Three-step preoperative sequential planning for pulmonary valve replacement in repaired tetralogy of Fallot using computed tomography

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Abstract

OBJECTIVES: Our goal was to compare results between a standard computed tomography (CT)-based strategy, the ‘three-step preoperative sequential planning’ (3-step PSP), for pulmonary valve replacement in repaired tetralogy of Fallot versus a conventional planning approach.

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METHODS: We carried out a retrospective study with unmatched and matched groups. The 3-step PSP comprised the planning of mediastinal re-entry, cannulation for cardiopulmonary bypass (CPB) and the main procedure, using standard 3-dimensional videos. Operative times (skin incision to CPB, CPB time, end of CPB to skin closure and cross-clamp time) as well as postoperative length of stay and inhospital mortality were compared.

RESULTS: Eighty-two patients (49% classical tetralogy of Fallot) underwent an operation (85% with pulmonary homograft) with 1.22% inhospital mortality. The 3-step PSP ($n = 14$) and the conventional planning ($n = 68$) groups were compared. There were no statistically significant differences in the preoperative characteristics. Differences were observed in the total operative time ($P = 0.009$), skin incision to CPB ($P = 0.034$) and cross-clamp times ($74 ± 33 \text{ vs } 108 ± 47 \text{ min}; P = 0.006$), favouring the 3-step PSP group. Eight matched pairs were compared showing differences in the total operative time ($263 ± 44 \text{ vs } 360 ± 66 \text{ min}; P = 0.008$), CPB time ($123 ± 34 \text{ vs } 190 ± 43 \text{ min}; P = 0.008$) and postoperative length of stay ($P = 0.031$), favouring the 3-step PSP group.

CONCLUSIONS: In patients with repaired tetralogy of Fallot undergoing pulmonary valve replacement, preoperative planning using a standard CT-based strategy, the 3-step PSP, is associated with shorter operative times and shorter postoperative length of stay.

Keywords: Tetralogy of Fallot • Pulmonary valve replacement • Computed tomography • Surgical planning • Three-step preoperative sequential planning

ABBREVIATIONS

| Abbreviation | Description |
|--------------|-------------|
| CI           | Confidence interval |
| CPB          | Cardiopulmonary bypass |
| CT           | Computed tomography |
| PVR          | Pulmonary valve replacement |
| TOF          | Tetralogy of Fallot |
| 3D           | 3-Dimensional |
| PSP          | Preoperative sequential planning |

INTRODUCTION

Repeat sternotomy in heart surgery poses a major risk for undesired outcomes. This is particularly the case in congenital heart diseases in which the patients usually undergo multiple operations during their lifetime [1]. The surgical risk is considerable in developed countries and exceedingly high in some developing countries in which these patients have their surgical procedures denied, because the risk of the surgical treatment surpasses that of the do-not-treat approach.

With the advent of new multidetector computed tomography (CT) scanners, as well as modern techniques of post-processing imaging, CT-based strategies have gained ground in providing 3-dimensional (3D) images (printed models or not) and an easy interface for surgeons to use in preoperative planning [2–4]. A recent systematic review points to the need for conducting research through comparative studies in order to measure the additional value of the 3D models in relation to the usual surgical planning [5].

Considering that tetralogy of Fallot (TOF) represents the most studied congenital heart disease in history due to its high prevalence and the need for follow-up throughout the patient’s life, this complex condition was chosen in order to gather a homogeneous sample. It is well known that, in the natural history of the ‘repaired right hearts’, pulmonary insufficiency is common, leading to impaired functional capacity and increased risk of death [6–8].

Bearing in mind these facts, our goal was to perform a study whereby we used our straightforward imaging and CT-based post-processing method, ‘three-step preoperative sequential planning’ (3-step PSP), in which we compared the use of this method with the conventional approach of preoperative planning for pulmonary valve replacement (PVR), considering intraoperative data and surgical outcomes.

MATERIALS AND METHODS

Patients

We conducted a retrospective analysis of outcomes in consecutive patients with repaired TOF (the full clinical spectrum) who underwent PVR at the Hannover Medical School, Hannover, Germany, from August 2012 to July 2017. A comparison between 3-step PSP (July 2016–July 2017) and conventional planning (August 2012–July 2016) groups was made. Patients who had concomitant aortic or aortic valve procedures were excluded. All patients in both groups underwent preoperative CT.

Most surgical procedures were elective, and the indications for PVR were those from the 2015 guidelines of the German Society of Paediatric Cardiology and other international guidelines [9, 10].

This research was registered and followed the necessary procedures; the project was approved by the ethics committee under the registration number CAAE: 82276418.0.0000.5192. The ethical standards were fulfilled because the patients were also participants in an ongoing study at the Hannover Medical School. They had a decellularized homograft implanted and participated in a trial registered at ClinicalTrials.gov under the identifier number: NCT02035540, the ESPOIR (European Clinical Study for the Application of Regenerative Heart Valves). The surgical PVR at the Hannover Medical School is the conventional surgical technique described in a previous publication [11].

Three-step preoperative sequential planning using computed tomography

So that we could obtain post-processing CT images for analysis, the patients (3-step PSP group), underwent a contrast-enhanced thorax examination on a 64-slice CT scanner (SOMATOM Force, Siemens Healthcare, Forchheim, Germany), with no electrocardiographic synchronization, without sedation, with slices thickness of 0.5–1.0 mm thick and using non-ionic low-osmolar contrast material.

The techniques for post-processing imaging were performed using the OsiriX MD (OsiriX MD. v7.0 64-bit. Pixmeo SARL, 2003,
Geneva, Switzerland). The videos created from the three-step PSP strategy were analysed for qualitative validation by the paediatric and surgical teams.

To simulate a ‘step-by-step’ surgical procedure, a 3-step sequential planning strategy was performed, comprised of mediastinal re-entry (step 1), cannulation for cardiopulmonary bypass (CPB) (step 2) and the main procedure (step 3), briefly demonstrated in Fig. 1 and in the Video 1 (Supplementary Material).

Ultimately, a total of 2160 images composed of CT-based 3D reconstructions (6 videos, 360 images/video) were displayed at a rate of 20 images per s. The videos were produced through a 360° loop around the longitudinal axis of the surgical site at each

Figure 1: Volume-rendered sample images of the three-step preoperative sequential planning. Step 1: planning the mediastinal re-entry: panel (A) shows the surgeon’s view and panel (B), the substernal anatomy. Step 2: planning the arterial and venous cannulation for cardiopulmonary bypass: panel (C) shows the ascending aorta and panel (D), a 90° rotation in the longitudinal axis; panel (E) shows the right atrium and (F), a 90° rotation in the longitudinal axis. Step 3: planning the pulmonary valve replacement: panel (G) shows the surgeon’s view of the main pulmonary artery and the right ventricular outflow tract; panel (H) shows a 90° rotation in the longitudinal axis.

Video 1: Videos of the three-step preoperative sequential planning.
step in an attempt to enhance the depiction of 3D anatomical relationships that could help the surgical team mentally visualize the patient’s mediastinal anatomy.

Outcomes

The variables chosen to represent the difficulty of the procedure were total operative time, time from the skin incision to CPB (skin-to-CPB time), CPB time, time from the end of CPB to skin closure (CPB-to-skin time) and cross-clamp time. The variables chosen to represent the safety of the procedure were the number of unplanned operative events and redoing any surgical step. The in-hospital mortality and the operative morbidity expressed by the postoperative length of stay were also assessed.

Statistical analyses

Data were described using absolute and percentage frequencies for categorical variables and means, standard deviations, medians and ranges for numerical variables.

For the inferential analysis through statistical tests, the differences between the groups or categories were evaluated using Pearson’s $\chi^2$ test or Fisher’s exact test for categorical variables and the Mann–Whitney test for the numerical variables. The exact Fisher’s test was used when the condition for use of the $\chi^2$ test was not found. The Mann–Whitney test was chosen when there was a lack of normality in at least 1 of the groups or categories. Normality was verified using the Shapiro–Wilk normality test.

For a more reliable comparison between 3-step PSP and conventional planning groups, a paired analysis was performed by matching the patients for the following variables: non-beating-heart surgery, diagnosis of TOF (except for associations with atrioventricular septal defect, absent pulmonary valve syndrome, post-Rastelli or post-Ross status), same age range and homograft implantation. Pairing procedures in cases of more than 1 possible matching partner were established on a random basis, and the comparison was performed using the McNemar’s test in relation to the categorical variables or the Wilcoxon test paired for the numerical variables. The paired Wilcoxon test was chosen because of the reduced number of paired samples. The statistical analysis was performed to obtain the largest number of similar pairs in terms of preoperative characteristics, considering the limitations of the available sample size.

The data were plotted in double entry in Microsoft Excel for Mac software, version 16.11 (180311) and then analysed using IBM SPSS software (IBM SPSS Statistics for Windows, Version 23.0, released 2015. IBM Corp., Armonk, NY, USA). $P$-values were considered statistically significant if lower than 0.05.

### Table 1: Preoperative characteristics: univariate analysis of categorical data

| Variables                                | 3-Step PSP (n = 14), n (%) | Conventional planning (n = 68), n (%) | Total sample (n = 82), n (%) | $P$-value |
|------------------------------------------|----------------------------|--------------------------------------|-----------------------------|-----------|
| Gender                                   |                            |                                      |                             |           |
| Male                                     | 7 (50)                     | 40 (59)                              | 47 (57)                     | $P^a = 0.543$ |
| Female                                   | 7 (50)                     | 28 (41)                              | 35 (43)                     |           |
| Age range (years)                        |                            |                                      |                             |           |
| <6                                       |                            |                                      |                             | $P^b = 0.419$ |
| 6–12                                     | 4 (29)                     | 22 (32)                              | 26 (32)                     |           |
| 13–18                                    | 2 (14)                     | 16 (24)                              | 18 (22)                     |           |
| >19                                      | 8 (57)                     | 23 (34)                              | 31 (38)                     |           |
| Weight range (kg)                        |                            |                                      |                             | $P^b = 1.000$ |
| <10                                      |                            |                                      |                             |           |
| 10–20                                    | 1 (7)                      | 8 (12)                               | 9 (11)                      |           |
| 21–80                                    | 12 (86)                    | 51 (75)                              | 63 (77)                     |           |
| >81                                      | 1 (7)                      | 7 (10)                               | 8 (10)                      |           |
| Diagnosis                                |                            |                                      |                             | $P^b = 0.068$ |
| TOF/PS                                   | 6 (43)                     | 34 (50)                              | 40 (49)                     |           |
| TOF/PA                                   |                            |                                      |                             |           |
| TOF/DORV                                 |                            |                                      |                             |           |
| TOF/AVSD or TOF/APV or post-Rastelli or post-Ross | 2 (14) | 16 (24) | 18 (22) |           |
| VSD/PS or PS/PI                          | 6 (43)                     | 7 (10)                               | 13 (16)                     |           |
| Previous operations                      |                            |                                      |                             | $P^b = 0.102$ |
| 1                                        | 12 (86)                    | 38 (56)                              | 50 (61)                     |           |
| 2                                        | 2 (14)                     | 18 (26)                              | 20 (24)                     |           |
| 3 or more                                | 12 (18)                    |                                      | 12 (15)                     |           |
| Previous interventional catheter procedures |                            |                                      |                             | $P^b = 0.301$ |
| 0–1                                      | 13 (93)                    | 48 (70)                              | 61 (75)                     |           |
| 2                                        | 10 (15)                    |                                      | 10 (12)                     |           |
| 3 or more                                | 1 (7)                      | 10 (15)                              | 11 (13)                     |           |

$^a$Pearson’s $\chi^2$ test.

$^b$Fisher’s exact test.

$^*$Statistically significant ($P < 0.05$).

PS/PI: pulmonary stenosis and insufficiency; TOF/APV: tetralogy of Fallot with absent pulmonary valve; TOF/AVSD: tetralogy of Fallot associated with atroventricular septal defect; TOF/DORV: double outlet right ventricle Fallot type; TOF/PA: tetralogy of Fallot with pulmonary atresia; TOF/PS: tetralogy of Fallot with pulmonary stenosis; VSD/PS: ventricular septal defect with pulmonary stenosis.
RESULTS

Between August 2012 and July 2017, a total of 82 patients underwent PVR. Almost half of the patients (49%) had the classical form of TOF. Thirty-nine patients (47%) were operated on with the beating-heart technique. From April 2015 to July 2017, the beating-heart technique was less prevalent: we had only 4 patients. Preoperative characteristics are described in Tables 1 and 2.

Eighty-five percent of the patients had a pulmonary homograft implanted, and 72% of all valves implanted were tissue-engineered.  

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**Table 2:** Preoperative characteristics: univariate analysis of numerical data

| Variables                      | 3-Step PSP (n = 14), mean ± SD (median) | Conventional planning (n = 68), mean ± SD (median) | Total sample (n = 82), mean ± SD (median) | P-value  |
|--------------------------------|----------------------------------------|---------------------------------------------------|-------------------------------------------|----------|
| Age (years)                   |                                        |                                                   |                                           |          |
| <18                            | 12.8 ± 4.5 (11.8)                      | 10.5 ± 5.3 (10)                                   | 10.7 ± 5.2 (10.2)                        | P* = 0.258 |
| >18                            | 32.6 ± 7.1 (32.3)                      | 34.9 ± 15.8 (29.9)                                | 34.3 ± 14 (29.9)                        | P* = 0.700 |
| Valve size (mm)                | 26 ± 3 (25)                            | 24 ± 4 (24)                                       | 24 ± 4 (24)                              | P* = 0.216 |
| BSA (m²)                       | 1.7 ± 0.4 (1.7)                        | 1.4 ± 0.5 (1.5)                                   | 1.4 ± 0.5 (1.5)                         | P* = 0.060 |

*Mann–Whitney U-test.
*Statistically significant (P < 0.05).
BSA: body surface area; SD: standard deviation.

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**Table 3:** Intraoperative characteristics: univariate analysis of categorical data

| Variables                      | 3-Step PSP (n = 14), n (%) | Conventional planning (n = 68), n (%) | Total sample (n = 82), n (%) | P-value  |
|--------------------------------|---------------------------|--------------------------------------|-------------------------------|----------|
| Bypass temperature (°C)        |                           |                                      |                               |          |
| >35                            | 4 (29)                    | 5 (7)                                | 9 (11)                        | P* = 0.059 |
| 32–35                          | 2 (14)                    | 16 (24)                              | 18 (22)                       |          |
| 28–32                          | 6 (43)                    | 21 (31)                              | 27 (33)                       |          |
| <28                            | 2 (14)                    | 26 (38)                              | 28 (34)                       |          |
| Valve type                     |                           |                                      |                               |          |
| TE homograft                   | 12 (86)                   | 47 (69)                              | 59 (72)                       |          |
| Homograft                      | 2 (14)                    | 9 (13)                               | 11 (13)                       |          |
| Contegra³                      | 4 (6)                     | 4 (5)                                |                               |          |
| Hancock³                       | 6 (9)                     | 6 (7)                                |                               |          |
| RVOT conduit                   | 1 (1.5)                   | 1 (1)                                |                               |          |
| Vascutek RVOT                  | 1 (1.5)                   | 1 (1)                                |                               |          |
| Maze procedure                 |                           |                                      |                               | P* = 1.000 |
| Yes                            | 4 (6)                     | 4 (5)                                |                               |          |
| No                             | 14 (100)                  | 64 (94)                              | 78 (95)                       |          |
| PA or PA branches              |                           |                                      |                               | P* = 0.724 |
| arterioplasty                  |                           |                                      |                               |          |
| Yes                            | 2 (14)                    | 16 (24)                              | 18 (22)                       |          |
| No                             | 12 (86)                   | 52 (76)                              | 64 (78)                       |          |
| Tricuspid valve plasty         |                           |                                      |                               | P* = 0.680 |
| Yes                            | 1 (7)                     | 10 (15)                              | 11 (13)                       |          |
| No                             | 13 (93)                   | 58 (85)                              | 71 (87)                       |          |
| Concomitant procedures         |                           |                                      |                               | P* = 0.869 |
| 0                              | 10 (71)                   | 38 (56)                              | 48 (58)                       |          |
| 1                              | 3 (21)                    | 22 (32)                              | 25 (31)                       |          |
| 2                              | 1 (7)                     | 6 (9)                                | 7 (9)                         |          |
| 3                              | 1 (1.5)                   | 1 (1)                                |                               |          |
| 4                              | 1 (1.5)                   | 1 (1)                                |                               |          |
| Unplanned events²              |                           |                                      |                               | P* = 1.000 |
| 0                              | 12 (86)                   | 57 (84)                              | 69 (84)                       |          |
| 1                              | 2 (14)                    | 9 (13)                               | 11 (13)                       |          |
| 2                              | 2 (3)                     | 2 (3)                                |                               |          |

*Fisher’s exact test.
²The need to repeat any surgical movement (for example, the changing cannulation site for the bypass) was also considered.
*Statistically significant (P < 0.05).
PA: pulmonary artery; RVOT: right ventricular outflow tract; TE: tissue-engineered.
Table 4: Intraoperative characteristics: univariate analysis of numerical data

| Variables                        | 3-Step PSP (n = 14), mean ± SD (median) | Conventional planning (n = 68), mean ± SD (median) | P-value |
|----------------------------------|-----------------------------------------|---------------------------------------------------|---------|
| Skin-to-CPB time (min) (skin incision to CPB) | 73 ± 25 (77) | 89 ± 32 (90) | \( P^* = 0.034 \) |
| CPB time (min)                   | 145 ± 57 (126) | 186 ± 94 (164) | \( P^* = 0.062 \) |
| CPB-to-skin time (min) (from end of CPB to skin closure) | 68 ± 28 (63) | 73 ± 25 (69) | \( P^* = 0.083 \) |
| Total time (min) (skin incision to skin closure) | 285 ± 71 (268) | 348 ± 107 (318) | \( P^* = 0.009 \) |
| Cross-clamp time (min)           | 74 ± 33 (57) | 108 ± 47 (89) | \( P^* = 0.006 \) |

\*Mann–Whitney U-test.
Statistically significant (\( P < 0.05 \)).
CPB: cardiopulmonary bypass; SD: standard deviation.

Figure 2: Conventional planning versus 3-step PSP. Box-and-whiskers plots of operative times in min. Each pair of box plots shows the distribution of the measures. The line in the middle of the box indicates the median. The first (Q1) and third (Q3) quartiles are the lower and upper edges of the box, respectively. The upper and lower whiskers show ±1.5 times IQR. The mild (farther than 1.5 times IQR) and the extreme (farther than 3.0 times IQR) outliers are shown as dots and asterisks, respectively. Because the number of measurements is <15 in the 3-step PSP group, each of the data points is plotted as a differently coloured dot. Median comparisons between the 3-step PSP and the conventional planning groups were made according to Mann–Whitney (statistical significance at \( P < 0.05 \)). 3-Step PSP: three-step preoperative sequential planning; CPB: cardiopulmonary bypass; IQR: interquartile range.

***DISCUSSION***

Preoperative planning using computed tomography data

Our findings are in accordance with those of Goldstein et al. [12], whose study of using or not using preoperative CT-based planning (364 patients, 137 vs 227) did not show differences in mortality but revealed statistically significant differences in CPB time (90.1 ± 34.2 vs 110.1 ± 63.8; \( P = 0.002 \)) and cross-clamp time (62.6 ± 23.7 vs 74.8 ± 38.0; \( P = 0.003 \)), even without a standard protocol based on 3D images.
Despite the evolution in perioperative care of adult congenital heart patients in recent years, CPB and cross-clamp times are still being identified as independent predictors of negative outcomes, as demonstrated by Haapanen et al. [14]. In their cohort of 1093 consecutive patients (from 1998 to 2015), including 280 PVRs in patients with TOF, CPB time was a predictor in both multivariate logistic regression (OR 1.11, 95% CI 1.06–1.16; P < 0.001) and the receiver operating characteristic curve (area under the curve 0.716; 95% CI 0.65–0.78; P = 0.001).

The shorter operative times found in the 3-step PSP group may reflect the greater confidence of the surgical team in view of greater exposure to preoperative imaging anatomical data provided by this method. We believe that exposure to anatomical imaging data may have prompted a more fluent course of the procedure, resulting in shorter times. Additionally, neither the main surgeon nor the assistants were aware that operative times would be closely evaluated. This fact reinforces the idea that our surgical planning method may have contributed to shortening operative times without increasing the number of intraoperative surgical complications.

Taking into account that our technique was developed by collaborating surgeons from Brazil and Germany, we speculate that a shortening in the operative times as well as in the postoperative length of stay might represent potential areas of improvement for clinical outcomes when this procedure is used with patients in developing countries.

### Three-step preoperative sequential planning in everyday practice

The surgical complexity of patients with congenital heart disease worldwide has been growing over the years and requiring both more preoperative information and improvement in the quality of imaging examinations [15]. There is an increasing need for an inter-stage moment between the diagnosis and the procedure, especially in centres involved in training new generations of surgeons. In our opinion, surgical planning has a great educational value, and our 3-step method is focused on creating a true roadmap of the entire procedure based on images.

The 3-step PSP method was developed based on 3D reconstructions using volume rendering, a well-known post-processing technique widely used in clinical practice for diagnosis. From our perspective, our method might play an important role in creating a ‘common language’ between clinical and surgical teams. The discussion about patients at weekly interdisciplinary meetings with intuitive images provides an environment of learning and cooperation, thereby strengthening the heart team.

As part of the natural process of the evolution of imaging, with the increasing availability of post-processing software and powerful laptop computers that bring 3D reconstruction technology closer to surgeons, we see a favourable scenario for the reproducibility of our 3-step PSP protocol worldwide, including in developing countries. Such a tool, combined with the growing development of high-definition monitors, will represent a real revolution in the way we preoperatively explain details to patients (and sometimes to their parents) and in the manner of planning and operating.

### Risk of bias and limitations

This is a retrospective study that includes data from a single centre in Germany, which evaluated the preoperative and operative characteristics of 2 similar groups of patients who were operated on at different times. Nevertheless, the effect of this

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**Table 5: Intraoperative characteristics: matched comparison analysis**

| Variables                        | 3-Step PSP (n = 8) | Conventional planning (n = 8) | P-value |
|----------------------------------|--------------------|-------------------------------|---------|
| Lowest temperature in CPB (°C)   | 31 ± 4 (31)        | 28 ± 5 (29)                  | P* = 0.148 |
| Valve size (mm)                  | 26 ± 3 (26)        | 25 ± 3 (24)                  | P* = 0.273 |
| Skin-to-CPB time (min) (skin incision to CPB) | 80 ± 21 (78) | 97 ± 27 (99) | P* = 0.313 |
| CPB time (min)                   | 123 ± 34 (113)     | 190 ± 43 (187)               | P* = 0.008* |
| CPB-to-skin time (min) (from end of CPB to skin closure) | 61 ± 11 (61) | 73 ± 15 (68) | P* = 0.047* |
| Total time (min) (skin incision to skin closure) | 263 ± 44 (261) | 360 ± 66 (351) | P* = 0.008* |
| Cross-clamp time (min)           | 62 ± 14 (56)       | 83 ± 30 (77)                 | P* = 0.078 |
| Postoperative length of stay (days) | 8 ± 5 (6)       | 13 ± 11 (8)                  | P* = 0.031* |

*Wilcoxon test (paired samples). Statistical significant (P < 0.05). CPB: cardiopulmonary bypass; SD: standard deviation.

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In a meta-analysis by Kirmani et al. [13] including 4 retrospective cohort studies that compared the use of preoperative CT for surgical planning (n = 369) versus no-CT (n = 531), all patients were included consecutively and had undergone a previous median sternotomy. On the one hand, no statistically significant differences were found in the risk of death, re-entry injury, renal failure or extracorporeal perfusion/cross-clamp times. On the other hand, the risk was reduced for stroke [relative risk 0.42, 95% confidence interval (CI) 0.19–0.93; P = 0.03] and major complications as a composite [relative risk 0.65, 95% CI 0.47–0.88; P = 0.006]. The authors recommended preoperative cross-sectional imaging to reduce the risk of complications following cardiac reoperation.

It is important to highlight that patients included in both studies [12, 13] were operated on more than 10 years ago. Since then, CT scanners and 3D post-processing techniques have evolved considerably, making it common to use 3D reconstructions for surgical planning in several centres, including the use of printing technology [4, 5].

Considering the aforementioned studies, as well as our findings, we believe that the use of surgical planning using CT represents an important tool for improving surgical care.

### Preoperative planning using 3-step preoperative sequential planning

Patients operated on using the 3-step PSP showed shorter total operative times and skin-to-CPB times, as well as shorter cross-clamp times, without any increase in the number of unplanned operative events. In addition, in our matched-comparison analysis, patients who underwent 3-step PSP showed shorter CPB and CPB-to-skin times as well as postoperative lengths of stay.
limitation was somewhat mitigated because no changes in clinical handling occurred during the entire period. The high prevalence of implanted homografts in both groups of our sample also contributed to their comparability, added to the fact that the surgical team was the same. There are inherent limitations with retrospective and small sample studies; consequently, robust statistical analyses are not possible. No adjustments were made for multiple comparisons. We believe that these limitations are relevant and can only be overcome by designing a new, prospective, randomized study that involves a dedicated multidisciplinary team for patient selection and recruitment in order to homogenize the samples as much as possible.

CONCLUSION

Surgical PVR using the 3-step PSP in patients with repaired TOF is associated with low hospital mortality and a low rate of unplanned operative events. In comparison with conventional planning, the 3-step PSP was associated with shorter operative times including cross-clamp time and lower operative morbidity expressed by a shorter postoperative length of stay.

Conflict of interest: none declared.

Author contributions

Paulo Ernando Ferraz Cavalcanti: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing—original draft; Writing—review & editing.

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REFERENCES

[1] Jacobs JP, Mavroudis C, Quintessenza JA, Chai PJ, Pasquali SK, Hild KD et al. Reoperations for pediatric and congenital heart disease: an analysis of the Society of Thoracic Surgeons (STS) Congenital Heart Surgery Database. Semin Thorac Cardiovasc Surg Pediatr Card Surg Annu 2014;17:2–8.

[2] Adibi A, Mohajer K, Plotnik A, Tognolini A, Tognolini, A, Biniwale R, Cheng W et al. Role of CT and MRI prior to redo sternotomy in paediatric patients with congenital heart disease. Clin Radiol 2014;69:574–80.

[3] Kogon BE, Daniel W, Fay K, Book W. Is the liberal use of preoperative 3-dimensional imaging and pre sternotomy femoral cutoff beneficial in reoperative adult congenital heart surgery? J Thorac Cardiovasc Surg 2014;147:1799–804.

[4] Valverde I, Gomez-Ciriza G, Hussain T, Suarez-Mejias C, Velasco-Forte MN, Byrne N et al. Three-dimensional printed models for surgical planning of complex congenital heart defects: an international multicentre study. Eur J Cardiothorac Surg 2017;52:1139–48.

[5] Batteux C, Haidar MA, Bonnet D. 3D-printed models for surgical planning in complex congenital heart diseases: a systematic review. Front Pediatr 2019;7:1–8.

[6] Valente AM, Gauvreau K, Assenza GE, Babu-Narayan SV, Schreier J. Gatzoulis M et al. Contemporary predictors of death and sustained ventricular tachycardia in patients with repaired tetralogy of Fallot enrolled in the INDICATOR cohort. Heart 2014;100:247–53.

[7] Gatzoulis MA, Balaji S, Webber SA, Siu SC, Hokanson JS, Poile C et al. Risk factors for arrhythmia and sudden cardiac death late after repair of tetralogy of Fallot: a multicentre study. Lancet 2000;356:975–81.

[8] Ferraz Cavalcanti PE, Sá MPBO, Santos CA, Esmeraldo IM, Escobar RR, Menezes AM et al. Pulmonary valve replacement after operative repair of tetralogy of Fallot: meta-analysis and meta-regression of 3,118 patients from 48 studies. J Am Coll Cardiol 2013;62:2227–43.

[9] Warnes CA, Williams RG, Bashore TM, Child JS, Connolly HM, Dearani JA et al. ACC/AHA 2008 guidelines for the management of adults with congenital heart disease: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (Writing Committee to Develop Guidelines on the Management of Adults With Congenital Heart Disease). J Am Coll Cardiol 2008;52:e143–263.

[10] Baumgartner H, Bonhoeffer P, De Groot NMS, Esmeraldo IM, Escobar RR, Galie N et al. ESC guidelines for the management of grown-up congenital heart disease (new version 2010). Eur Heart J 2010;31:2915–57.

[11] Sankouch S, Horke A, Tudorache I, Beerbaum P, Westhoff-Blick M, Boethig D et al. Decellularized fresh homografts for pulmonary valve replacement: a decade of clinical experience. Eur J Cardiothorac Surg 2016;50:281–90.

[12] Goldstein MA, Roy SK, Hebsur S, Maluenda G, Weissman G, Weigold G et al. Relationship between routine multi-detector cardiac computed tomographic angiography prior to reoperative cardiac surgery, length of stay, and hospital charges. Int J Cardiovasc Imaging 2013;29:709–17.

[13] Kirmani BH, Bazeria A, Sirkandarajah S, Azzam R, Keenan DJ. A meta-analysis of computerized tomography scan for reducing complications following repeat sternotomy for cardiac surgery. Interact Cardiovasc Thorac Surg 2016;22:472–9.

[14] Haapanen H, Tsang V, Kempny A, Neijenhuis R, Kennedy F, Cullen S et al. Grown-up congenital heart surgery in 1093 consecutive cases: a "hidden" burden of early outcome. Ann Thorac Surg. 2020;S0003-4975(20)30338-6. doi:10.1016/j.athoracsur.2020.01.071.

[15] Sachdeva R, Valente AM, Armstrong AK, Cook SC, Han BK, Lopez L et al. ACC/AHA/ASE/HRS/SCACHD/SCCT/SCMR/SOPE 2020 appropriate use criteria for multimodality imaging during the follow-up care of patients with congenital heart disease. J Am Coll Cardiol 2020;75:657–703.

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