# Cardiovascular 3-D Printing: Value-Added Assessment Using Time-Driven Activity-Based Costing

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# Cardiovascular 3-D Printing: Value-Added Assessment Using Time-Driven Activity-Based Costing

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## DESCRIPTION OF PROBLEM

Growing evidence supports the use of cardiovascular 3-D-printed models in areas of preoperative planning, intervention simulation, intraoperative navigation, and physiology simulation [1,2]. Although applications for 3-D printing in health care continue to expand, barriers to routine clinical use exist. Of these barriers, cost is a substantial consideration that institutions face when deciding to embark upon an in-house printing program [1]. A cost-accounting method that incorporates material costs, time, and personnel labor is essential in determining relative value units. The relative value unit system is used by Medicare to establish billable services, as described by Current Procedural Terminology codes. Current Procedural Terminology and relative value unit determination are current strategies for valuation of physician work [3].

Time-driven activity-based costing (TDABC) accounts for the total costs of all resources consumed by a given process or service [4,5]. Standard top-down hospital accounting methods, which divide total health care system costs across individual services, reinforce an imprecise costing system that infers cost from reimbursement rates rather than direct measurement [5,6]. Bottom-up accounting methods, such as TDABC, in contrast, will sum the costs of resources to perform a particular service for one patient and will reflect the inherent complexity of the health care system. Therefore, a bottom-up approach may capture health care costs more accurately than traditional accounting methods [6,7].

We aimed to develop a process map for 3-D printing laboratory operations as an initial value assessment for cost-benefit models, which may be used by institutions to guide respective 3-D printing investment or service decisions.

## WHAT WE DID

This was an observational analysis of current cardiovascular 3-D printing workflow at a quaternary care institution (David Geffen School of Medicine at UCLA). Data collection was both initiated and completed in June 2019. We selected Children's Hospital of Philadelphia (CHOP) as a model institution because of its existing in-house 3-D printing program, which has an established dedicated bioengineering 3-D laboratory since 2012. The program's total annual 3-D print volume is 500 models, of which 60 to 120 models are cardiovascular (inclusive of both cardiac and vascular prints). All models printed for the cardiology department are used for presurgical planning and are viewed by an interdisciplinary medical and surgical cardiac team along with patient care coordinators. Over the course of 3 days, we interviewed and observed a team of four individuals whose roles included attending physicians (n = 2), fellows, and engineers to understand workflow, personnel, space, materials, and devices required for cardiovascular 3-D printing at CHOP. Based on the collected information and over the course of 40 hours, we generated the process maps.

Cost determination and analysis were performed based on TDABC using TDABC Designer, a software application created by the UCLA Department of Radiology to estimate cost for diagnostic and interventional medical procedures. The application integrates data from multiple sources (eg, radiology finance and human resources) and organizes them into four TDABC cost domains: personnel, space, materials, and devices. Costs from these four domains were divided by the practical capacity of each resource. To obtain a resource-specific cost per step, the resulting capacity cost rate was multiplied by the activity probability and duration of time the resource is engaged. The costs of each


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Table 1. Resources and materials required for functional capacities and activity processes

| Resource Required | Availability or Capacity (hours/week) |
|---|---|
| Space | |
| 1. Academic office—133 $ft^2$ | 40 |
| 2. MRI procedure room—429 $ft^2$ | 45 |
| 3. Equipped wet laboratory—361 $ft^2$ | 80 |
| Device | |
| 1. MRI scanner with annual service contract | 45 |
| 2. Thinkstation P500 computer workstation (Lenovo; Morrisville, NC) | 30 |
| 3. Mimics Innovation Suite (Materialise; Plymouth, MI) | 30 |
| 4. Objet Connex 500 3-D printer (Stratasys; Poway, CA) | 80 |
| 5. Powerblast water cleaner (Balco; Wichita, KS) | 20 |
| Personnel | |
| 1. Attending physician | 60 |
| 2. Cardiology fellow | 80 |
| 3. Senior administrative analyst | 35 |

*Description of space, device, and personnel with associated availabilities and capacities. Capacity is based on the number of hours the site or device is in operation each day. Personnel capacity is based on the number of hours an individual is spending on productive work related to cardiovascular 3-D printing.

procedure step were added together to obtain an overall procedure cost.

Space-related costs considered new construction costs, useful life, utilities, lease costs, and square footage. Space- and device-related capacities are based on daily hours of operation and reflect the time that a site or device is being used for productive work involving solely 3-D printing–related activities. Personnel costs are calculated from salary and benefits costs and additional role-specific costs. Device-specific (eg, CT scanner, MRI device) costs include acquisition cost, useful life, and service contract costs. Material costs are calculated based on the purchase price of one-time use materials and the quantity of these materials used in a procedure. Personnel salary and cost of square footage were based on local costs (specific to UCLA, a quaternary academic university medical center in a metropolitan area) because of sensitivity of financial information; whereas, unit pricing for materials and devices were estimated using market pricing.

To capture a representative range of costs, separate cost calculations were made for “low-resource” and “high-resource” utilization models. Low-resource utilization models were defined as vascular models without inclusion of intracardiac structures and are about the size of an infant heart. This type of model inherently requires less image segmentation and processing compared with a model with complex intracardiac anatomy (such as complex congenital heart defects) and less printing time compared with a model of an adolescent-sized heart. High-resource utilization models were defined as those with complex intracardiac anatomy, about the size of an adolescent heart. Material costs of infant and adolescent-sized hearts were based on reported averages of 460 g and 650 g of required combined print and support material, respectively. The e-only Figure S1 (Appendix) provides 3-D PDF illustrative examples of low- and high-resource models.

Table 2. Materials required for printing of 3-D models and postprinting washing and cleaning steps

| Activity Processes | Materials Description |
|---|---|
| Printing of 3-D model | SUP705 support material (Stratasys; Poway, CA)<br>Vero/Tango print material (Stratasys; Poway, CA)<br>Microfiber wipes<br>70% isopropyl alcohol<br>Waste cartridges<br>Nitrile examination gloves<br>Laboratory coat<br>Scraper blades ZICO ZI-4080 (ZicoTech, Israel) |
| Postprinting washing and cleaning | Waterjet gloves<br>Handle scalpel |

*Materials are defined as nonreusable consumable products.

## OUTCOMES AND LIMITATIONS

The e-only Table S1 (Appendix) summarizes the personnel, space, and devices that contribute to overall


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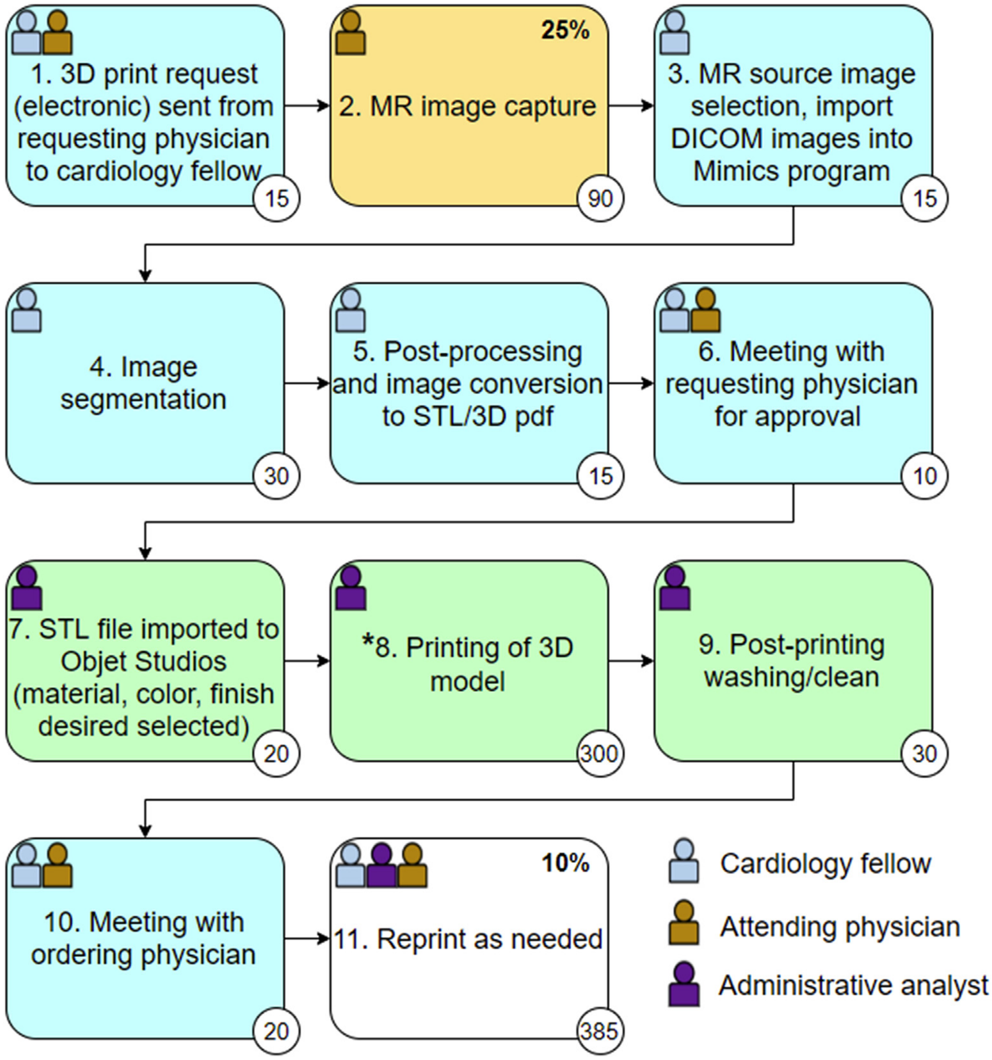


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Fig 1. Process map and time expenditure for printing of low-resource utilization model. Process mapping resulted in a total of 11 procedural steps. Personnel required for each step is denoted by icons in the upper right-hand corner of each individual step. Numerical value encircled on the bottom right of each individual box denotes time (minutes) required for the associated activity. Steps 2 and 11 are associated with 25% and 10% activity probability, respectively. These activities may be included or excluded depending on individual patient-specific clinical evaluation and management. *The total process time for all steps was equivalent to the total personnel time expenditure exclusive of step 8, in which personnel time expenditure was 20 min for both low- and high-resource models. Activity locations are color coded as academic office (blue), procedure room (yellow), equipped wet laboratory (green). DICOM = ; STL = standard triangle language.

costs of each step of the 3-D printing workflow. Table 1 summarizes the capacities and availability of required resources, and Table 2 summarizes consumable materials required for printing and washing and cleaning steps, respectively. Figure 1 provides an overview of the workflow activities and time expenditure involved in 3-D printing for a low-resource utilization cardiovascular model. All 11 steps in the workflow were associated with a 100% activity probability, except for MRI capture and reprint, which hold a 25% and 10% activity probability, respectively. Total process time from order initiation to print completion was 7.6 hours for low-resource and 19.3 hours for high-resource models, exclusive of mapping activities with <100% activity probability. In cases in which existing clinical MRI studies were insufficient for 3-D printing (approximately 25% of cases) or in which reprint of a model occurred because of unsatisfactory print quality (approximately 10% of cases), the cumulative time expenditure increased to 15.5 (low-resource model) and 27.3 (high-resource model) hours (Fig. 2).

The entire process required contributions from three personnel

| Activity | Additional time increase (minutes) | Personnel cost increase (USD) | Materials cost increase (USD) | Space cost increase (USD) | Devices cost increase (USD) |
|---|---|---|---|---|---|
| Image segmentation (Step 4) | 210 | $114.03 | $0.00 | $17.85 | $54.60 |
| Post-processing (Step 5) | 105 | $57.01 | $0.00 | $8.92 | $0.31 |
| Printing of 3D model (Step 8) | 360 | $0.00 | $44.60 | $41.40 | $42.84 |
| Post-printing and washing/clean (Step 9) | 30 | $37.71 | $0.00 | $3.45 | $0.30 |


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Fig 2. Flowchart of TDABC costing methodology and effect of low- and high-resource utilization classifications on time and cost expenditure. Of the 11 steps, four activities had substantial time variation in time expenditure and were dependent on low- or high-resource utilization. Additional time required for completion of high-resource cardiovascular 3-D models is displayed with corresponding cost increases. Additional time increase reflects increase in activity time (minutes) required for high-resource cardiovascular 3-D prints compared with low-resource cardiovascular 3-D prints. Study flowchart illustrates cardiovascular model cost determination based on process map creation and TDABC application. Icons were made using Smashicons (www.flaticon.com). TDABC = time-driven activity-based costing; USD = US dollars.

categories: attending physician (associate professor level), senior administrative analyst, and cardiology fellow. Three different operational spaces were used: standard cardiology faculty office space (includes desk, desktop computer) that is also used for other clinical activities, wet laboratory equipped with plumbing, and procedure room. Steps in the process map resulted in five major workflow classifications: interdisciplinary meetings, imaging studies, image segmentation and processing, printing, and post-printing modification. Steps 1, 6, and 10 involve meetings between the ordering attending physician and cardiology fellow to discuss anatomical representation, print material, potential challenges, and quality control. The primary objective is outlining desired outcomes of the print model. Steps 2 and 3 involve acquisition of imaging studies and manual selection of images by a radiologist or cardiologist for segmentation based on selection criteria inclusive of image quality and clear depiction of desired anatomical structures. Steps 4 and 5 are performed by a cardiology fellow and involved image segmentation and thresholding, mesh generation and refinement, segregation of regions of interest, and postprocessing along with conversion of DICOM images to standard triangle language 3-D PDF files. Steps 7 and 8 involve machine printing of the models. Lastly, step 9 comprised postprinting steps, which included washing, cleaning, and removal of support material.

Compared with low-resource utilization cardiovascular models, high-resource utilization models took 11.7 hours longer from print initiation to completion. Size and anatomic complexity affected the time required for four different steps (Fig. 2): image segmentation, postprocessing, printing of model, and postprinting. The largest difference in time expenditure was for machine printing; high-resource models of adolescent hearts took 6 hours longer than lower-resource models of infant hearts. Image segmentation and postprocessing activities also required more personnel time expenditure, at 3.5 and 1.75 additional hours, respectively.

Cost determination of low- and high-resource utilization models by expense category is reported in Table 3. Currently, the main option at institutions without an in-house program is outsourcing print needs to a third-party company such as Materialise (Plymouth, Michigan), which offers services inclusive of imaging segmentation and 3-D model printing. Single cardiovascular model quotes from these companies range from US$1,500 to $2,500. The total average cost for our low-resource models is $717.19 and for high-resource models is $1,157.85, but in-house costs and outsourced costs may not be directly comparable because of heterogeneity and variation in processes.


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Table 3. Cost determination of low-resource and high-resource utilization model by expense category

| Expense Category | Cost (US$) | Percent Total Cost (%) |
|---|---|---|
| Low-resource utilization model | | |
| Personnel | 364.93 | 50.88 |
| Space | 59.07 | 8.24 |
| Device | 94.49 | 13.18 |
| Material | 198.70 | 27.70 |
| Total cost | 717.19 | 100 |
| High-resource utilization model | | |
| Personnel | 80.16 | 50.11 |
| Space | 135.61 | 11.71 |
| Device | 194.32 | 6.78 |
| Material | 247.76 | 21.40 |
| Total | 1,157.85 | 100 |

Personnel costs represented the most significant cost expenditure, and occupation and use of productive space were the lowest contributors to total cost. However, the workflow and associated costs are only representative of one institution, with roles and responsibilities likely to vary at other institutions. For example, a 3-D laboratory technologist or engineer may not be available at most institutions. Segmentation of the initial MRI scan and postprocessing edits require specific skill sets and training to ensure accurate anatomical representation and high-quality final prints but may not require the highest level of medical expertise such as the knowledge and skills typical of a supervisory, MD-level personnel (attending physician). These variations subsequently affect the overall cost calculations. Because of this fluidity, the TDABC process maps may be helpful for determining how changes in personnel, space, materials, and devices affect the cumulative cost of a 3-D print and can serve as an adaptable tool that can be applied iteratively to establish institution-specific derivation of costs.

Our study has several limitations. First, to fully and accurately capture costing of cardiovascular 3-D printing, subprocesses within the workflow require their own process maps and individual cost calculations. For example, an MRI examination requires personnel time to schedule, order, and perform the examination, which was not factored into our cost calculation. Because other imaging modalities aside from MRI may be used for image segmentation, process mapping for each modality would be needed to improve cost accuracy. Second, the studied host institution is a pediatric hospital, whose cardiology department is world-renowned in congenital heart disease. We acknowledge generalizability limitations of our cost estimations to institutions primarily involved in pediatric care, because material costs for 3-D print materials, among other considerations, may differ. Third, space construction and maintenance costs, along with personnel salaries, were estimated based on data representative of UCLA and not of the evaluated host institution. However, we chose CHOP as a model for the workflow because of their established practices and experience in 3-D printing, both of which could factor into accurate cost modeling.

Despite the limitations, our process maps may serve as an initial framework for institutions to determine financial feasibility of an in-house 3-D printing program. Current funding sources for 3-D printing come from donors, grants, or departmental resources. Ongoing effort to develop reimbursement models could benefit from this work by translating our 3-D printing process maps into billable Current Procedural Terminology codes, which would represent a more reliable form of financial sustenance. Future work on cost-benefit modeling against commercially available outsourcing options is needed to justify the sustainability of in-house 3-D print laboratories and to increase accessibility of 3-D printing across institutions.

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## ADDITIONAL RESOURCES

Additional resources can be found online at: https://doi.org/10.1016/j.jacr.2020.05.007.

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