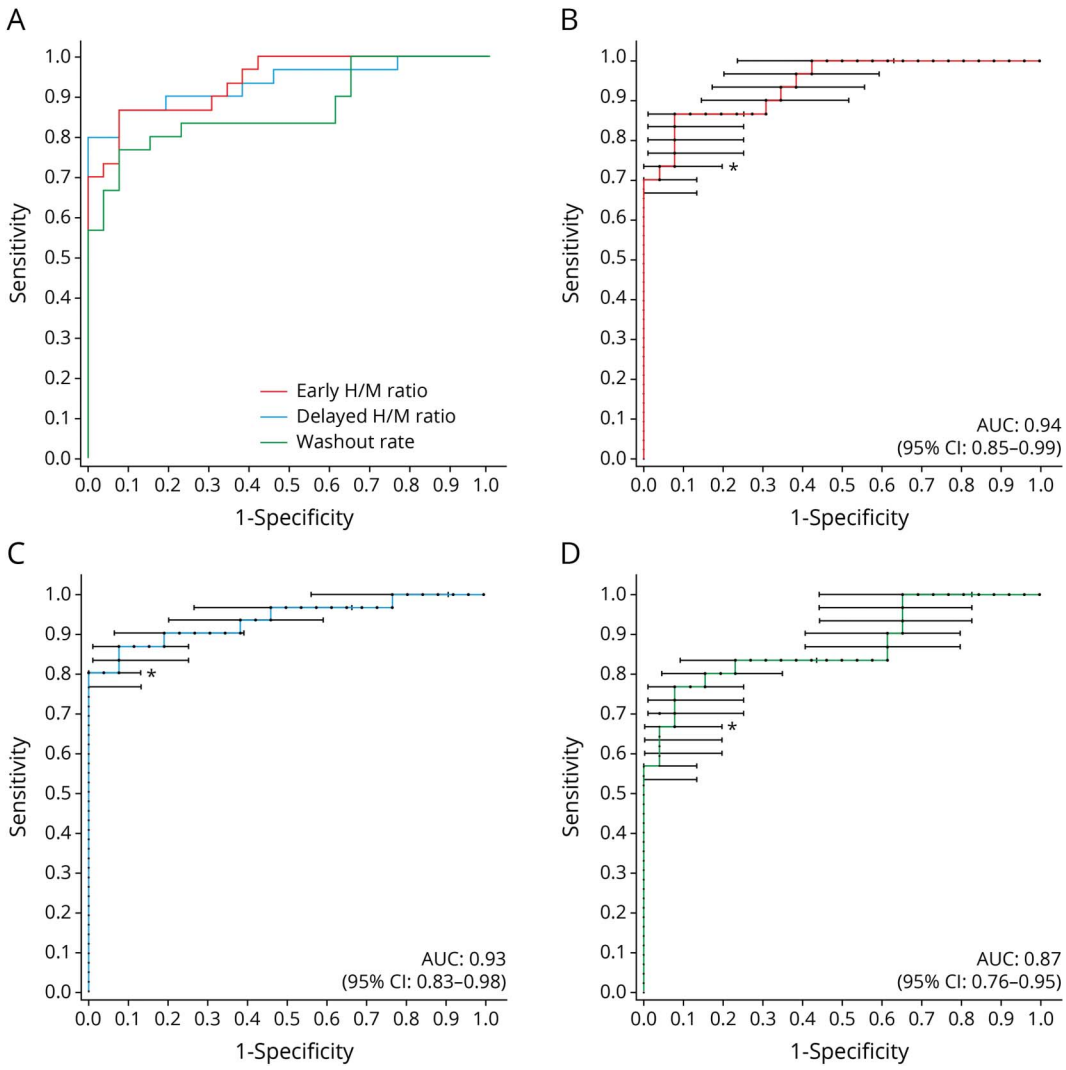
To assess whether specific diseases among patients with non-LBD would show abnormal ^{123}I-MIBG myocardial scintigraphy results, we examined the H/M ratio values for patients with PSP, MSA, or AD, which constituted the majority of non-LBDs in this study, as well as the primary differential diagnoses of LBD. In patients with PSP (n = 10), the mean early and delayed H/M ratios were 2.99 ± 0.54 (range 2.43–3.96) and 2.98 ± 0.52 (range 2.32–4.03), respectively. In patients with MSA (n = 3), the early and delayed H/M ratios were found to be 3.75 and 4.08, 3.11 and 3.36, and 3.69 and 4.45, respectively. Furthermore, in patients with AD without LBD (n = 3), the early and delayed H/M ratios were found to be 3.14 and 2.34, 2.99 and 2.71, and 2.42 and 2.54, respectively.

Discussion

Our clinicopathologic validation study revealed that ^{123}I-MIBG myocardial scintigraphy exhibited a robust diagnostic accuracy in differentiating LBDs from other similar diseases, demonstrating 70.0% sensitivity and 96.2% specificity for the early H/M ratio, 80.0% sensitivity and 92.3% specificity for the delayed H/M ratio, and 80.0% sensitivity and 84.6% specificity for the washout rate. These findings corroborate previously reported studies that used the clinical diagnosis by expert neurologists as the reference standard.[12-16] Our results demonstrated that, owing to its high specificity, ^{123}I-MIBG myocardial scintigraphy is an effective tool to enhance the diagnostic accuracy, considering that a diagnostic test with high specificity (≥80%) is required.[4]

Furthermore, on limiting the analysis to the subgroup of patients who first presented with motor symptoms, we found that

Figure 3 ROC Curves for Detecting LBDs From the H/M Ratios and Washout Rate



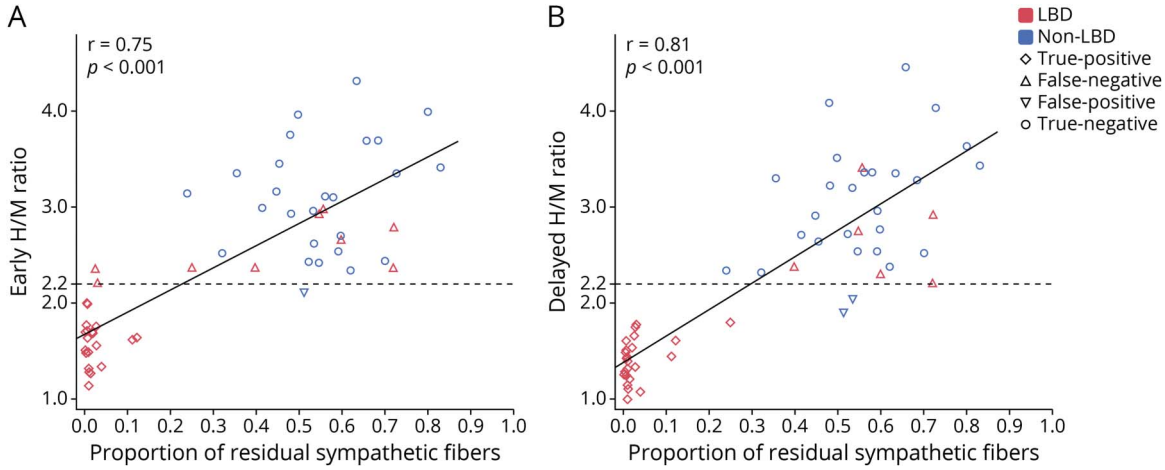
Receiver operating characteristic (ROC) curves based on the early (A [red], B) and delayed (A [blue], C) heart-to-mediastinum (H/M) ratios and washout rate (A [green], D). Bars indicate 95% CIs at representative points. AUC = area under the ROC curve; LBD = Lewy body disease. *Optimal cutoff point at which the sensitivity is maximized with the lower limit of the CI for a specificity of ≥0.80.

H/M ratios had a higher specificity with no false-positive results. In contrast, dopamine-transporter imaging, another widely used diagnostic aid imaging tool for LBDs, is known to be ineffective in differentiating LBD from other similar diseases presenting with parkinsonism.[42,43] This high specificity of ^{123}I-MIBG myocardial scintigraphy in differentiating LBDs from other similar diseases presenting with parkinsonism will strongly enhance the importance of ^{123}I-MIBG myocardial scintigraphy. Therefore, there will be situations in which ^{123}I-MIBG myocardial scintigraphy becomes the decisive factor in diagnosis.

Among the indicators considered, early and delayed H/M ratios were more useful, showing large AUCs. Our study could not provide evidence of whether the washout rate was superior to the H/M ratios in terms of sensitivity, specificity, or AUC. Unlike the H/M ratios, the washout ratio has no established standardization method, thus affecting its diagnostic accuracy. It is possible that adding the washout rate in the assessment for cases when there is a discrepancy between early and delayed H/M ratios could lead to a correct diagnosis. Indeed, when we explored this hypothesis, the washout rate results suggested the correct pathology in 3 of the 4 H/M ratio–discrepant cases in this study. Future clinical studies focusing on this hypothesis may clarify the significance of adding the washout rate to the H/M ratios.

This study corroborated the LBD diagnostic capability of ^{123}I-MIBG myocardial scintigraphy by comparing its results with the results of a systematic pathologic evaluation, including quantitative analysis of the cardiac sympathetic nerve fibers. A previous study revealed that cardiac TH-immunoreactive sympathetic fibers were reduced in LBDs with a decreased H/M ratio, although the non-LBD group in that study included only a small number of patients.[11] With a quantitative analysis of a larger number of patients, including patients without

Figure 4 Correlation Between the Proportion of TH-Immunoreactive Residual Cardiac Sympathetic Fibers and Cardiac ^{123}I-MIBG Uptake

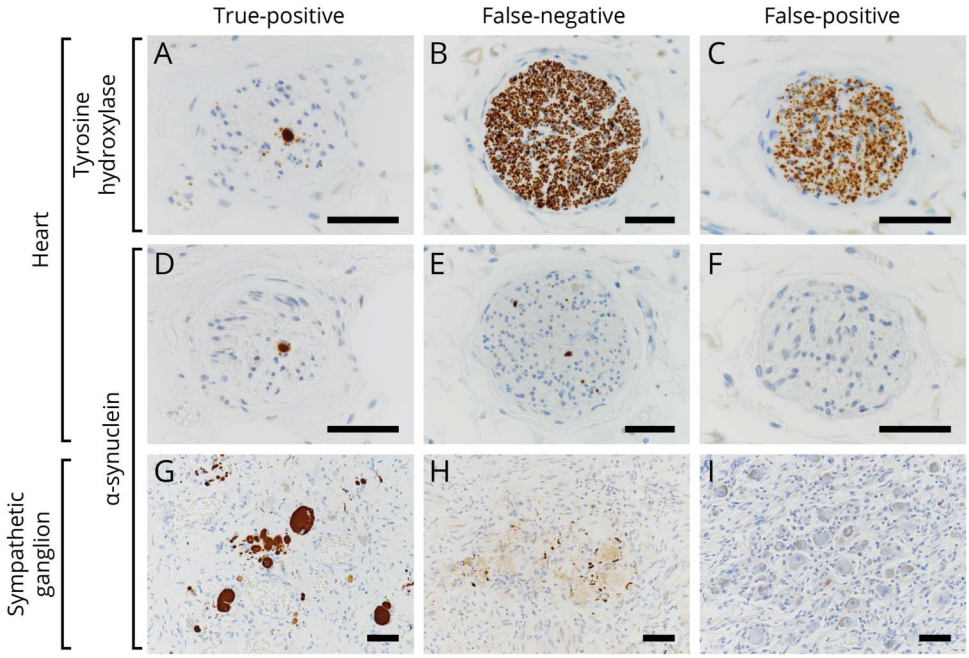


Scatterplots show the relationship between the proportion of residual tyrosine hydroxylase (TH)–immunoreactive sympathetic fibers in the anterior wall of the left ventricle and the cardiac ^{123}I-meta-iodobenzyl-guanidine (^{123}I-MIBG) uptake in the early (A) and delayed (B) heart-to-mediastinum (H/M) ratios.

LBD, our investigation provided further pathologic evidence of the cardiac sympathetic nerve fibers in the LBD group with decreased H/M ratios in ^{123}I-MIBG myocardial scintigraphy and in the group with preserved H/M ratios including with or without LBD pathology. As a result, we showed a strong correlation between the H/M ratio and residual cardiac TH-immunoreactive sympathetic fibers.

A small number of patients in our study had false-positive or false-negative ^{123}I-MIBG myocardial scintigraphy results, even for the H/M ratios. In total, 6 patients had false-negative results (LBDs without decreased H/M ratio) for both of the H/M ratios. In 1 patient, the interval from the onset of disease to ^{123}I-MIBG myocardial scintigraphy was as short as 1 year, while in the remaining 5 patients, ^{123}I-MIBG myocardial scintigraphy was performed >3 years after disease onset; of note, 4 of the 5 patients had both LBD and AD pathologic findings. LBD pathology and concomitant AD pathologies are infrequently associated with the accumulation of α-synuclein and denervation in the heart.[6,39,44] Our study further confirmed these findings

Figure 5 Typical Microscopic Images of True-Positive, False-Positive, and False-Negative Cases of ^{123}I-MIBG Myocardial Scintigraphy



True-positive case with Lewy body disease (LBD) and abnormal ^{123}I-meta-iodobenzyl-guanidine (^{123}I-MIBG) myocardial scintigraphy presents with marked denervation of tyrosine hydroxylase (TH)–immunoreactive sympathetic fibers (A) and accumulation of α-synuclein (D) in the heart. Accumulation of α-synuclein is also identified in the sympathetic ganglion (G). False-negative case with LBD and normal ^{123}I-MIBG myocardial scintigraphy presents with obscure denervation of TH-immunoreactive sympathetic fibers (B) and adequate accumulation of α-synuclein (E) in the heart. Only a small amount of α-synuclein accumulation is observed in the sympathetic ganglion (H). False-positive case without LBD and with abnormal ^{123}I-MIBG myocardial scintigraphy presents with generally preserved TH-immunoreactive sympathetic fibers but sparse in some nerve fascicles (C), without accumulation of α-synuclein in the heart (F) or sympathetic ganglion (I). Counterstain is hematoxylin. Scale bar represents 50 μm (A–I).

and revealed that a decrease in the H/M ratios on ^{123}I-MIBG myocardial scintigraphy also tends to occur less frequently in such conditions. Thus, the presence of the LBD pathology should not necessarily be excluded on the basis of the normal results of ^{123}I-MIBG myocardial scintigraphy alone, especially when other biomarkers suggest the presence of comorbid AD pathology. This discrepancy should be recognized as a pitfall of ^{123}I-MIBG myocardial scintigraphy. Furthermore, 2 entries/pathways or multicentric occurrence has been hypothesized for LBD pathology propagation[45,46]; this hypothesis and infrequent peripheral LBD pathology in the presence of comorbid AD pathology suggest that the presence of AD pathology may influence the spread or distribution of LBD pathology. Moreover, all the false-negative cases in our study had amounts of residual cardiac TH-immunoreactive sympathetic fibers similar to those in the non-LBD group, even at the time of the autopsy. This finding suggests that repeating the ^{123}I-MIBG myocardial scintigraphy after a time interval is not always helpful. As per the subgroup analysis results, motor symptom–onset LBDs were associated with false negatives mainly in the group within 3 years of onset, while dementia-onset LBDs were associated with false negatives even after >3 years from onset. Considering these observations, when false-negative results are suggested, especially in dementia-onset cases, the use of other modalities should be considered.

In contrast, 2 patients exhibited false-positive results (non-LBDs with decreased H/M ratio) for 1 or both of the H/M ratios; both patients had no history of cardiovascular disease or diabetes and did not take any relevant medications. One patient had FTLD-TDP, and the other had AGD. In rare situations, the H/M ratio is mildly decreased in association with neurodegenerative diseases such as PSP and MSA,[47,48] although all the patients with PSP or MSA in the present study had normal ^{123}I-MIBG myocardial scintigraphy results. To the best of our knowledge, there is a lack of evidence on the decreased H/M ratio in FTLD-TDP or AGD. In fact, both patients in our study had a mean proportion of residual TH-immunoreactive sympathetic fibers comparable to those of true-negative cases and showed no accumulation of TDP-43 protein, argyrophilic grain, or α-synuclein in the spinal cord, sympathetic ganglia, or heart. Of note, previous studies have shown that the H/M ratios decrease with age, especially in the delayed phase,[49,50] and could decrease slightly below the cutoff value of 2.2 even in healthy people.[49] In fact, in a database of the Japanese Society of Nuclear Medicine working group, a healthy 64-year-old participant exhibited slightly decreased H/M ratios below the cutoff value (2.1 for the early and 2.0 for the delayed H/M ratio).[49] Certainly, both patients who had a false-positive H/M ratio in our study were older (78 and 84 years of age at the time of ^{123}I-MIBG scintigraphy) and their hearts were visible, resulting in H/M ratios only slightly below the cutoff value. Our data also indicated that variations in the H/M ratio values and residual cardiac sympathetic nerve fiber among individuals with non-LBD exist; thus, the cutoff threshold for LBDs should be carefully considered. The present ROC curve analysis suggests that lowering the cutoff threshold for delayed H/M ratio to 1.8 increases the specificity without reducing the sensitivity, thereby allowing enhancement of the diagnostic utility of ^{123}I-MIBG myocardial scintigraphy. Given that ^{123}I-MIBG myocardial scintigraphy cannot avoid false-negative results, lowering the cutoff threshold for the H/M ratios, especially in the delayed phase, and emphasizing specificity may be a reasonable option for LBD diagnosis.

This study has some limitations. First, although this was a large consecutive autopsy cohort study, consent for craniotomy and registration to BBAR was not obtained from 340 of 1,187 (28.6%) potentially eligible patients. However, only 5 patients underwent ^{123}I-MIBG myocardial scintigraphy among the patients without consent for craniotomy or registration to BBAR. In addition, no significant difference in patients' background was observed between patients with and without consent for craniotomy or registration to BBAR. Second, because of the retrospective nature of the study, the clinical information, including clinical characteristics and neurologic examination, was obtained from medical records. In particular, data on the possible presence of autonomic dysfunction were not systematically recorded. Third, this study may have a potential selection bias, although ^{123}I-MIBG myocardial scintigraphy was performed regardless of whether LBD was suspected. The reason is that the study included mainly patients who were seen for the screening of dementia or movement disorders, and therefore, the study might potentially have missed some patients with very early or silent LBD who did not visit the hospital. This factor may have resulted in the slight inflation of the reported sensitivity. Last, the intervals from ^{123}I-MIBG myocardial scintigraphy to death differed among patients, and this variability might have affected the extent of cardiac sympathetic denervation.

Our autopsy study revealed a strong correlation between abnormal cardiac sympathetic activity, evaluated with ^{123}I-MIBG myocardial scintigraphy, and LBD diagnosis, confirming the utility of this imaging test for the diagnosis of LBDs. Altered ^{123}I-MIBG myocardial scintigraphy strongly supports the presence of LBDs. However, the presence of LBD pathology should not necessarily be excluded with normal myocardial scintigraphy results, especially when other biomarkers suggest the presence of comorbid AD pathology, and this discrepancy should be recognized as a pitfall of ^{123}I-MIBG myocardial scintigraphy. Future studies on different patient populations are needed to confirm these findings.

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Disclosure

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Noriko Tanaka, PhD, MHS	Tokyo Metropolitan Geriatric Hospital and Institute of Gerontology, Japan	Drafting/revision of the manuscript for content, including medical writing for content; analysis or interpretation; other
Renpei Sengoku, MD, PhD	Tokyo Metropolitan Geriatric Hospital and Institute of Gerontology, Japan	Drafting/revision of the manuscript for content, including medical writing for content; major role in the acquisition of data
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eReferences e1 and e2 are available at links.lww.com/WNL/B851.

Autopsy Validation of the Diagnostic Accuracy of ^{123}I-Metaiodobenzylguanidine Myocardial Scintigraphy for Lewy Body Disease

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