Nerves of Steel: a Low-Cost Method for 3D Printing the Cranial Nerves

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Abstract Steady-state free precession (SSFP) magnetic resonance imaging (MRI) can demonstrate details down to the cranial nerve (CN) level. High-resolution three-dimensional (3D) visualization can now quickly be performed at the workstation. However, we are still limited by visualization on flat screens. The emerging technologies in rapid prototyping or 3D printing overcome this limitation. It comprises a variety of automated manufacturing techniques, which use virtual 3D data sets to fabricate solid forms in a layer-by-layer technique. The complex neuroanatomy of the CNs may be better understood and depicted by the use of highly customizable advanced 3D printed models. In this technical note, after manually perfecting the segmentation of each CN and brain stem on each SSFP-MRI image, initial 3D reconstruction was performed. The bony skull base was also reconstructed from computed tomography (CT) data. Autodesk 3D Studio Max, available through freeware student/educator license, was used to three-dimensionally trace the 3D reconstructed CNs in order to create smooth graphically designed CNs and to assure proper fitting of the CNs into their respective neural foramina and fissures. This model was then 3D printed with polyamide through a commercial online service. Two different methods are discussed for the key segmentation and 3D reconstruction steps, by either using professional commercial software, i.e.,

Materialise Mimics, or utilizing a combination of the widely available software Adobe Photoshop, as well as a freeware software, OsiriX Lite.

Keywords 3D printing · Rapid prototyping · Anatomy · Radiology · Education · 3D model · Cranial nerve · Skull base · Cerebellopontine angle · Simulation · Surgical planning

Abbreviations

3D	Three-dimensional
CT	Computed tomography
CN	Cranial nerve
DICOM	Digital Imaging and Communications in Medicine
FSPGR	Fast spoiled gradient echo
HU	Hounsfield units
MRI	Magnetic resonance imaging
PACS	Picture archiving and communication system
SSFP	Steady-state free precession
STL	Standard tessellation language

Background

Applications of three-dimensional (3D) printing in medicine have grown exponentially in recent years especially in pre-surgical planning and development of prosthetics as well as in the education and research arenas [1–3]. Generally, cross-sectional imaging serves as the basis for developing 3D reconstructions, which are subsequently used for 3D printing. It is important to use source images with thin slices in order to produce accurate smooth borders in 3D reconstruction. This is best achieved with high-resolution computed tomography (CT) (0.6-mm thickness) or steady-state free precession

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(SSFP) and fast spoiled gradient echo (FSPGR) magnetic resonance imaging (MRI) (0.5–1-mm thickness). SSFP sequences are gradient-echo sequences with short echo and repetition times that have high signal-to-noise ratio, effective at displaying small structures [3].

The process of 3D printing simply refers to constructing an object in a layer-by-layer fashion in the *z* direction. Different materials may be used for 3D printing; categories of materials include various plastics, metals, ceramics, and gypsum [4]. Accordingly, there are different techniques implemented, including fused deposition modeling, selective laser sintering, stereolithography, colorjet printing, polyjet printing, lost wax printing and casting, ceramicjet printing, indirect metal printing, and direct metal printing [4].

From an educational perspective, 3D anatomic models are another way of representing cross-sectional imaging of the human body, one that allows true three-dimensional and multisensory inspection of the human anatomy, without the use of a cadaver. Furthermore, anatomy can be reproduced in a larger size to improve understanding of fine detail. Also, anatomy, and for that matter pathology, can be customized in such a way that different components are printed simultaneously with different materials or printed separately (e.g., vessels, nerves), allowing physical manipulation or disassembly for the purpose of inspection and learning [5]. While recent randomized controlled trials have shown the effectiveness of 3D models for educational purposes [6–8], more work still remains.

There is relative paucity of previous work on the use of 3D printing for teaching the intricate anatomy of the skull base, especially in the context of the cranial nerve (CN) neuroanatomy. Standard commercial models mostly available at the medical student level are limited by only including the CNs as they originate from the brain stem and are aimed for a general audience. However, knowledge of the remainder of their course as they cross their respective neuroforamina is of great value for training of radiology residents, neuroradiology fellows, and neurosurgeons. An absolute understanding of their expected course is crucial as these small structures are generally difficult to visualize or are not visualized on standard imaging techniques. Therefore, detecting pathologic conditions affecting them, such as perineural spread of tumor, require one's complete familiarity with the subject.

Many technical notes in the literature purely describe 3D printing from a Digital Imaging and Communications in Medicine (DICOM) file. Here, we describe an additional step beyond editing the DICOM file, i.e., enhancing the reconstructed 3D model through graphic design software. This hybrid technique is ideal for educational models, partly because of the complex and small-scale nature of the anatomy of interest, hence the added need for the “enhancement” step. In addition, the main method described here that allows for anatomically targeted segmentation and eventual 3D

reconstruction is based on software that can be obtained at no cost in an academic institution.

Methods

The developed 3D model consists of three main components: the CNs themselves, the brain stem (serving as the trunk of the CNs), and the osseous skull base. Fitting these three components together is an important consideration during the initial design so that these can physically be put together and are easily separable. In other words, not only does each of the fitting parts of the components have to be assessed but also the components as a whole need to be evaluated to ascertain that assembly and disassembly is possible in at least one direction. Ideally, these components should be from the same patient; however, if from different patients, the components can be adjusted in the graphic design software once digital 3D reconstruction is performed.

Hardware and Software

A MacBook Pro Retina Display device (designed by Apple in California, assembled in China) Intel Quad Core 2.4 GHz with 16 GB RAM was utilized with VMWare Fusion Windows installed. The utilized software necessary is listed in Table 1 with their respective purpose. Autodesk 3D Studio Max is Windows-based and can be obtained through a student/educator license free of charge for educational purposes. Adobe Photoshop, also a Windows-based application, is widely available through institutional or personal licenses. OsiriX Lite is a Mac-based picture archiving and communication system (PACS) and freely available. The entire process of creating the standard tessellation language (STL) files can therefore essentially be performed at no cost if Materialise Mimics is not implemented, granted it would be more time-consuming and tedious. Materialise Mimics is a Windows-based commercially available software with an available free 30-day trial version.

Breakdown of Steps Involved

A set of high-resolution SSFP-MRI images of the brain was exported from PACS as a stack of JPEG files with appropriate window/level settings where cranial nerves are well visualized in the background of cerebrospinal fluid. There is no set value for window/level as there is for CT since the values vary significantly between exams even on the same scanner and PACS. The stack of JPEG images was used to create the foundation for three-dimensionally reconstructing an initial rough model of the CNs I–XII as they exit the brain stem. This was achieved by manually segmenting the CNs slice-by-slice using Adobe Photoshop, implementing the “Magic Wand”

Table 1 Specific application of software tools for each of the steps involved in the process of developing the 3D-printed cranial nerves

Software	Purpose
PACS	Export each slice of DICOM series as a JPEG image
Adobe Photoshop	Segmentation of the cranial nerves and brain stem
OsiriX Lite	Conversion of stack JPEG images to a DICOM series to perform volumetric surface rendering and export resultant 3D mesh as STL
Autodesk 3D Studio Max	Modify and create 3D meshes as well as performing quality control for 3D printability of models using the “STL check” function
Materialise Mimics	Alternative commercial software combining all the above steps

tool in high-magnification views, which is a time-consuming process.

The magic wand feature serves the purpose of a semi-automatic segmentation tool based on the color of the pixels, which in our case of a grayscale image is the CT density, i.e., Hounsfield units (HU). There are a few important settings to consider while working with this tool. One is the “Tolerance” setting, which defines the tool’s sensitivity/threshold, i.e., the higher the value the wider the selected areas. The value of 50 is appropriate for our purpose since a high degree of contrast exists between the cranial nerves and the surrounding cerebrospinal fluid. This, however, can be adjusted accordingly. The “Contiguous” setting forces selecting the same colors only in adjacent areas on each selection, which must be kept turned on in order to allow the selection of only the cross section of the cranial nerve of interest on each selection. The “Anti-Alias” setting is chosen by default to smoothen the selection edges. In order to add multiple segmentation areas to one another, which are necessary in this project, either the “Add to selection” option has to be chosen or the Shift key is held down while clicking on the area of interest to make subsequent selections. Similarly, subtraction of segmentation may be performed using the Alt key.

For the CNs, the original grayscale images were used to manually segment the CNs. For the brain stem, grayscale images were converted to black and white first in Photoshop, for ease of segmentation, since the brain stem and cerebellum were only being used as the support structure where the CNs originate from and the surface details were not important in the context of this project. Of note, the 3D-reconstructed CNs only served as a rough road map and exact details were not of high importance, as they were discarded and replaced by the graphically designed smooth tubular structures representing the CNs.

The stacks of segmented JPEG images of the CNs and the brain stem were then separately imported into OsiriX Lite using the JPEG to DICOM converter database plug-in. In order to perform surface rendering, 3D volume reconstruction is needed, which in turn requires volumetric data, i.e., slice thickness and spatial resolution in the axial dimension. For this purpose, the entire stack of imported JPEGs has to be

exported as a DICOM dataset first. Subsequently, under the “3D Viewer” tab, “Surface Rendering” is chosen, resulting in a “Data Error” message box, requiring the appropriate volumetric information. In the case of SSFP-MRI, the axial spatial resolution is $0.3125 \text{ mm} \times 0.3125 \text{ mm}$ and the slice thickness depends on the acquisition, which in our case was 1 mm. The resulting 3D surface rendering was then exported as a STL file from the “Export 3D-SR” button. Separately, the native DICOM dataset of a high-resolution CT of the base of the skull was used in OsiriX Lite for 3D reconstruction.

As an alternative to the above steps, the commercial software Materialise Mimics with an annually renewed commercial license may be utilized for performing the manual segmentation of the CNs on each slice as well as separate automatic segmentation of the bony skull base. Subsequently, 3D surface volume reconstruction is performed in the same software, allowing for export of each mesh as an STL file. The detailed step-by-step instructions for using this software are beyond the scope of this technical note and are available through online tutorials, but essentially involve appropriate “thresholding” for segmenting an initial “mask,” editing it either slice-by-slice or in the 3D viewer, and eventually 3D reconstructing a mesh to develop an STL file. Additionally, a new feature of the software, i.e., the “Nerve Tracing” tool, allows for creation of a spline, a curved path defined by sequential points in 3D space, chosen by the user along the course of the nerve on each slice (a sequence of multiple “scroll-click” events), which can eventually be given a thickness thus representing an individual nerve.

Autodesk 3D Studio Max was subsequently used to enhance and modify the initial 3D model’s design by importing each STL file into the same design environment. Given a significant staircase appearance involving the native 3D reconstructed CNs, they were replaced by manually created virtual 3D tubular structures that follow the path of the reconstructed CNs, as if tracing a road map in 3D space. The CNs were then digitally attached to the brain stem. The CNs should also conform and fit into the 3D reconstructed bony skull base, which contains spaces that allow passage of the CNs into their respective foramina and fissures. The skull base is then halved using a sagittal mid-line plane to allow for better visualization.

These steps require basic skills that may be acquired through online tutorials or using the help of freelance graphic artists or students of graphic design.

3D Printing

The 3D printing itself was performed through a commercially available online service (i.e., Materialise, Lueven, Belgium) using polyamide material after increasing the scale to 120% for better visualization and increasing the thickness of the delicate free-hanging CNs, which would increase their chance of surviving the 3D printing process and preventing damage while handling the model. The time required for developing the models with the freeware software was about 2–3 weeks for the digital design, with an additional 1–2 weeks for the 3D printing and shipping of the models. The cost of each model depends on the size and/or amount of material used (\$1.4/cm³ for polyamide) [4], with the cost of each model being approximately \$120. Models can be scaled based on the formula provided below such that a price target or size is met, as long as other considerations such as minimum wall thickness and design gaps are taken into consideration [9].

$$\text{Scale}_{\text{target}} = \sqrt[3]{\frac{\text{Price}_{\text{target}}}{\text{Price}_{\text{current}}}}$$

Results

A durable and accurate 3D printed model of the CNs was successfully designed and created using actual patient SSFP-MRI and CT images of the cerebellopontine angle/skull base. The two printed parts, including when fitted into one another, are demonstrated in Figs. 1, 2, 3, and 4. This model is mainly utilized as an educational and testing tool for understanding the spatially complex anatomy of the CNs and the skull base providing an opportunity for hand-held spatial reasoning for medical students as well as radiology and neurosurgical trainees. They may also be used in the settings of patient counseling and consenting. Ultimately, patient-specific models that contain pathology can be created for pre-surgical planning once the process is streamlined.

The models, made of polyamide material, have a white, very fine, granular powder-like surface, resulting in strong, subtly flexible material that can take small impacts and resist some pressure while being bent [4]. Certain important 3D anatomic characteristics and corollaries were incorporated in this model, beyond that of which is available in most commercial products. For example, one can visualize the course of the CN VI as it exits the pontomedullary junction, ascending in the prepontine cistern and through Dorello's canal, to become the most medial CN within the cavernous sinus. One can see

that CN IV is the only CN that exits the pons posteriorly. Also, CNs III, IV, V₁, and VI are noted to converge together to form the contents of the superior orbital fissure after coursing through the cavernous sinus. Even though CN V₂ also passes through the cavernous sinus, it exits the skull base through the foramen rotundum. In addition, CN VII is positioned anterosuperior relative to CN VIII within the internal auditory canal. These anatomic relations are of diagnostic importance to the neuroradiologist during imaging interpretation, for example in determining which exact cranial nerve a schwannoma arises from. From the standpoint of neurosurgical approach, a trainee can get a better sense of where the interior structures are located relative to the skull surface landmarks such as the mastoid process.

Discussion

Utilizing 3D printing in academic institutions and hospitals is on the rise. The use of online services have numerous advantages compared to owning 3D printers, which include no upfront cost, no need for technical expertise on actually using a 3D printer, and also having access to a multitude of different 3D printing techniques and materials [5]. Once the number of cases increases in a higher volume setting, however, owning an in-house 3D printing program may eventually be more cost effective [10]. The material used for this model is polyamide, which is sturdy and versatile. Selective laser sintering technique is used, which allows for the greatest freedom of design amongst all 3D printing techniques [4]. It is ideal for beginner designers who want a well-priced model and a maximum freedom of creation and who do not want to be troubled significantly with the limitations of the printing process. The walls of a model need to be at least 1-mm thick and on-surface details or imprints can have a 0.3-mm level of detail [4]. It is well suited for anatomic models since it can show very small details and is strong enough for long free-hanging components.

One limitation of this material is that it only comes in one color, limiting color-coding and labeling ability. However, it can be spray painted or colored with wax pastel. Another limitation is that while this material is durable, it is still breakable. Specifically, some structures are more amenable to damage than others, such as CNs IV and VI, which are long and thin structures. Also, the cost of this material, while reasonable, is higher than that with models made with a desktop 3D printer. This material can be used for developing other anatomic models that contain branch or segmental anatomy [5] and is also ideal for 3D printing osseous anatomy. Multicolor 3D printing with low-cost gypsum-based Z-Corp technology is possible; however, this material is relatively fragile and design of long overhanging structures is not possible. Alternatively, high-end polyjet multimaterial 3D printers can

Fig. 1 Sequence of steps in reconstructing a 3D mesh from segmented axial JPEG images using OsiriX Lite is demonstrated, which in this case is the brain stem

be used, which are widely used for reconstructing models from cross-sectional imaging in the clinical setting. However, again, the ability to design long, thin structures such as the nerves incorporated in the current model is limited, as these parts require support struts while being printed, which are removed after. A new faster and lower cost multihead

technology has been recently introduced into the market by Hewlett Packard, which at the time of submission of this article has not been explored in the medical literature for clinical applications.

As mentioned earlier, the process of modifying the 3D meshes in Autodesk 3D Studio Max does require graphic

Fig. 2 Demonstration of 3D reconstruction of the cranial nerves. **a** Photoshop “Magic Wand” tool used to segment the visualized cranial nerves on each slice. **b** Final reconstructed 3D mesh imported into 3D Studio Max along with the separately reconstructed brain stem. **c** Fitting

of the cranial nerves that are 3D tracings of the reconstructed cranial nerves, into their respective foramina in the separately reconstructed skull base. **c** View of the anterior aspect of the final cranial nerves and brain stem 3D mesh

Fig. 3 Cranial nerve and brainstem. **a** Lateral, **b** inferior, and **c** medial rendered views of the final 3D mesh of the cranial nerves and brainstem. **d** Lateral, **e** inferior, and **f** medial views of the final 3D printed model of the cranial nerves and brain stem

design skills. This could be a limiting step for developing custom, advanced, and complicated 3D printed models. However, apart from self-teaching, fee-for-service graphic artists or students at academic centers are available for assistance

in this step of the process. Other graphic design software programs that are simpler may also be used depending on the level of complexity needed and time one is willing to allocate for learning the skills necessary. Some of the popular 3D

Fig. 4 Demonstration of how the two separate 3D printed models of cranial nerves and the skull base fit into one another. **a** Overall view of the three initial 3D meshes before being cut in half. **b** Medial rendered view of the cranial nerves fitting into the skull base. **c, d** Posterosuperior view of the rendered view of the cranial nerves fitting into their respective foramina in the skull base. **e** Lateral view of the 3D printed skull base half.

f View of the middle cranial fossa of the 3D printed skull base model demonstrating the *superior orbital fissure*, *foramen rotundum*, and *foramen ovale*, where cranial nerves III–VI fit into. **g, h** Posterosuperior view of the 3D printed model of the cranial nerves fitting into their respective foramina and fissures in the skull base

design softwares especially for 3D printing applications include Autodesk products (123D Design, Meshmixer, Tinkercad, and Maya), Blender, SketchUp, SolidWorks, ZBrush, and Rhinoceros [4]. The previously mentioned Materialise Mimics software also has a design modification plug-in as part of the basic package, named “3Matic.” Recently, a separate plug-in, dubbed “Mimics InPrint,” has been made available specifically tailored for 3D printing solutions in the clinical setting with direct DICOM compatibility and semi-automatic segmentation.

Probably the biggest challenge in graphically designing 3D models is meeting all requirements for an STL file, which essentially means that it can truly exist in the real physical world accounting for all vertices, edges, and faces. There is a long list of requirements pertaining to this subject, which is beyond the scope of this technical note. The “non-manifold” and “mixed normals” errors are two of the most common of these. Manifoldness means that models cannot be “open,” i.e., containing “holes” that are not part of the intended design, meaning that there cannot be missing faces on the surface. Models cannot contain unwanted faces or edges (coincident edges and overlapping faces). Surface normals (3D vectors perpendicular to each individual face) should be appropriately directed outwards. These are often impossible to spot by simply visually inspecting the outside of the model and special software features are needed, which in the case of 3D Studio Max is addressed in the “STL check” modifier.

Specific to this project or similar cases where 3D reconstruction of patient cross-sectional images is performed, there is an extremely high polygon count of the 3D meshes, due to the inherent detailed nature of the raw data. This necessitates a significant amount of CPU power and RAM for the workspace where 3D design software must be executed. Freeware software programs such as Meshmixer or Meshlab have features, such as “triangle reduction,” that decrease the surface detail in a model to decrease the need for high processing power, at the cost of potentially more crude-appearing surfaces of models. At the other end of the spectrum, “smoothing” of surfaces can be performed to increase surface triangles at the cost of creating larger STL files.

An important topic in the discussion of preparing digital files for 3D printing is the process of segmentation and the algorithms used. One practical aspect of this technical note is that the most widely available image manipulation software, i.e., Adobe Photoshop, is used for this crucial step. As mentioned in “Methods,” the Tolerance option is implemented for this purpose. This tool essentially forces the software to include all the adjacent pixels within a certain tone and color range along with the user-selected pixel. This range is set by the Tolerance value entered by the user and the tone and color in a grayscale image is essentially the CT density, i.e., the HU values. For example, the value of 50 means that Photoshop will automatically select any pixel that is the same CT density

as the user-selected pixel, in addition to any pixels that are up to 50 HU higher or 50 HU lower. Manual addition of adjacent pixels (region growing) or non-adjacent pixels can also be performed as detailed in “Methods.”

There is little published on custom 3D printing of CN models. The physical models that are commercially available tend to be for the entire brain and only contain the root entry zone, therefore not tailored for the course of the CNs fitting into the skull base and lack customizability such as that of the model presented here. Aside from the obvious potential application in surgical planning, this model could be developed for the purpose of surgical simulation, for example using skull base models made of gypsum, which allows for drilling and tactile feedback such as that of bone tissue, to practice surgical procedures such as neurovascular decompression microsurgery for trigeminal neuralgia, or resection of vestibular schwannoma and cerebellopontine angle masses [11, 12]. Lastly, one could create the CN nuclei in the brain stem with the intraparenchymal segment of the CNs to demonstrate concepts such as looping of the CN VII around the CN VI nucleus while forming the facial colliculus in the floor of the fourth ventricle utilizing polyjet technology that allows for simultaneous printing of transparent and opaque materials.

In addition to teaching the neuroanatomy of the cranial nerves, i.e., their course and their respective foramina and fissures in the skull base, educators may use the current model to detail relevant information regarding numerous pathologic conditions. Some of these, for example pertaining to CN I, include the development of anosmia in the setting of trauma due to shear injury to the olfactory nerves along the cribriform plate in the anterior cranial fossa or demonstration of the location of esthesioneuroblastomas. Sellar and suprasellar masses, such as pituitary macroadenomas, may cause mass effect on the central portion of the optic chiasm leading to bitemporal hemianopia or can cause diplopia by invading the cavernous sinus, where CN III, IV, V₁, V₂, and VI reside. Ptosis or pupillary dilatation can result from uncal herniation or basilar tip and PCA aneurysms secondary to mass effect on CN III in the region of the interpeduncular cistern. Other demonstrable common conditions include vascular and non-vascular causes of trigeminal neuralgia as well as schwannomas in the internal auditory canals. Furthermore, lower cranial nerves may be affected by cerebellopontine angle masses, leptomeningeal metastases, perineural spread of tumor, or intracranial hypotension that leads to a drooping brain stem, leading to deviation of the tongue (CN XII) and uvula (CN IX), dysphagia (CN X), facial palsy (CN VII), or winged scapula (CN XI).

The replacement of the original CNs that have a staircase appearance with graphically designed tubular structures is difficult given their multidimensional nature in space being traced on a two-dimensional flat-screen view. Another challenge is the ideal scale of a model. The larger the model, the

more the material used, and the more expensive the final product. However, the compounding factor in the scale equation [9] mentioned earlier is the minimum thickness required for various materials, which puts quite a significant limitation on design, especially given the long, thin nature of the CNs. The minimum thickness ranges from 0.2 mm for titanium and 0.8 mm for polyamide to 3 mm for steel. Surface minimum detail is also a consideration, ranging from 0.1 mm for titanium and 0.3 mm for polyamide to 0.8 mm for steel [4].

For practical purposes, streamlining this process would be the next step if it were to be used in the clinical setting. To avoid the need for full manual segmentation, one technique to consider may be subtraction of accurately co-registered CT or MR angiography or susceptibility-weighted imaging MRI images from the FIESTA-MRI images. On the other hand, for educational purposes, the addition of the arterial system using the aforementioned imaging techniques would be of added value, especially for demonstrating a number of unique and clinically relevant topics. These include the concept of contact of the superior cerebellar artery to the root entry zone of CN V in the setting of trigeminal neuralgia, proximity of the basilar artery tip, which can become aneurysmal, to CNs III that can lead to diplopia, or knowledge of the fact that the vessels that enter the internal auditory canals are the anterior inferior cerebellar arteries. By combining CT and MRI modalities, different MRI sequences, or even different phases of contrast enhancement, multiple segmentation masks may be created, distinguishing CNs from tumor, bone, arteries, and veins. This hybrid technique has been implemented in 3D printing of congenital heart disease [13].

The complex neuroanatomy of the CNs may be better understood and depicted by the use of highly customizable advanced 3D printed models. These may be used for teaching, patient counseling, or surgical planning. Pathologic conditions can also be easily incorporated, both for educational and clinical purposes. Radiologists can take a leading role in developing custom 3D printed teaching anatomic models as well as imaging and simulation phantoms. There is a need for randomized controlled studies to prove their efficacy, such as ones that have shown that 3D printed and/or 3D virtual models are superior to 2D images for teaching anatomy and preparing for surgery [6–8]. Furthermore, sharing of data for crowd sourcing and collaborations is encouraged, such as one made available through the National Institute of Health [5] (<http://3dprint.nih.gov/>).

Compliance with Ethical Standards

Financial Disclosure We report no financial relationship with a commercial organization that may have a direct or indirect interest in the content.

Conflict of Interest The authors declare that they have no conflict of interest.

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