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Medial temporal atrophy on MRI in normal aging and very mild Alzheimer's disease

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Article abstract—Magnetic resonance imaging (MRI)-based volumetric measurements of medial temporal lobe (MTL) structures can discriminate between normal elderly control subjects and patients with Alzheimer's disease (AD) of moderate to advanced severity. In terms of clinical utility, however, a more important issue concerns the ability of the technique to differentiate between normal elderly control subjects and AD patients with the very mildest form of the disease. We performed MRI-based volumetric measurements of the hippocampus, parahippocampal gyrus, and amygdala in 126 cognitively normal elderly control subjects and 94 patients with probable AD. The diagnosis of AD was made according to NINDS/ADRDA criteria, and disease severity was categorized by Clinical Dementia Rating (CDR) scores. Patients with CDR 0.5 were classified as very mild, CDR 1 as mild, and CDR 2 as moderate disease severity. Volumes of each structure declined with increasing age in control subjects and did so in parallel for men and women. The volume of each measured MTL structure also declined with age in patients with AD. The volume of each MTL structure was significantly smaller in AD patients than control subjects ($p < 0.001$). Of the several MTL measures, the total hippocampal volumetric measurements were best at discriminating control subjects from AD patients. The mean hippocampal volumes for AD patients relative to control subjects by severity of disease were as follows: very mild AD (CDR 0.5) −1.75 SD below the control mean, mild AD (CDR 1) −1.99 SD, and moderate AD (CDR 2) −2.22 SD. Age- and gender-adjusted, normalized MRI-based hippocampal volumetric measurements provide a sensitive marker of the MTL neuroanatomic degeneration in AD early in the disease process.

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Alzheimer's disease (AD) is the most common cause of dementia in individuals older than 60 years of age.[1-3] A well-accepted biological concomitant of AD is cerebral atrophy.[4] The rationale for quantitative MRI of medial temporal lobe (MTL) atrophy in the diagnosis of AD is: (1) a memory impairment is usually the earliest and most severe clinical manifestation of AD, (2) MTL limbic structures are central to the integrity of declarative memory function,[5] (3) MTL limbic structures are involved earliest and most extensively in the pathology of AD,[6,7] and (4) several principal MTL limbic structures are amenable to accurate volumetric quantitation by MRI—the hippocampal formation, amygdala, and parahippocampal gyrus (PHG).[8-12] Based on initial studies, MRI-based volumetric measurements of the MTL have been proposed as a clinically useful test for the diagnosis of AD.[13-21] Some limitations of the published data include: (1) anatomic boundary criteria for the various MTL structures varied significantly among the different studies, (2) different structures or combinations of MTL structures were evaluated in the various studies, (3) relatively small numbers of subjects were included in individual studies, and (4) rigorous definitions of the severity of AD often were not employed. Most previous studies have primarily included subjects with AD of moderate severity. Consequently, the differences between the AD patients and control subjects with regard to MTL atrophy have been dramatic. The most important test of the utility of the technique would be in patients with very mild AD in whom the diagnostic decision-making process is difficult.

We report a large series of carefully evaluated and longitudinally followed subjects with AD and a large group of prospectively studied normal elderly control subjects. The AD patients were categorized on basis of severity and include a large sample of individuals with very mild AD. As such, we are able to evaluate the utility of volumetric MRI in assisting in the clinical diagnosis of AD at its most mild stages. The goals of this study were (1) to characterize volumetric changes in the hippocampus, amygdala, and PHG in normal aging and in AD; and (2) to estimate the ability of these measures to discriminate between

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normal aging and AD of varying degrees of severity with an emphasis on mild disease.

Methods. *Recruitment and characterization of subjects.* Patients with AD and the cognitively normal control subjects for this study were recruited from the Mayo Clinic Alzheimer's Disease Center (ADC)/Alzheimer's Disease Patient Registry (ADPR),[22-25] which promote prospective, longitudinal studies of aging and dementia. Informed consent was obtained for participation in the longitudinal studies, which included clinical/cognitive assessment as well as MRI studies, and all studies were approved by the Mayo Institutional Review Board. Patients with a suspected cognitive impairment were identified during general medical examinations by Mayo primary care physicians. A neurologist then performed a detailed neurologic examination and obtained a complete history from the patient and a collateral source. Two sets of neuropsychological tests were administered in two sessions to assess memory, attention, language, visuospatial skills, and problem solving.[26,27] One set was used for diagnostic purposes and the second was used for research goals. Laboratory studies included a sensitive thyroid-stimulating hormone, vitamin B12, folic acid, syphilis serology, sedimentation rate, and if clinically indicated an EEG, single photon emission computed tomographic scan, CSF analysis, HIV, Lyme disease titer, antinuclear antigen, extractable nuclear antigen, and a 24-hour urine collection for heavy metals. Patients were not excluded for the presence of ongoing medical problems such as diabetes, hypertension, or heart disease. The diagnosis of AD was made according to the NINCDS-ADRDA criteria[1] at a consensus conference attended by behavioral neurologists, nurses, a geriatrician, and neuropsychologists. Disease severity in AD patients was assessed by the Clinical Dementia Rating (CDR) scale: very mild, CDR 0.5; mild, CDR 1; moderate, CDR 2.[28] An important distinction is made between establishing a diagnosis of AD and ranking its severity. The former was done according to NINCDS-ADRDA criteria, which emphasize a decline in cognitive performance over time as an important benchmark in establishing the diagnosis of AD.[1] The CDR score was used as a staging instrument to rank disease severity at a specific point in time. It was therefore possible for patients to meet NINCDS-ADRDA criteria for AD and also be ranked as only very mildly demented (CDR 0.5).

Control subjects were recruited from the same pool of patients coming to Mayo primary care physicians for a general medical examination. Control subjects were evaluated in the same way as patients, with the exception of the additional laboratory studies for cognitive impairment. Their status was reviewed at the consensus conference. The criteria for cognitively normal control subjects were (1) no active neurologic or psychiatric disorders and (2) like the patients, some had ongoing medical problems, however the illnesses or their treatments did not interfere with cognitive function.

An MRI examination of the brain was performed within 4 months of the clinical assessment, including CDR scoring, in all subjects. For all AD patients in this study the MRI was therefore performed with close temporal proximity to the *initial* diagnosis of AD. These MR studies were used in the diagnostic process only to exclude treatable causes of dementia. The volumetric data were not used to aid in the clinical diagnosis of AD.

MR image acquisition. All subjects were imaged at 1.5 T (Signa, General Electric, Milwaukee, WI) using a standardized imaging protocol. The first sequence was a T1-weighted sagittal set of images that was used to measure total intracranial volume and for landmarking subsequent image acquisitions. The other MRI pulse sequence relevant to this report was a T1-weighted (three-dimensional) volumetric spoiled gradient echo sequence with 124 contiguous partitions, a 1.6-mm slice thickness, a 22 × 16.5-cm field of view, 192 views, and a 45-degree flip angle. Volume measurements of the hippocampus, PHG, and amygdala were derived from this pulse sequence.

Image processing. All image processing steps (including boundary tracing) in every subject were performed by the same trained research assistant who was blinded to all clinical information to ensure that the volumetric data were generated in an unbiased fashion. The reformatting and realignment of the MR images and all anatomic tracings in every subject were reviewed by a three-member panel who were likewise blinded to all clinical information, and corrections were made at that time if necessary. This ensured rigorous quality control as well as uniformity in the subjective aspects of image processing across all the subjects in this study. Validation studies show the intrarater test-retest coefficient of variation of hippocampal volumetric measurements to be 1.9% with this method.[12]

The 3D MRI data were first interpolated in the slice select dimension to give cubic voxels.[29] When necessary the images were reformatted so that the image sections were oriented perpendicularly to the principal axis of the left hippocampal formation. Any rotation of the subject's head with respect to the orthogonal coronal plane was corrected as well during this reformatting and realignment step. The image data were then interpolated in plane to the equivalent of a 512 × 512 matrix and magnified two times. The voxel size of the fully processed image data was 0.316 mm^3. The borders of the hippocampi, PHG, and amygdala were manually traced sequentially with a mouse-driven cursor on each slice from posterior to anterior.[29] Having identified the boundaries of these MTL anatomic structures, the number of voxels in each was counted automatically using a summed region of interest function. These were multiplied by voxel volume to give a numeric value in cubic millimeters. The processed image files as well as the accompanying region of interest tracing files were saved for subsequent review.

In-plane hippocampal anatomic boundaries were defined to include the CA1 to CA4 sectors of the hippocampus proper, the dentate gyrus, and the subiculum[10-12,14,29,30] (figure 1). The posterior boundary of the hippocampus was determined by the oblique coronal anatomic section on which the crura of the fornices were identified in full profile.[31] Thus, essentially the entire hippocampus from the tail through the head was included in these measurements. These same neuroanatomic hippocampal boundary criteria are employed by many epilepsy research groups.[31-37] Subdivision of the hippocampus along its septotemporal axis into three segments labeled head, body, and tail was accomplished as follows: The hippocampal head was defined to encompass those imaging slices extending from the intralimbic gyrus forward to the anterior termi-

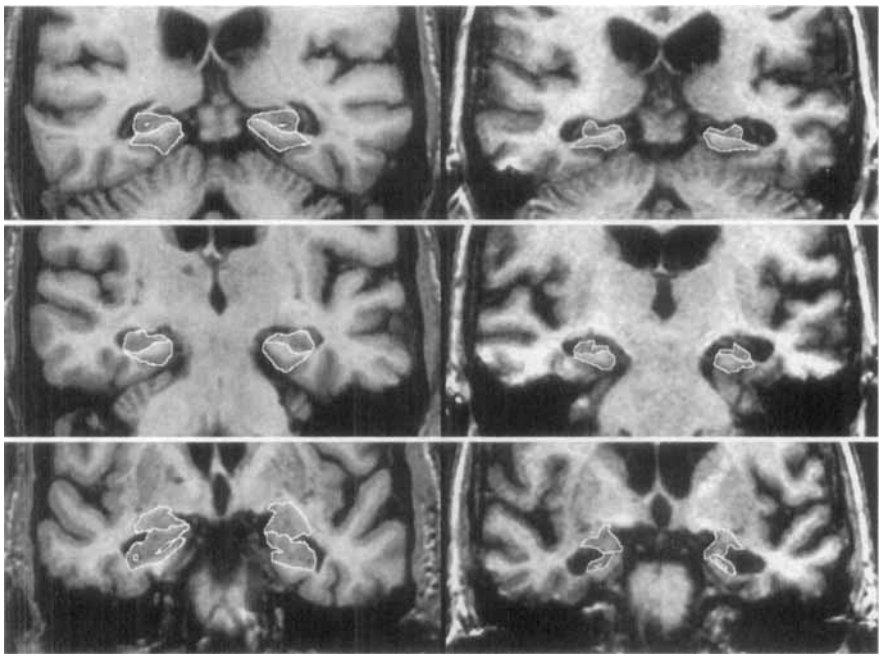

Figure 1. Neuroanatomic boundaries. Two columns of images are presented: cropped oblique coronal MR images through the temporal lobes of a 75-year-old female control subject (left) *and images from a 73-year-old female AD patient* (right)*, CDR 1. In each column, three images are present. From top to bottom these represent sections at the level of the hippocampal tail, hippocampal body, and hippocampal head. The anatomic outlines of the hippocampus, and parahippocampal gyrus are indicated on images of the hippocampal head and hippocampal body. The outline of the amygdala and hippocampus are indicated in the bottom image of the hippocampal head. Neuroanatomic criteria employed when tracing the boundaries of these three medial temporal lobe structures are indicated in the text.*

nation of the hippocampal formation. If the posterior margin of the hippocampal head was labeled as imaging slice x, then the volume of the hippocampal tail was determined by summing the area of the hippocampus on successive slices beginning from the forniceal crura to slice $\frac{x-1}{2}$. The volume of the body consisted of the sum of areas on successive slices beginning with slice $\left(\frac{x-1}{2}\right) + 1$ and extending to slice $x - 1$.

The posterior boundary of the PHG was defined in a manner identical to that for the hippocampal formation. The superior boundary of the PHG was defined as the gray-white matter interface between the subiculum and the PHG white matter. Medially the PHG was demarcated by CSF in the uncal cistern. Laterally and inferiorly its boundary was the collateral sulcus. The imaging slice immediately preceding that in which the hippocampal intralimbic gyrus first appeared when progressing from posterior to anterior was defined as the anterior boundary of the PHG. In some patients a clearly identifiable collateral sulcus was not present along the entire anteroposterior extent of the PHG. For this reason, PHG measurements were not possible in 16 control subjects and 14 AD patients.

The posterior, superior, medial, and lateral boundaries of the amygdala were defined by gray-white matter borders or, where appropriate, CSF in the uncal cistern. The inferior border of the amygdala was either the uncal recess of the temporal horn or the alveus covering the hippocampal head. The anterior boundary of the amygdala is ill defined in nature, and we defined it operationally to be the most anterior slice on which the head of the hippocampus was present.

Statistical methods. Individual MTL structure volumes were normalized for intersubject variation in head size by dividing structure volume (in cubic millimeters) by the total intracranial volume (TIV, in cubic centimeters) of that particular subject.[10,14] Associations between normalized MTL volumes, age, and gender, in normal subjects were evaluated using stepwise regression, including evaluation of nonlinearity and interactions. Stepwise regression was also used to determine if variability was associated with age or gender.

Volumetric percentiles in controls specific for age and gender were obtained using the algorithm described by O'Brien and Dyck.[38] Age- and gender-specific volumetric percentiles among AD patients were determined and converted to W scores (normal deviates) using the inverse of the standard normal distribution (a percentile value of 95 corresponding to a W score of 1.645, for example).[38] The W score value is a covariate-adjusted Z score relative to the control group. Comparison of W values among MTL anatomic structures for AD patients was performed using ANOVA for repeated measures and paired *t*-tests. To identify the MTL limbic structures that best distinguish between AD and control subjects, we performed a stepwise discriminant analysis including normalized volumes, age, and gender as predictor variables.

Results. Two hundred twenty subjects are included in this report—126 control subjects and 94 AD patients (table 1). The control and AD patients were well matched on education and gender distribution with approximately a 2:1 female-to-male ratio in both groups. The age range of control subjects was 51 to 89 years and of AD patients was 50 to 89 years. Forty-four of the 126 control subjects were men, 16 of the 36 CDR 0.5 Alzheimer disease patients were men, 10 of the 43 CDR 1 patients were men, and seven of the 15 CDR 2 patients were men. As expected, Dementia Rating Scale[39] and Mini-Mental State Examination[40] scores declined with increasing CDR grade in AD patients.

The results from this study are discussed in three parts: (1) descriptive statistics of the control subjects, which characterize the relationship between normal aging, gender, and MTL volumes; (2) similar descriptive statistics of the AD patients, which are compared with those of control subjects; and (3) analysis of the ability of MTL volumetric

Table 1 *Characterization of subjects*

Variable	Controls, CDR 0 (N = 126) (mean ± SD)	AD, CDR 0.5 (N = 36) (mean ± SD)	AD, CDR 1 (N = 43) (mean ± SD)	AD, CDR 2 (N = 15) (mean ± SD)
Age	79.15 ± 6.73	72.92 ± 8.43	73.47 ± 9.68	75.87 ± 8.71
Education	13.43 ± 2.96	13.33 ± 2.91	12.98 ± 2.69	12.38 ± 2.47
MMSE*	28.60 ± 1.26	21.60 ± 4.36	18.16 ± 4.47	13.93 ± 5.99
DRS†	135.14 ± 6.95	112.79 ± 13.72	101.33 ± 20.75	89.62 ± 25.58

* One patient in each CDR group with missing values.
† One control subject, three patients in CDR 0.5, four patients in CDR 1, and two patients in CDR 2 with missing values.

CDR = Clinical Dementia Rating; MMSE = Mini-Mental State Examination; DRS = Dementia Rating Scale.

measurements to discriminate between control and AD subjects with varying disease severity.

Control subjects. Normalized MTL volumes declined with age in a linear fashion (table 2, figure 2). The segment of the hippocampus that demonstrated the greatest decline with age was the head. No significant hemispheric differences in volume loss with age were observed in any MTL structure, except the PHG where the age-related volume loss was greater on the left than the right side ($p = 0.024$). The mean unnormalized volumetric decline with age was 45.63 mm^3 per year for the total hippocampus, 27.43 mm^3 for the hippocampal head, 8.84 mm^3 for the hippocampal body, 9.68 mm^3 for the hippocampal tail, 46.65 mm^3 for the PHG, and 20.75 mm^3 for the amygdala. Mean total intracranial volume in control subjects was 1,393 cm^3 ± 133 cm^3 (SD).

The unnormalized MTL structure volumes of men were generally larger than those of women, while the normalized MTL volumes of women were generally larger than those of men (see table 2 and figure 2). That is, these MTL limbic structures occupied a larger percentage of TIV in women than in men. The decline in volume associated with age did not differ significantly between men and women. These associations were used to estimate age- and gender-specific normal percentiles for TIV-normalized MTL volumes (table 3).

Alzheimer's disease patients. A decline in normalized MTL volumes with age was observed among AD patients. The slopes of the age-volume regression lines were not significantly different between patients and control subjects over the age range studied (see table 2 and figure 2). As with controls, unnormalized volumes were generally larger among men than women, while larger normalized volumes were observed among female AD patients. Associations between MTL volume and age were linear, and did not differ between men and women. The segment of the hippocampus showing the greatest decline with age was the head.

Age- and gender-specific percentiles for normalized volumes were computed for each of the AD patients, and these were converted to W scores (corresponding to a normal distribution; table 4). Thus, values of $W < 0$ indicate that volume is less than the mean value expected for a normal subject after adjustment for age and gender. A value of −1.96 corresponds to a value that is at the 2.5 percentile among normal controls.

We assessed the extent to which patients differed from control subjects, and for each anatomic structure W scores were significantly <0 among AD patients ($p < 0.001$). As would be expected from table 2, the deficit in volumes relative to controls was not associated with age or gender. We also assessed whether the magnitude of the volumetric deficit in cases relative to controls was greater in some structures than others. The differences among the hippocampus, PHG, and amygdala were significant ($p \leq 0.001$, ANOVA), and all pairwise comparisons (paired *t*-tests) were also significant (hippocampus versus amygdala, $p < 0.001$; hippocampus versus PHG, $p < 0.001$; amygdala versus PHG, $p = 0.006$; see table 4). Within the hippocampus, volumes differed significantly among the

Table 2 *Relationship between normalized volume, age, and gender in controls and Alzheimer's disease (AD) patients**

	Controls			AD patients		
Normalized structure volume	Intercept	Age	Gender	Intercept	Age	Gender
Total hippocampus	6.359	−0.0357	0.263†	5.135	−0.029	—
Hippocampal head	3.421	−0.0185	—	2.991	−0.020	—
Hippocampal body	1.409	−0.0074	0.097	1.186	−0.006	—
Hippocampal tail	1.442	−0.0084	0.110	0.911	−0.003†	0.079†
Amygdala	2.414	−0.0143‡	—	1.790	−0.011‡	—
Parahippocampal gyrus	5.458	−0.0371	0.390	4.216	−0.025	0.250‡

* The entries in the table may be used to predict volumes. For example, the predicted normalized total hippocampal volume for a control subject is 6.36 − 0.0357 age (in years) + 0.263 gender (1 if female, 0 if male). All associations shown are significant with $p < 0.001$, except as indicated.
† $p < 0.01$.
‡ $p < 0.05$.

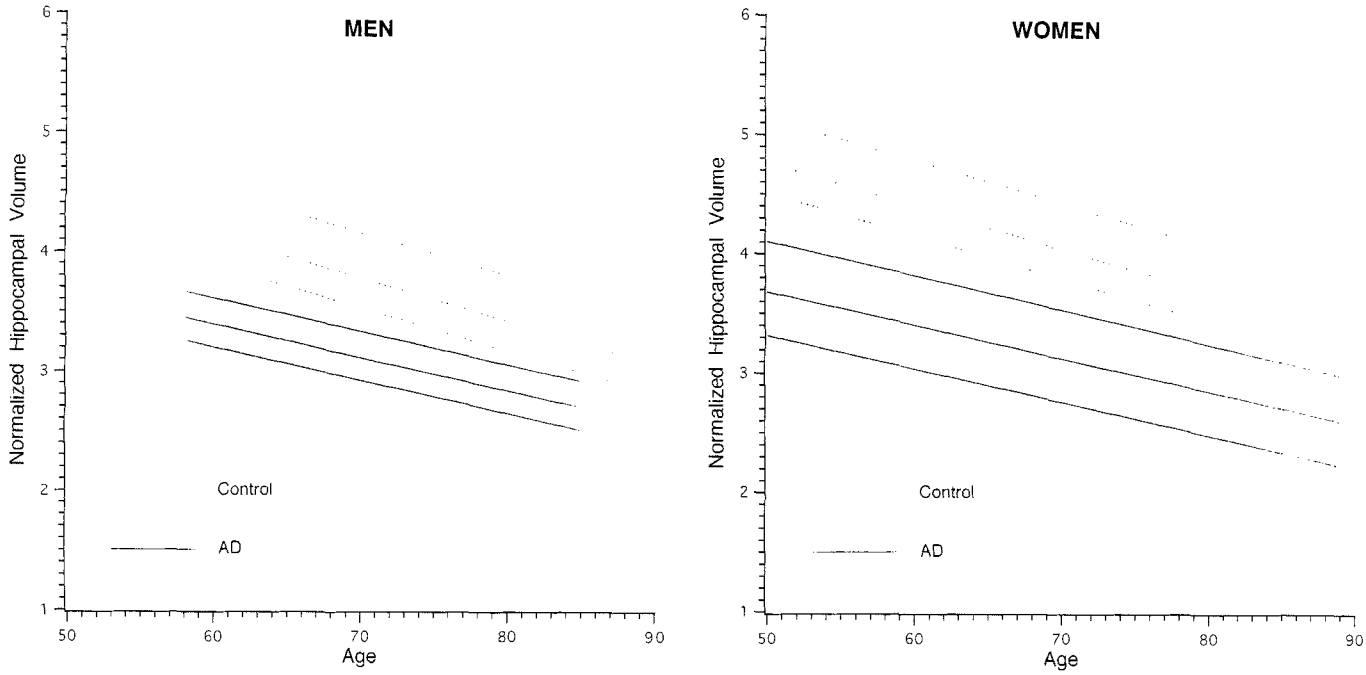

Figure 2. Normalized hippocampal volume by age in control subjects and Alzheimer's disease (AD) patients. Regression of the mean normalized hippocampal volume by age in male (A) and female (B) control subjects and AD patients. The upper and lower limits (dashed lines) *represent the 75th and 25th percentile values for each group. Hippocampal volumes of AD patients are smaller than those of age-matched control subjects. Volumes in both groups decline linearly and in parallel with advancing age. For clinical purposes the position of a memory-impaired elderly subject may be plotted and compared to age- and gender-matched control subjects and AD patients.*

head, body, and tail ($p \leq 0.001$, ANOVA), and pairwise differences between the head and body, and body and tail were also significant ($p < 0.001$, paired t-tests). The mean TIV of AD patients, 1,369 ± 138 cm^3, was not significantly different from that of control subjects.

When AD patients were categorized by disease severity into those with very mild, mild, or moderate disease, W scores within each group remained significantly less than 0, ($p < 0.001$; see table 4). The MTL structure with the lowest W scores was the hippocampus for all three AD groups. Within the hippocampus, W values were the most negative for the head (see table 4). W scores for the total hippocampus ($p < 0.05$) and hippocampal head ($p < 0.001$) were significantly different among AD patients of different CDR severity grades (Spearman's rank correlation). Pairwise comparison of the W scores was also signif-

Table 3 *Age- and gender-specific normal percentiles (mm/cm × 10) for hippocampal volume normalized by total intracranial volume**

		Normal percentiles				
Age (yr)	Gender	1	5	10	20	50
50	M	3.736	3.953	4.059	4.184	4.491
	F	4.000	4.216	4.323	4.447	4.754
60	M	3.379	3.595	3.702	3.827	4.133
	F	3.642	3.859	3.965	4.090	4.396
70	M	3.022	3.238	3.344	3.469	3.776
	F	3.285	3.501	3.608	3.733	4.039
80	M	2.664	2.880	2.987	3.112	3.418
	F	2.928	3.144	3.250	3.375	3.682
89	M	2.343	2.559	2.665	2.790	3.097
	F	2.606	2.822	2.929	3.054	3.360

* Values in the body of the table represent age- and gender-specific mean, normalized hippocampal volume in control subjects. The first, fifth, 10th, 20th, and 50th percentile values in control subjects are reported. The presence of hippocampal atrophy in an individual patient can be assessed by comparing the total intracranial volume normalized hippocampal volumes of that patient against those of age- and gender-matched control subjects reported in this table.

Table 4 *W scores* in Alzheimer's disease patients*

	CDR 0.5 (N = 36)		CDR 1 (N = 43)		CDR 2 (N = 15)	
Variable	Mean W value	SD	Mean W value	SD	Mean W value	SD
Total hippocampus	−1.752	0.939	−1.989	1.193	−2.225	1.183
Hippocampal head	−1.146	0.853	−1.650	1.084	−1.986	0.906
Hippocampal body	−1.163	0.859	−1.067	0.950	−1.236	1.087
Hippocampal tail	−1.448	0.903	−1.200	1.063	−1.559	1.301
Parahippocampal gyrus	−0.874	1.035	−0.996	1.101	−0.512	1.344
Amygdala	−1.026	0.973	−1.337	0.839	−1.355	1.035

* The W score is the normal deviate relative to control subjects, adjusted for age and gender. All mean W scores were significantly different from 0 (the expected value for normal subjects). $p < 0.001$.

CDR = Clinical Dementia Rating.

icant for the total hippocampus—CDR 0.5 versus 1.0 ($p < 0.01$), CDR 1 versus 2 ($p < 0.01$) (rank sum test).

Discrimination between controls and AD patients of varying severity. Using stepwise linear discriminant analysis (including age, gender, and TIV-normalized volumes as independent variables) to predict AD, the only variables that appeared in the final model were hippocampal volume, hippocampal volume squared, and age. Although all these terms were significant at the 0.02 level, the prediction equation was dominated by the linear hippocampal volume term, and the accuracy of the prediction was identical to that obtained using hippocampal W scores alone. The sensitivity of hippocampal volumes to distinguish AD patients from control subjects was assessed by computing the percentage of AD patients with W scores at selected percentiles among control subjects (table 5). For example, at a fixed specificity of 80%, the sensitivity of hippocampal volumetric measurements in discriminating control subjects from patients was 77.8% for CDR 0.5, 83.7% for CDR 1, and 86.7% for CDR 2. Discrimination between control subjects and AD patients was roughly equivalent among the three AD severity groups at the 50th and 20th percentiles of normal. Discrimination was greater for CDRs 1 and 2 than CDR 0.5 patients at the 10th and fifth percentile of normal. At the first percentile of normal, discrimination improved as the patient's disease severity (CDR score) increased.

Discussion. In this study involving a large group of well-characterized AD patients and elderly control subjects we have demonstrated that MR volumetric measurements of the hippocampal formation are useful in discriminating between very mild AD and elderly control subjects. The very mild AD subjects (CDR 0.5) qualify for the diagnosis of probable AD by clinical research criteria yet exhibit only the minimal symptoms necessary for this diagnostic classification. These patients present significant diagnostic difficulties for the clinician and constitute an area where a structural imaging test may be particularly useful.

Control subjects. All MTL limbic structures measured declined in volume with advancing age. This is consistent with observations of age-related brain atrophy in other imaging and autopsy studies.[14,41-46] It is not clear whether this volume loss is an inevitable consequence of aging.[14,41-47] Subjects enrolled as normal control subjects in this study were community-dwelling individuals with no evidence of cognitive impairment. Subjects with medical conditions (e.g., heart disease, diabetes, hypertension) were included as normal control subjects. It is possible that medical conditions that increase in prevalence with advancing age and that may be associated with brain atrophy such as hypertension, diabetes, or atherosclerosis might account for some of the observed correlation between age and volume loss in these normal control subjects.[48-50] Yet, this control population is typical of what a clinician faces in daily practice. These data do not address the issue of optimal

Table 5 *Diagnostic discrimination of normalized total hippocampal volume adjusted for age and gender**

	Indicated percentile of normal				
AD patients	50	20	10	5	1
CDR 0.5 (N = 36)	97.2	77.8	72.2	58.3	36.1
CDR 1 (N = 43)	90.7	83.7	81.4	67.4	53.5
CDR 2 (N = 15)	93.3	86.7	80.0	66.7	66.7
Overall (N = 94)	93.6	81.9	77.7	63.8	48.9

* Percentage of Alzheimer's disease (AD) patients below indicated percentile of normal.

CDR = Clinical Dementia Rating.

aging or the aging process without any comorbid illnesses. In analyzing the association between MTL volume and age we recognize that this is a cross-sectional sample and that secular effects of different environmental or socioeconomic conditions experienced by successive age groups may be unrecognized.[4]

Alzheimer's disease patients. The duration of disease in younger AD patients in this study was not different from that in older AD patients. Our data therefore reflect a cross-sectional sample at the time of the initial diagnosis of AD across an age spectrum from 50 to 89 years. In AD patients, MTL volumes declined with advancing age in parallel with those of control subjects. However, the age- and gender-adjusted normalized MTL volumes of AD patients were significantly smaller than those of control subjects. This was true for each MTL structure, at all ages, and for both men and women. We hypothesize that the volume loss in AD patients represents the progressive atrophy associated with the degenerative disease, superimposed on that associated with aging.

The analysis of segmental hippocampal volumes in control subjects demonstrated that age-associated volume loss in the head of the hippocampus exceeds that of either the body or the tail. In addition, of the hippocampal segments, the largest volumetric difference between control subjects and AD patients was found in the hippocampal head. This observation is in agreement with a similar analysis that was performed on autopsy specimens.[51] These data would suggest that the head of the hippocampus is more susceptible to age-related atrophy and also more susceptible to the degenerative change associated with AD. The observed differential sensitivity of the hippocampal head to age-related and AD-related atrophy may be related to differences in the nature of the cortical input between the hippocampal head and the more posterior segments of the hippocampus.[52-54]

Discrimination between control subjects and AD patients of varying severity. Although all the MTL limbic structures measured were significantly smaller in AD patients than control subjects, the structure that best discriminated between AD patients and controls was the total hippocampal volume. When a linear discriminant function model was constructed, essentially all the discriminatory power was found in the hippocampal volume alone. These results are at odds with those published by several other investigators who found that combinations of different volumetric measurements more effectively separated controls from AD patients than measurement of any single structure.[15,16,19,55,56] It is possible that measurement of brain structures other than the ones evaluated here may be useful in a discriminant function analysis. However, the large number of subjects and careful attention to details of technical and neuroanatomic boundary criteria employed in this study should convincingly demonstrate the absence of additional discriminatory power provided by measurements of the PHG or amygdala. Of the three MTL structures measured, the anatomic boundaries presented by MRI are more precise, and less normal anatomic variability exists, for the hippocampus than for the amygdala or PHG.[29] Hippocampal measurements therefore have less measurement error and also less "noise" introduced as a function of normal anatomic variation than those of the PHG or amygdala.[57]

Hippocampal W-values progressively decline (increasing atrophy) with increasing CDR score in table 4. This suggests that hippocampal volumetric measurements are a sensitive marker of the degenerative neuroanatomic substrate of the progressively more severe memory impairment seen with advancing CDR scores in AD. Hippocampal volumetric measurements will not, however, discriminate among different conditions that share MTL atrophy as a common pathologic feature.[58] Nevertheless, we believe that this type of MRI-based hippocampal volumetric measurement may be helpful to the clinician as an adjunctive piece of diagnostic information in situations when the clinical diagnosis is difficult. A comparison of the normalized hippocampal volumetric measurements of an individual patient with age- and gender-specific normal percentiles (as illustrated in figure 2 and table 3) would provide a clinically useful assessment of the presence and severity of hippocampal atrophy. An elderly patient complaining of a memory impairment whose hippocampal volumes fell into the AD range might be more closely scrutinized for a diagnosis of AD, while a patient with a similar complaint whose hippocampal volumes fell into the control range might be reassured that AD was less likely. One caveat, however, is that the absolute numeric output of any image-based volumetric measurement technique is methodology dependent.[29] Therefore while the associations reported should be generalizable, the specific numeric values may vary among different sites.

In summary, the most encouraging finding in this study was the ability of hippocampal volumetric measurements to discriminate between control subjects and AD patients with very mild disease. The mean hippocampal volume in very mild (CDR 0.5) AD patients was 1.75 SD below the control mean, and 97.2% of all CDR 0.5 AD patients had hippocampal volumes below the 50th percentile of normal. These data, derived from a large number of subjects, demonstrate that MRI volumetric measurements of hippocampal atrophy are a sensitive marker of the pathology of AD in its most mild form. The ability of quantitative MRI volumetric measurements to predict which currently normal or mildly impaired elderly subjects will develop AD in the future will, however, require longitudinal studies, which are in progress.

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The apolipoprotein E ϵ4 allele is not associated with psychiatric symptoms or extrapyramidal signs in probable Alzheimer's disease

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Article abstract—The objective of our study was to examine the relationship between the presence of the apolipoprotein E (apo E) ϵ4 allele, psychiatric symptoms, and extrapyramidal signs (EPS) in probable Alzheimer's disease (AD). The apo E ϵ4 allele modifies the risk and age at onset of AD. However, it still needs to be determined whether it is a marker for specific clinical subgroups. The frequency of clinical signs and symptoms was examined in 194 AD patients with the apo E ϵ3/3 (N = 79), ϵ3/4 (N = 96), and ϵ4/4 (N = 19) genotypes participating in a longitudinal study of dementia. Each patient was assessed with semistructured psychiatric and neurologic examinations. Patients with the ϵ4/4 genotype had an earlier age at onset of dementia ($p = 0.03$). However, no individual psychiatric symptom or neurologic sign was associated with the presence of the apo E ϵ4 allele, including major depression (odds ratio [OR], 1.14; CI, 0.50 to 2.45; $p = 0.78$), psychosis (e.g., delusions and hallucinations) (OR, 0.66, CI, 0.35 to 1.25; $p = 0.20$), and EPS (in neuroleptic-free patients) (OR, 0.82, CI, 0.45 to 1.49; $p = 0.52$), after controlling by age at onset, duration of the symptoms, education, and severity of dementia. The presence of the apo E ϵ4 allele has limited utility in the characterization of neurologic and psychiatric subgroups in probable AD patients. The apo E ϵ4/4 genotype appears to be related to age at onset of AD, consistent with previous findings.

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The apolipoprotein E (apo E) ϵ4 allele has been shown to modify risk and age at onset of Alzheimer's disease (AD).[1-3] Neuropathologic studies have found more severe AD pathology in subjects carrying the apo E ϵ4 allele than in those without the allele. This includes more cortical neurofibrillary tangles and senile (neuritic) plaques (SP),[4] and a more severe cholinergic deficit in the frontal lobes.[5] Moreover, neuroimaging studies have shown greater atrophy in medial temporal structures in AD patients carrying the apo E ϵ4 allele.[6]

The development of psychiatric symptoms appears to be related to more severe neuropathologic changes[7-9] and to specific neurotransmitter imbalances, notably acetylcholine[10] and serotonin.[11] Consequently, given that patients carrying the apo E ϵ4 allele have more severe structural and neurochemical abnormalities, psychiatric symptoms should be

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