Review Article

Three-Dimensional Model Printing in Congenital Heart Disease

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Abstract

Introduction: **Three-dimensional (3D) printing refers to a set of methods used to create solid 3D objects, based on digital files. The use of 3D models can improve understanding and knowledge about congenital heart diseases. Their usefulness has been demonstrated in preoperative planning, simulation of interventional procedures, and in surgical decision-making. The objective of this study is to offer a review of the literature on the various rapid prototyping methods and their applicability in medical practice, especially in congenital heart diseases.**

Methods: **This is a literature review study. Data for discussion were collected by consulting the following electronic database: LILACS, MEDLINE, SCOPUS, and the Scientific Electronic Library Online.**

Results: **During the period evaluated by the study, a total of 480 articles were published addressing the topic of 3D printing (TDP) for heart disease, with 196 articles related to TDP for congenital heart disease. Of these, 22 were included in this study.**

Conclusion: **TDP is a technology that is still under construction. It has the potential to assist physicians and surgical teams in therapeutic decision-making, to promote learning for students in specialization and postgraduate studies, to contribute to surgical skills training, and to clarify information for family members.**

Keywords: **Cardiology; Thoracic Surgery; Congenital Heart Defects; Three-Dimensional Printing.**

Introduction

Three-dimensional (3D) printing or rapid prototyping refers to a set of methods used to create solid 3D objects (models or prototypes), based on digital files. There are different forms of 3D printing (TDP); one of the most popular is the one that uses the technique of additive processing, in which the object is created layer by layer, by successive depositions of a highly resistant plastic polymer. The images are acquired from the patient's exams, such as 3D echocardiography, computed tomography (CT), or magnetic resonance imaging (MRI). It is possible to create highly complex customized parts that would not be feasible using conventional manufacturing techniques. Although the use of 3D technology has been a recurring topic in the medical literature since 1988, 95% of studies on TDP were published since 2012.[1]

In recent decades, the use of this technology in the medical field has shown exponential growth due to the reduced production costs, the breaking of patents, the fact that health professionals have mastered the creative process, and investments in research. 3D modeling and printing is currently used in diverse scenarios, such as dentistry, tissue engineering, manufacturing of medical devices, formulating new drugs, and creating anatomical models for education, training, and surgical planning.[2]

For cardiovascular diseases, the use of 3D models can improve understanding and knowledge about congenital heart diseases. Studies have demonstrated their usefulness in preoperative planning, in the simulation of interventional procedures, and in individualized intraoperative surgical decision-making.[3,4]

The majority of 3D images for diagnosing congenital heart diseases currently used in clinical practice are derived from high-resolution methods, such as CT, MRI, and, to a lesser extent, 3D echocardiography.[5] For the pediatric population and for the mother-fetus dyad, imaging modalities that use radiation, contrast, and sedation, such as CT and MRI, constitute limiting factors. The development of ultrasound scanning images, in both 3D and 4D, has expanded the capacity to achieve a complete assessment of the fetal heart, generally between 24 and 28 weeks of gestation, making it possible to create excellent 3D models.[6,7]

The objective of this study is to offer a review of the literature on the various rapid prototyping methods and their applicability in medical practice, opening new horizons and perspectives in medicine.

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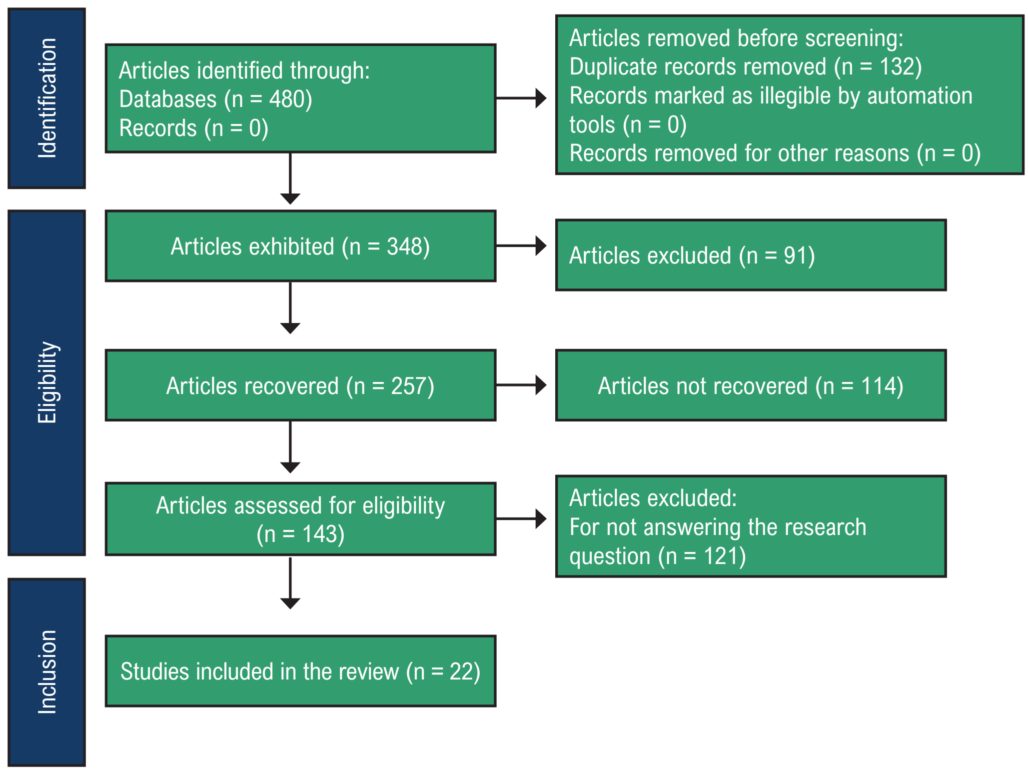
Central Illustration: **Three-Dimensional Model Printing in Congenital Heart Disease**



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Flowchart of the article selection process, adapted from PRISMA

Methods

This is a literature review study. The following inclusion criteria were determined for article selection: addressing 3D prototyping; congenital heart disease in the title and/or abstract; being an original work; available for full-text reading; and published in Portuguese, English, or Spanish. The following were excluded: editorials, letters to the reader, studies whose full texts were not available, and case reports. The search period was defined as 2014 to 2022, making it possible to highlight scientific evolution on this topic.

The following online databases were used in the literature search: Latin American and Caribbean Literature in Health Sciences (LILACS); Medical Literature Analysis and Retrieval System Online (MEDLINE), SCOPUS, and the Scientific Electronic Library Online (SciELO).

The search for indexed articles was based on the following Health Sciences Descriptors (DeCS): “children,” “heart surgery,” “congenital heart disease,” and “3D prototyping.” The following terms from the Medical Subject Headings (MeSH) were also adopted: “cardiac surgery,” “congenital heart diseases,” and “TDP.” The planning was guided based on the combination of the Boolean operators AND and OR, carrying out a joint and individual search so that there would be no possible divergences.

Two researchers independently selected the studies to be used, and there was no disagreement. Initially, duplicate studies were eliminated through the use of the Zotero data and reference formulator. Rayyan® software was then used to organize and consult the titles and abstracts of articles by peers, aiming to verify the inclusion/exclusion criteria. Subsequently, the 22 articles included in the study were read in full.

Analysis was subsequently conducted based on the level of evidence, in accordance with the methodological approach of the Agency for Healthcare Research and Quality (AHRQ) and the GRADE system. The selected studies were ordered in a Microsoft® Excel table, including the following data: database, author, year of publication, location and language, methodological design, and level and quality of evidence. The investigation was based on a meticulous reading of the selected studies, prioritizing qualitative analysis.

Results

During the period evaluated by the study, a total of 480 articles were published addressing the topic of TDP for heart disease, with 196 articles related to congenital heart disease. Of these, 22 were selected to be part of this review (Table 1).

Table 1 – Summary of the articles included in the study

Author	Type of study	Results	Conclusions
Oliveira et al.[1]	Systematic review	A total of 9,253 publications on TDP and 497 on 3D heart printing were included in the study.	Prints of 3D models are helping surgeons in surgical planning and promoting a greater understanding of the pathologies for patients and family members.
Liaw et al.[2]	Systematic review	The main applications of TDP are in dentistry, tissue engineering, anatomical models, medical devices, and drug formulations. Currently, more than 85 medical devices are 3D printed.	New TDP technologies are expanding their use in medical areas and reducing their production costs.
Lau et al.[3]	Systematic review	A total of 28 studies were included in the review: 61% case reports and 36% expert opinions	The use of TDP in models of congenital heart disease has applications in teaching, preoperative planning, and simulations.
Han et al.[4]	Clinical study	The use of 3D prototypes reduces surgical time, without impact on hospital stay or complications.	The use of 3D prototypes facilitates surgical planning and reduces operation time.
Chen et al.[5]	Descriptive study	Image acquisition with Voluson E10 (ultrasonography) and use of Mimics and Meshmixer software for segmentation and modeling of 3D prototypes.	First publication demonstrating the method of TDP of a fetal heart with images derived from echocardiography.
Byrne et al.[6]	Systematic review	A total of 136 studies were included in the review: 1 clinical study, 80 journal articles, and 55 case reports.	Image segmentation methods require a high degree of software knowledge and operator time.
Olivieri et al.[7]	Cohort study	Nine patients underwent 3D echocardiography to study their pathologies, and 3D prototypes were produced based on the images.	It is technically feasible to produce 3D prototypes, and they accurately reflect pathologies.
Alves et al.[8]	Cohort study	Based on patients' CT image, after segmentation and processing, a 3D model was produced using the SLA technique.	The use of rapid prototyping is an extremely valuable tool in supporting medical activities. Based on 2D medical images from CT and MRI, it is possible to obtain 3D models.
Gou et al.[9]	Descriptive study	Image acquisition by Voluson (ultrasonography) and use of Mimics software for segmentation and 3D prototype modeling. The 3D objects were then generated, smoothed, and exported as STL files and subsequently printed in resin.	3D prototypes of tetralogy of Fallot are technically feasible to produce and can be printed in multicolored resin.
Shui et al.[10]	Cohort study	Based on CT, MRI, and echocardiography images, it is possible to produce 3D prototypes.	The accuracy of 3D prototypes is mainly determined by the quality of the images obtained.
Bagaria et al.[11]	Multi-center cohort study	Fifty 3D prototypes were produced to assist surgical cases.	All surgeons reported that the prototypes were useful for planning, simulation, and reference in the surgical field.
Marro et al.[12]	Systematic review	The study details the stages of preparing 3D prototypes and the most used forms of printing.	3D prototypes are expanding their use in diverse medical areas to the extent that new technologies emerge.
Bagaria et al.[13]	Systematic review	The study details the evolution of prototyping and applications in the medical field.	The use of TDP, with technological advances, will allow the production of bioprototypes, tissues, and organs.
Rayan et al.[14]	Cohort study	The study compared surgical variables in 79 cases of congenital heart diseases with the production of prototypes in relation to cases without 3D models.	The use of 3D models reduced surgical time in the operating room by favoring better planning and anatomical references.

Rankin et al.[15]	Systematic review	A total of 261 studies were included in the review: 5% used DICOM, 38% CT, 20% MRI, 28% ultrasound, and 9% bioprint.	3D prototyping is widely used in the planning, simulation, and manufacture of prostheses. The simplification of software will favor greater application of this technology.
Fadero et al.[16]	Descriptive study	The study describes the stages of 3D image processing based on CT and its applications in medicine.	The processing of 3D images needs to be simplified in order to expand the use of this technology.
Bizzotto et al.[17]	Cohort study	In the study, 40 prototypes were produced, and their impact on surgical planning and providing information for patients was analyzed.	The use of 3D prototypes facilitates surgical planning and increases patients' understanding of the procedures performed.
Karsenty et al.[18]	Clinical trial	The study assessed the understanding of heart conditions by dividing them into two groups: one with 3D models and another without	The use of 3D models improved students' understanding and satisfaction with the learning process.
Preece et al.[19]	Clinical trial	The study assessed students' understanding of heart disease by dividing them into 3 groups: 3D models, text books, and computer models.	The group of students with 3D prototypes showed a better understanding of anatomy.
Biglino et al.[20]	Cross-sectional study	The use of 3D prototypes facilitated students' understanding: in relation to anatomy (86%), spatial orientation (70%), and anatomical complexity (66%).	3D prototypes are important tools for understanding congenital heart disease.
White et al.[21]	Cross-sectional study	The use of 3D prototypes facilitates the understanding of complex congenital heart diseases (tetralogy of Fallot), but there was no difference in pathologies such as atrial septal defect and ventricular septal defect.	3D prototypes facilitate students' understanding, but the biggest impact is on complex heart diseases.
Su W et al.[22]	Cross-sectional study	Students who had contact with 3D prototypes had a better understanding of congenital heart disease.	The use of 3D prototypes increases student interest and learning about heart diseases.

CT: computed tomography; DICOM: digital imaging and communications in medicine; MRI: magnetic resonance imaging; STL: standard triangle language; 3D: three-dimensional; SLA: stereolithography.

Steps of TDP

Rapid prototyping comprises 2 production stages: first, the virtual stage and second, the physical stage. The virtual stage can use solid modeling computer-aided design (CAD) software to obtain the virtual geometry of the biomodel. Alternatively, files obtained by 3D scanners, CT, or MRI can be converted to obtain the virtual geometry of the prototype.[8,9]

There are multiple steps in the printing process for the production of 3D prototypes, namely: image acquisition, segmentation, creation of a 3D mesh, post-processing of the 3D mesh, and printing of the 3D model (Figure 1). 3D prototypes are basically created by reading a numerical code (G Code) developed through CAD and computer-aided manufacturing (CAM) programs, which are capable of segmenting and modeling structures.

The initial step in printing 3D objects is image acquisition. This is considered the most important step, seeing that the quality of the printed models directly depends on the quality of the data acquired (image resolution).[10] This file is obtained by acquiring sectional images using digital equipment, such as MRI, CT, or even 3D/4D ultrasound.[11] The digital imaging and communications in medicine (DICOM) format is currently a standard in the medical equipment industry; as it is globally accepted, it is the format that provides the greatest interoperability between computer systems and medical equipment.

The second step is image segmentation, which consists of delimiting the area of interest for the study, thus making it possible to determine which region will be studied. To determine the region of interest, some aspects must be taken into consideration, such as anatomical area and types of tissues to be studied. The objective of segmentation is to isolate the area of interest, within the set of volumetric data that was collected, extracting a segmented data surface, which makes it possible to generate the surface mesh. There are several free open-source programs that contain a variety of manual

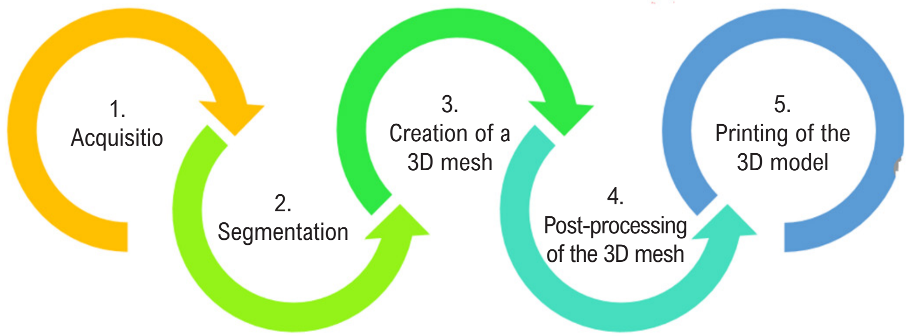

Figure 1 – *Required steps to create anatomical models based on imaging exams and TDP*

and automatic tools, thus making it possible to manipulate DICOM data in print-ready files.

Among the tools available for image segmentation, the threshold is widely used in CT and is based on the definition of density intervals that express, for example, only the voxels that correspond to the tissue studied. In segmentation based on 3D ultrasound, not all software can open volumetric blocks such as that performed by 3D Slicer (open-source software) and Mimics (paid software), which, at the end of the process, generate a virtual model in wavefront object format (WFO) and standard triangle language (STL), the latter geared toward TDP. In some cases, manual editing of images is necessary, with tools such as cropping, erasing, and selecting.

After segmentation, the creation of the mesh begins, which consists of reconstructing individual 2D segments in a 3D volume interface. The reconstruction process basically consists of obtaining a 3D model of the objects of interest, making it possible not only to visualize them, but also to better understand their structure through the extraction and analysis of the objects' geometric parameters.

The rapid prototyping machine cannot directly process the acquired images due to 2 main reasons: the image format provided and the thickness of the images which is in the range of 1 to 5 mm, whereas the image slices used in the rapid prototyping processes are around 0.25 mm. There are numerous methods for reconstructing and visualizing 3D objects based on their cross sections. The main methods can be classified into the following 2 categories, volume-based and surface-based methods.[12]

After acquiring the 3D object, post-processing of the 3D object mesh is carried out. This consists of making it visually pleasing and highlighting the characteristics necessary to understand the part. At this stage, 3 steps must be strictly followed to carry out the process in the best way possible: repairing, cleaning, and smoothening. When repairing, it is fundamental to locate the places where there are flaws in the image and thus correct them, making the surface of the object as regular as possible. One of the most used software programs for this step is currently Meshmixer, free software from Autodesk; however, there are others with additional tools such as Mimics. During cleaning, an algorithm is used to reduce noise without losing anatomical information. Smoothening regularizes and smooths the image surface to improve the quality and definition of the 3D image to be printed.[11]

In TDP, several technologies are used to manufacture 3D models, including the following: fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), TDP, laminated object manufacturing (LOM), among others of greater specificity, and inkjet. The most used in the medical field are FDM, SLA, and SLS.[13]

FDM constructs parts by depositing an extruded thermoplastic material. The injector head traces the perimeters of the transversal section and fills them, thus constructing each layer. On the other hand, SLS allows the construction of physical models using materials in powder form. The powder is processed in an inert, thermally controlled environment inside a chamber. It reaches the melting temperature (sintering) due to the action of a CO_2 laser. After a layer is sintered, a new one is deposited and so on, until the construction of the part is completed (Figures 2 and 3). The principle of the SLA technique is the photopolymerization of a liquid resin, where a laser beam traces a pattern on the surface of the liquid resin that solidifies and builds the part layer by layer. SLA has made TDP cheaper and popularized it, because it allows the production of various parts at once, with a high degree of precision.

The costs of producing prototypes or 3D models have reduced with the introduction of these new technologies and cheaper materials. FDM 3D printers cost approximately 1,000 Brazilian reais (BRL), while professional SLS printers cost around 25,000 BRL. The material for 3D printers costs 250 to 500 BRL per kg, while the SLS material costs 500 to 2,000 BRL per kg.

Discussion

In recent years, there has been progress in the application of rapid prototyping systems in diverse medical specialties. Therefore, it has become necessary to develop a literature review on the

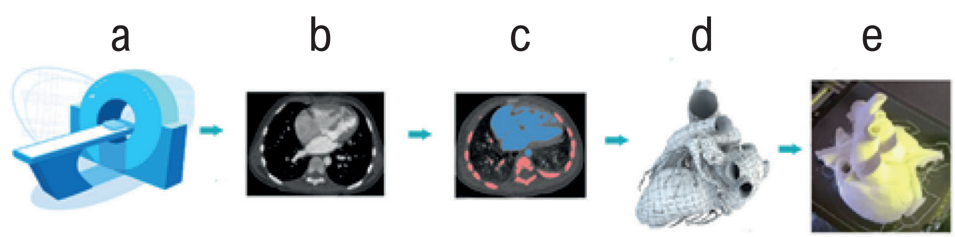

Figure 2 – *Stages of 3D model creation: a) use of image production equipment; b) image acquisition; c) image segmentation; d) reconstruction of a 3D model; e) printing of a computational model by the 3D printer (original figures).*

Figure 3 – *Construction of 3D models: a) cleaning and smoothening carried out using the software; b) estimated model for production by the printer; c) produced model (original figures).*

applicability of the technique in this area of health, considering the scarcity of studies in the literature that can, in a synthetic manner, assist in the production of 3D models.

Applications in medicine

Preoperative analysis can be considered one of the most useful applications of TDP technology. Surgical procedures in areas of complex anatomy with a high risk of injury to important structures benefit from rapid prototyping of 3D models.[15]

Various CAD programs currently allow virtual surgical planning (VSP) to be carried out with a better understanding of spatial geometry, anatomical relationships, and the possibility of programming less invasive surgical access.[16]

Some studies demonstrate that TDP technology in planning and carrying out surgical procedures leads to reduced surgical time, reduced intraoperative blood loss, reduced time of exposure to ionizing radiation during the surgical procedure, reduced complications, and probable improvement in surgical results.[13]

Another major benefit of applying this technology is also in the communication between the medical team and patients and family members. The use of anatomical models to provide information about the type of surgical treatment proposed promotes a better understanding of the patient's clinical condition, surgical programming, rehabilitation, and greater adherence to treatment, contributing to an improved doctor-patient relationship.[17]

Importance of 3D prototypes in congenital heart diseases

Congenital heart disease is the most common birth defect, occurring in approximately 9 out of every 1,000 live births. This corresponds annually to 1.35 million newborns with heart disease, 70% of whom will require treatment during the first year of life.[18] These patients require care and monitoring throughout their lives, from interdisciplinary management in primary care to specialized follow-up with clinical cardiology, interventional cardiology, and pediatric cardiac surgery.

Congenital heart defects are predominantly taught based on 2D representations of heart defects. Educational tools for teaching in this context include simple diagrams in books or texts and images from echocardiography, angiography, or even advanced imaging modalities such as CT or MRI. The ability to translate 2D images into 3D mental representations of injuries is a crucial point in learning. Tactile manipulation and the use of various senses are capable of promoting greater spatial appreciation and understanding of complex anatomies.[19]

Promising initiatives using 3D modeling and printing technology have been developed to better understand complex cardiac anatomies. Biglino et al.[20] cite the importance of this tool in the training of cardiology nursing professionals and reinforce the optimization of prototypes through stripes and colors that highlight important injuries and the use of complementary educational material. White et al.[21] describe that the incorporation of 3D printed models during didactic teaching sessions provided greater immediate understanding for pediatric and pediatric emergency residents. In a controlled study, Su et al.[22] used 3D prototypes of ventricular septal defects as an aid in teaching medical students. The post-test results showed better results in the domains of "knowledge acquisition" and "structural conceptualization" in the 3D group, reiterating the effectiveness of using this technology for medical education.

In a recent Brazilian systematic review, Oliveira et al.[1] compiled 9,253 publications on "TDP" and 497 publications on "heart TDP" and concluded that 3D printed models are helping fellows, residents, and surgeons in practice and surgical planning, even of rare cases; helping other health professionals to better understand diseases; and increasing parents' and family members' understanding of the child's pathology.

The limitations of this study include the heterogeneity of the selected studies, possible biases in individual studies, and the rapid evolution of rapid prototyping methods, leading to some methods being less used today.

The majority of 3D cardiac studies and models are obtained from CT angiography or MRI, which generally produce images with better resolution. However, thin mobile structures are better visualized by 3D echocardiography. TDP reproduces the differences between the imaging methods from which it was constructed; therefore, septal defects and valve diseases are better represented by 3D echocardiography, and the anatomy of large vessels and their relationships with the chambers are well represented by CT and MRI. In some cases, it is possible to use biomodels made by means of both methods.

Conclusion

Printing 3D prototypes is a technology that is under construction. It still presents limitations and challenges to ensure better product quality. Among them, we can highlight the precision of the assembly, the construction of models with the same mechanical properties as the tissues, the shorter preparation time, and the economic cost.

TDP models of congenital heart diseases are helping fellows, residents, and surgeons in surgical practice and planning, even in rare cases; helping other health professionals to better understand diseases; and increasing parents' and family members' understanding of the child's pathology.

Author Contributions

Conception and design of the research: Freitas MB; acquisition of data: Freitas MB, Lima RM; analysis and interpretation of the data: Freitas MB, Figueiredo JL, Cajueiro FC, Lima RM; statistical analysis: Cajueiro FC; writing of the manuscript: Freitas MB, Freitas MH; critical revision of the manuscript for intellectual content: Figueiredo JL, Freitas MH, Lima RM, Teixeira CM.

Potential Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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Study Association

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Ethics Approval and Consent to Participate

This article does not contain any studies with human participants or animals performed by any of the authors.

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