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Three-dimensional reconstruction based on images from spiral high-resolution computed tomography of the temporal bone: anatomy and clinical application

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Abstract

The aim of this study was to investigate the usefulness of a three-dimensional (3D) reconstruction of computed tomography (CT) images in determining the anatomy and topographic relationship between various important structures. Using 40 ears from 20 patients with various otological diseases, a 3D reconstruction based on the image data from spiral high-resolution CT was performed by segmentation, volume-rendering and surface-rendering algorithms on a personal computer. The 3D display of the middle and inner ear structures was demonstrated in detail. Computer-assisted measurements, many of which could not be easily measured *in vivo*, of the reconstructed structures provided accurate anatomic details that improved the surgeon's understanding of spatial relationships. A 3D reconstruction of temporal bone CT might be useful for education and increasing understanding of the anatomical structures of the temporal bone. However, it will be necessary to confirm the correlation between the 3D reconstructed images and histological sections through a validation study.

Key words: Temporal Bone; Tomography, Spiral Computed; Anatomy, Inner Ear, Middle Ear

Introduction

The rapid development of spiral high-resolution computed tomography (HRCT) has resulted in exciting new applications for computed tomography (CT). One of these applications, a three-dimensional (3D) reconstruction technique based on the CT images, has attracted a great deal of clinical and academic interest. The 3D reconstruction technique proves to be far more than just a diagnostic tool in search of a problem, and provides clinically accurate images from the CT data, which are immediately available without extensive editing. Recent advances in computer hardware and image-processing software have made it possible to reconstruct immediately available 3D images, describe the detailed 3D anatomy, and measure a 3D relationship, such as length, area, volume and angle.[1] In this article, the 3D reconstruction technique based on images from spiral HRCT was used for the anatomical consideration of complex structures in the temporal bone, with a view to proving the clinical usefulness of the technique.

Subjects and methods

A prospective study was performed on 20 patients who underwent temporal bone CT for various otologic diseases from January to April 2003 at the Uijeongbu St Mary's Hospital, The Catholic University of Korea. The acquisition parameters used for the most commonly used protocols are described as follows. The spiral temporal bone HRCT scan (Somatom Plus 4; Siemens Medical Systems, Erlangen, Germany) was taken with a 1.0-mm slice thickness, 140 kV, 100 mAs, and continuous non-overlapping sections. The field of view was reduced from 150 to 80 mm^2, which resulted in a 512 $\times$ 512 matrix. After the imaging data were stored in a DICOM (Digital Imaging and Communication in Medicine) file, they were imported to a personal computer, which ran on VworksTM 4.0 software (Cybermed Inc., Seoul, Korea). The window widths and levels on the voxel scale need to be varied, depending on the type of tissue being examined. Adjustments in the window width and level alter the attenuation of the structures displayed in a 3D mode. In this study, a lower threshold of +250 HU (Hounsfield unit) and

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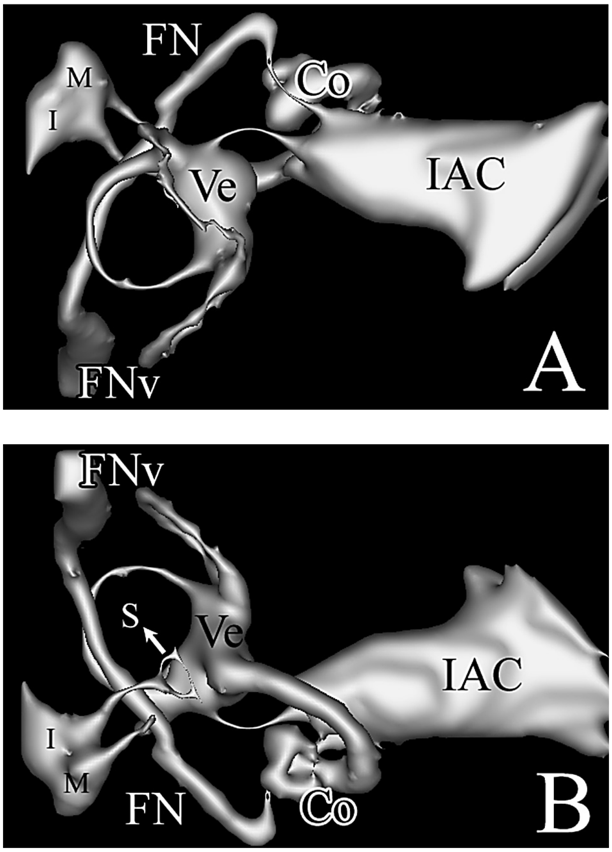

FIG. 1

3D reconstruction by segmentation. (a) Superior view and (b) inferior view of inner ear structures (a normal left temporal bone). The cochlea (Co), vestibule (Ve), three semicircular canals, three ossicles (M, malleus; I, incus; S, stapes), and facial canal can be seen in relation to the ossicles and the internal auditory canal (IAC). FN, facial nerve; FNv, vertical segment of facial nerve.

an upper threshold of +3071 HU were used to give the best result in representing the ossicles and the bony labyrinth. In addition, the lower threshold of -1024 HU and the upper threshold of -200 HU were used to give the best result in representing the mastoid air cell tracts.

The segmentation algorithm was used in this study to describe the spatial relationships between the various structures in the middle-ear cavity and the inner ear: the internal auditory canal, facial nerve, cochlea, ossicles, and internal carotid canal. Because the dimensions of the middle and inner ear were too small for automated segmentation to be feasible, the segmentation of minute structures in the temporal bone was performed by hand. Surface-rendering and volume-rendering algorithms were used to describe the 3D details of the anterior, posterior and medial walls of the middle ear cavity, and to measure the structures in the temporal bone. By rotating the 3D reconstructed images about three axes (X, Y, Z), it is possible to describe the detailed anatomy of the oral and round windows, ponticulus, subiculum, promontory, chordal ridge, pyramidal eminence, and ossicles, as well as the facial recess, lateral tympanic sinus, and tympanic sinus.

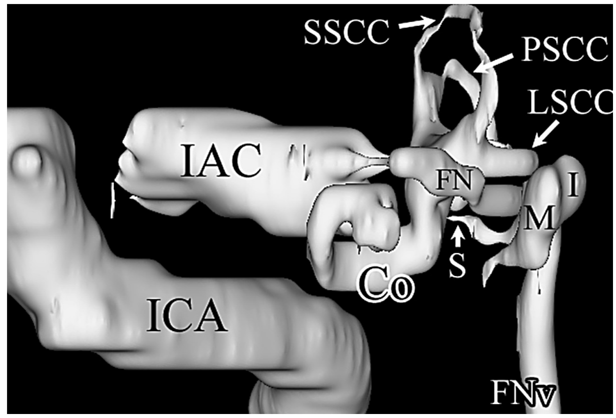

FIG. 2

3D reconstruction by segmentation. Anterior view of inner ear structures and internal carotid artery (a normal left temporal bone). The ossicles and vestibulocochlear apparatus can be seen in relation to the internal carotid artery. ICA, internal carotid artery; SSCC, superior semicircular canal; PSCC, posterior semicircular canal; LSCC, lateral semicircular canal; for other abbreviations see Figure 1.

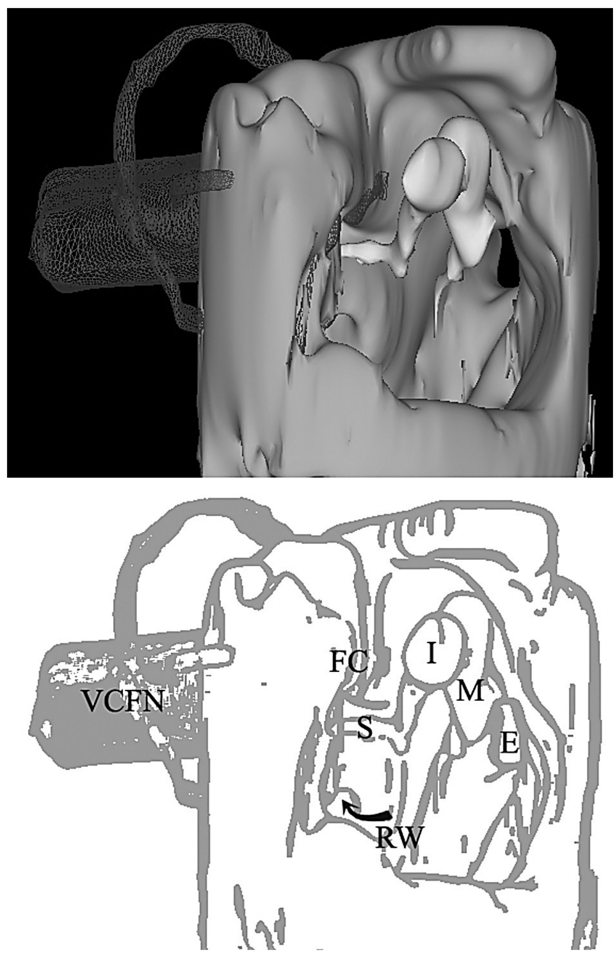

FIG. 3

3D reconstruction by surface-rendering. Posterior view of E-tube orifice (a normal right temporal bone, in a virtually canal-wall-down mastoidectomized state). The dotted area on the walls of the middle ear cavity represents the tympanic segment and mastoid segment of the facial nerve. FC, facial canal; M, malleus; I, incus; S, stapes; RW, round window niche; E, eustachian tube orifice; VCFN, vestibulocochlear and facial nerves.

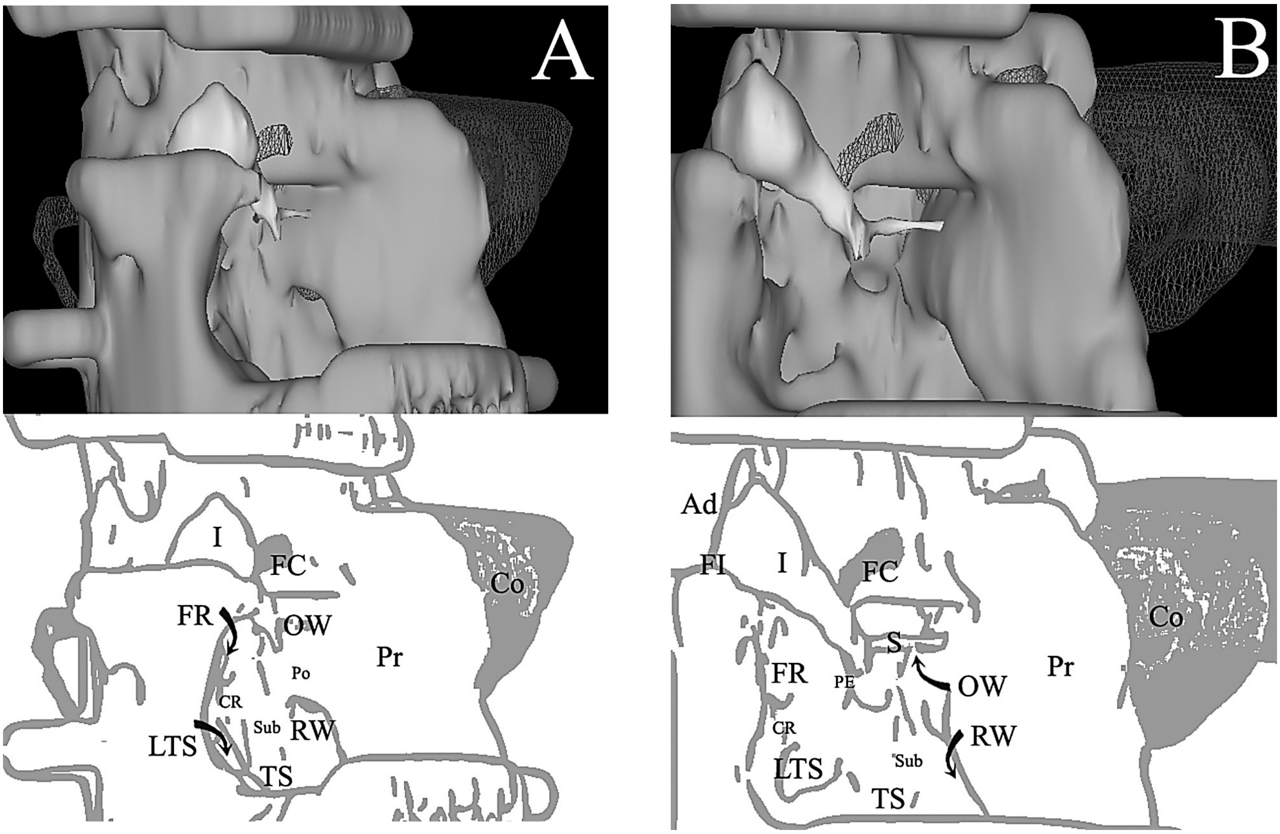

FIG. 4

3D reconstruction by surface-rendering. (a) Antero-lateral view and (b) more anterior view of posterior wall of middle ear (a normal right temporal bone, after removing malleus). The dotted area behind the ossicles is the tympanic segment of the facial nerve. AD, aditus ad antrum; FI, fossa incudis; I, incus; S, stapes; FC, facial canal; OW, oval window niche; RW, round window niche; Po, ponticulus; Sub, subiculum; Pr, promontory; FR, facial recess; LTS, lateral tympanic sinus; TS, tympanic sinus; PE, pyramidal eminence; CR, chordal ridge; Co, cochlea.

Results

3D reconstruction based on the images from spiral HRCT of the temporal bone was achieved using the segmentation, surface-rendering, and volume-rendering algorithms. Both the axial and coronal images of the spiral HRCT data were used in these algorithms.

The following figures give examples of the different 3D reconstructed images of the temporal bone obtained during routine clinical diagnosis of various otologic diseases. Selected examples of the 3D reconstructed images of the temporal bone were focused on normal ears, in an attempt to demonstrate the 3D reconstruction technique and enhance its clinical usefulness.

Spatial relationship between structures in the temporal bone

The segmentation algorithm was used to describe the spatial relationships of the internal auditory canal, facial nerve, cochlea, ossicles, and internal carotid canal in the temporal bone (Figures 1 and 2). A surface-rendering algorithm was used to describe the 3D details of the anterior and postero-medial walls of the middle ear cavity. The 3D images made it easier to understand the spatial relationship of the eustachian tube. In addition, the spatial relationships between the oral and round windows, ponticulus, subiculum, promontory, chordal ridge, pyramidal eminence, and ossicles, as well as the facial recess, lateral tympanic sinus, and tympanic sinus, were more easily understandable after rotating the 3D reconstructed images about three axes (Figures 3 and 4).

3D reconstruction of the mastoid air cell system

A lower threshold of -2048 HU and an upper threshold of -1024 HU were used to represent the mastoid penumatization system. Accordingly, the 3D images of the mastoid air cell tracts and the epitympanum could be reconstructed using the surface-rendering algorithm (Figure 5).

Discussion

Understanding the complex and minute 3D anatomy of the temporal bone is a challenge for otologic surgeons. It is very important for the beginner as well as the experienced surgeon to be familiar with the precise relationships of the complicated and elaborate structures such as the facial canal, oval window, round window, cochlea, and semicircular canal. Although HRCT is generally accepted for evaluating the temporal bone anatomy and making a

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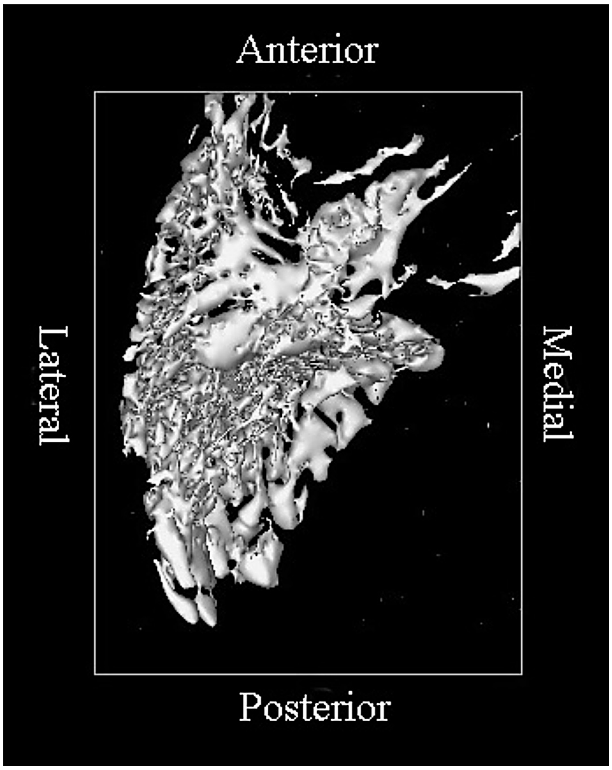

FIG. 5

3D reconstruction by surface-rendering. Pneumatization of a left temporal bone, including the mastoid air cell system and epitympanum.

diagnosis of temporal bone diseases, the exact topographic relationships between minute structures or between pathologic lesions and functionally important structures in the temporal bone might be difficult to determine using cross-sectional 2D images alone. In particular, detailed information or precise measurement of the structure of interest is impossible when the axis or plane of the structure is not matched to that of a CT section.

The first 3D reconstructions of several structures in the temporal bone were based on digitized histologic microsections of cadaveric temporal bone;[2,3] a method where the 3D reconstruction was based on video camera pictures of the CT images was also used.[4] Traditional computer graphics defined a 3D object as a wireframe composed of a large number of geometric primitives such as point, line, plane, and polygon. Recently, a method has been used to reconstruct the image stack, after it has been processed by 2D image-processing techniques, into a 3D volumetric dataset. This is usually achieved by either a surface- or volume-rendering algorithm. A surface-rendering algorithm is an indirect method of obtaining an image from a volume dataset. The volumetric data must first be converted into geometric primitives, by a process such as isosurfacing, isocontouring, surface extraction, or border following. These primitives are then rendered for display using conventional geometric rendering techniques. In contrast, a volume-rendering algorithm provides a method of directly displaying the data without any intermediate surface representations. A volume-rendering algorithm is a computer graphics technique whereby the object or phenomenon of interest is sampled or subdivided into many cubic building blocks, called voxels (or volume elements). A voxel is the 3D counterpart of the 2D pixel and is a measure of unit volume. Both algorithms have advantages and disadvantages. A major advantage of the volume-rendering algorithm is that the 3D volume can be displayed without any knowledge of the geometry of the dataset and hence without intermediate conversion to a surface representation. This conversion step in a surface-rendering algorithm can sometimes be quite complex, especially if surfaces are not well defined, and can require a lot of user intervention (such as manual contour tracing in segmentation). On the other hand, because the 3D dataset is reduced to a set of geometric primitives in a surface-rendering algorithm, this can provide fast display and manipulation of the 3D reconstructions produced by this method. However, a surface-rendering algorithm has the following disadvantages: it discards the interior of the object and maintains the object's shell; it does not facilitate real-world operations such as cutting, slicing, or dissection; and it does not enable artificial viewing modes, such as semi-transparency.

TABLE I

CLINICAL APPLICATIONS OF 3D RECONSTRUCTION OF THE TEMPORAL BONE FROM SPIRAL HIGH-RESOLUTION CT

Clinical application	Examples
Studying anatomy of the temporal bone	No need for cadaver study; more wide-ranging study possible To provide information about normative data of normal temporal bone To provide incidences of anatomic variations
Pre-operative evaluation of a patient's individual anatomy	To provide more information about individual pathologic lesions To provide correlation of pathologic changes to surgical landmarks
Surgical navigator	To provide image-guided surgery, 3D perspective volume-rendering of patient's anatomy, the perspective of surgical instruments, especially in real time during surgery
Education, training and simulation	To provide students or residents with more comprehensive understanding of complex anatomy of temporal bone To provide students or residents with information about spatial relationships of various structures By computerized simulation, to be useful for training purposes
Functional study (in the future)	In combination with functional imaging techniques, may provide comprehensive understanding of the relationship between morphologic changes and pathophygiologic mechanisms of the inner ear

By contrast, since all of the image stack data is used for a volume-rendering algorithm, computers with lots of memory and processing power are required to handle volumes rendered in this manner. Because the entire dataset is preserved in a volume-rendering algorithm, any part, including internal structures and details (which may be lost when reducing to geometric structures with surface rendering) may be viewed. For medical purposes, a volume-rendering algorithm is preferred because of its ability to contain data on the internal architecture, to give a texture for the density changes in the data, to allow easy and natural exploration of volumetric data, and to exclude the need for classifying or segmenting the data.

- **This paper uses three dimensional (3D) reconstruction based on images from spiral high-resolution computed tomography (CT) to image the temporal bone**
- **The technique accurately demonstrates the spatial relationship of temporal bone structures. In addition the authors use an application of volume measurement to assess mastoid pneumatization**
- **Further work is needed to correlate 3D CT images with temporal bone histologic sections**

While the raw image can be readily displayed as 2D slices, 3D analysis and visualization require explicitly defined object boundaries, particularly when creating 3D surface models. The pixel detection process is called segmentation; it identifies the attributes of the pixels and defines the boundaries for the pixels that belong to the same group. Furthermore, measurements and quantitative analysis for the parameters such as length, area, and volume can be easily obtained when the object boundaries are defined. Segmentation by thresholding is a simple but powerful approach for images containing solid objects that are distinguishable from the background or other objects in terms of pixel intensity values. The segmentation technique can be used to reconstruct a 3D image of the facial canal, internal auditory canal, cochlea, vestibule, ossicles, and internal carotid artery, but requires manual contour tracing which is quite time consuming (in this study, 20-30 minutes were needed to reconstruct the images of these structures per single temporal bone). Moreover, the substructures of the temporal bone are too small for automated segmentation to be used, and this technique has many problems when it is applied to clinical situations, such as diagnosis and surgery.

The 3D reconstruction technique helps to achieve a comprehensive understanding of various structures in the temporal bone. This study shows that this technique can provide the surgeon with a spatial relationship between the pathologic lesions and surgical landmarks. In addition, a simulation of the various surgical approaches to the middle ear and inner ear can be helpful for beginners and used for training purposes.

In this study, the volume of the mastoid air cell tract as well as the epitympanum was calculated after they were reconstructed as 3D images. The reason why we have not reported the measured values is that the field of view was too reduced, in order to obtain a better spatial resolution, to contain whole mastoid air cell tracts. For example, the mastoid tip air cells and sinodural air cells were excluded from the CT data in some cases of well-pneumatized temporal bone. However, all the pneumatization in the cases of chronic otitis media and/or mastoiditis was included in the field of view. In these 19 cases, the mean volume of the mastoid pneumatization was 0.63 ml. The number of applications of the 3D technique for measuring mastoid pneumatization is increasing, and its precision and repetition have been demonstrated.[5-12] The mean volume of mastoid pneumatization was reported to be 5.5-8.5 ml in the general adult population.[5-9] When measuring the volume of mastoid pneumatization using a 3D technique, the selection of the window thresholds is critical for making an accurate volume measurement. An upper threshold at a setting too high includes the soft tissues in the mastoid, which can result in an overestimation of the mastoid pneumatization volume. In contrast, an upper threshold at a setting too low excludes some of the air cells, which can result in an underestimation of the mastoid pneumatization volume.

In order to obtain a detailed 3D rendering of the structures in the temporal bone, Schubert *et al.*[13] emphasized two essential preconditions: a thin slice section and a high spatial resolution. To get thin slice sections, a CT scanner allowed a slice thickness of 1 mm. Spiral HRCT was used to increase the spatial resolution and the field of view was reduced to 80 mm^2. A spiral CT scan works by continuous X-ray tube rotation with a constant table shift, and creates better conditions for data acquisition than a conventional CT scan. Therefore, improving the quality of the HRCT scan data can reduce the many problems associated with 3D reconstruction processing.

In the future, 3D reconstruction based on spiral HRCT images will be of great assistance in diagnosing facial bone fractures and anomalies of the ossicles, inner ear, etc. In addition, it appears that this technique has the potential to improve the planning of otosurgery, such as providing a pre-operative simulation and a post-operative confirmation in cochlear implantation.[14–16] This technique will contribute to investigating and classifying the middle and inner ear anomalies; acting as the education media for the normal anatomy of the temporal bone to students; providing a pre-operative delineation of the patient's individual anatomy to the surgeon; and simulating the otosurgical procedure (Table I). However, more advanced computer technology is needed to acquire more detailed CT images of thinner slices and a higher spatial resolution regardless of the wider field of view. Therefore, validation studies will be needed to determine the correlation between the 3D reconstructed images and histologic sections of the temporal bone.

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