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Assistive technology using regurgitation fraction and fractional-order integration to assess pulmonary valve insufficiency for pre-surgery decision making and post-surgery outcome evaluation

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ABSTRACT

Valvular heart diseases in pulmonary valves may exhibit different degrees of aortic stenosis or congenital defects. Valve repair or replacement surgery is one of the important procedures commonly performed to relieve valvular dysfunction and improve the significant regurgitation. Hence, it is necessary to assess pulmonary valve insufficiency for pre-surgery decision-making and post-surgery outcome evaluation. This study proposes an assistive technology to quantify regurgitation using the regurgitation fraction (RF) and heart pump efficiency (HPE). In signal preprocessing stage, the detrending and zero-crossing processes are used to remove the unwanted flow fluctuations and identify the end-systolic and end-diastolic periods per each cardiac cycle. The fractional-order integrations are employed to calculate the stroke volume (SV) and regurgitation volume (RV). Then, the regurgitation flow can be quantified that indicates the high correlation with HPE. For a mimicking pulmonary circulation loop system, the proposed screening model can be validated to assess the valve stent efficacy. Experimental results also indicate that pulmonary valve replacement, such as handmade trileaflet valves, can improve severe pulmonary regurgitations. Combining the noninvasive measurement device and the proposed screening model can provide an accurate assessment in clinical applications.

1. Introduction

Valvular heart diseases, including valvular stenosis or regurgitation, might occur in all heart valve positions, such as the aortic valve and the pulmonary valve. Valvular stenosis can limit the blood flow trans-cross the valve and increase the work loading; therefore, the heart needs to pump hard to push out the blood through the stenotic valve. Left valvular stenosis diseases are more prevalent than pulmonary valve diseases [1], occurring in aged patients and represented by outflow obstruction in the left ventricle. Valvular insufficiency is an inability of the valve leaflet to close at the end-systolic period, resulting in flow of blood backward into the ventricle. Aortic valve diseases are left heart diseases that might be caused by aortic diseases, bicuspid aortic valve, rheumatic heart disease, and aging degenerative disease, whereas pulmonary valve diseases are right heart diseases that might occur in children or adults as a result of congenital malformations, postoperative degeneration, or calcification on previous substitutes for valvular leaflets with aging [2].

Pulmonary valve diseases cause abnormalities in the right ventricle, pulmonary artery, and pulmonary parenchyma [3,4]. Despite correcting the right ventricular outflow tract (RVOT) obstruction disease in the early infant stage, sometimes, the valve might still present with a certain degree of defect conditions. Over time, the substitutes of the valve might undergo a degenerative change and result in valve regurgitation or stenosis deterioration. Implantation of a right ventricle–pulmonary artery conduit instead of the

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Nomenclature

$detrend$	Detrending process
Z_n	Zero-crossing rate
$sgn[\bullet]$	Sign function
$w(\bullet)$	Weighting function
$floor(\bullet)$	Greatest integer function
SV	Forward stroke volume
RV	Regurgitation volume
$RF\%$	Regurgitation fraction
$SRR\%$	Ratio of SV and RV
$\Gamma(\bullet)$	Gamma function
$()$	Binomial coefficient
$f(t)$	Time-varying signal
$D^{-\alpha}$	Fractional-order integral and derivative processes
SV_α, RV_α	SV and RV are calculated using the discrete fractional-order integration
Δt	Sampling time
CO	Cardiac output
$HPE\%$	Heart pump efficiency
P	Perimeter
D	Diameter of the conduit
W	Width of single leaflet
H	Length of single leaflet
$C_1(\bullet)$	Lower semilunar cup
$C_2(\bullet)$	Upper semilunar cup

defective pulmonary valve to improve blood flow into the lungs is an important surgical strategy for these patients. Since a majority of children with an RVOT defect receive surgical correction in their early life stage, a re-do surgical correction for the RVOT condition in their later life sometimes becomes inevitable. Identifying the suitable timing for the re-do open-heart surgery might be important for such children and for the surgical decision. Quantitation of blood flow regurgitation is an important indicator. Color Doppler flow, two/three-dimensional echocardiographic Doppler, and cardiovascular magnetic resonance (CMR) are important non-invasive methods to quantify the significant regurgitation for the early assessment of patients requiring valve surgery and for outcome evaluations [5–7].

Traditionally, open-heart surgery to repair or replace the pulmonary valve is the standard strategy to treat pulmonary dysfunction condition. However, open-heart surgery has uncertain morbidity and mortality surgical risk and requires a 2- to 5-inch long surgical wound on the chest wall. Minimally invasive or robotic-assisted cardiac surgery has also been applied with good results. However, catheter-based endovascular surgery is also an emerging treatment strategy. Endovascular surgery employs only puncture wound, reduces surgical risk, and improves patient care by resulting in faster recovery periods and shorter hospital stays. Melody® transcatheter pulmonary valve replacement (TPVR) is a good example that can treat narrowed or leaking pulmonary valve conduits between the right ventricle and the pulmonary artery without the need for open-heart surgery [8–11].

Previous studies had [8–11] designed a handmade expanded polytetrafluoroethylene (ePTFE) trileaflet conduit for TPVR. This technique provided a suitable alternative procedure for both adult and child patients [12]. Most of the patients were able to return home without a prolonged recovery period. The handmade trileaflet valves can be rapidly designed with different range of diameters for patch-valved conduit reconstruction. In addition, the ePTFE material had good biocompatibility and possesses low tissue affinity, which could resist valve degeneration and calcification [7,12,13]. However, handmade valve function assessments

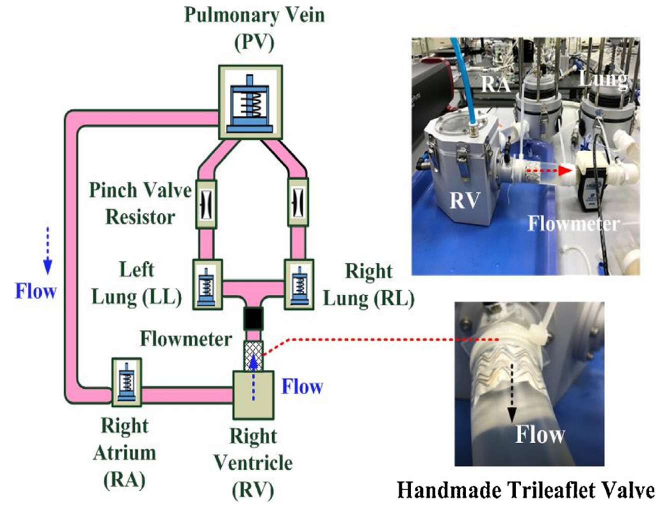

Fig. 1. The schematic diagram of mimicking pulmonary circulation system and metering system.

are required to verify the hemodynamic status, cardiac outputs, and heart pump efficiency (HPE) for presurgery decision-making and postsurgery outcome evaluation. Therefore, this study tested different conditions of pulmonary valve stents in an experimental human circulation system, including valveless, defected valves, mechanical heart valve [14–16], and handmade valve [8,9]. In this study, a handmade trileaflet valve conduit was used for pulmonary valve replacement in a mimicking circulation loop (MCL) system. Using valve competency tests, the regurgitation fraction (RF) and HPE were employed to validate whether the handmade trileaflet valve also had good outcome performances when compared to those with commercial mechanical valve or tissue annulus valve conduits.

Time-domain signal process is applied to analyze pulmonary arterial flow (PAF) for valvular insufficiency evaluations. The quantitation of valvular insufficiency uses the RF to evaluate pulmonary valve efficiency with the stroke volume (SV) and regurgitation volume (RV) of PAF [5–7]. In addition, systolic flow reversal in the pulmonary artery indicates the quantity of blood delivered to the right and left lungs. Hence, detrending and zero-crossing processes [17–21] are used to remove the unwanted flow fluctuations and identify the end-systolic and end-diastolic periods. A quantitative method based on discrete fractional-order integration [22–27] with finite computations, short-memory requirements, and finite power series is designed to calculate SV and RV. This computing method can overcome the limitations of traditional integration, such as the choices of trapezoidal integration and the large number of numerical computations, memory, and sampling data requirements. Experimental results will indicate that the handmade trileaflet valve replacement is a significant improvement as evidenced by decreasing the regurgitation volume and increasing the HPE.

The remainder of this paper is organized as follows: Section 2 describes the methodology, including the experimental setup, signal preprocessing, and the definitions of RF and HPE, and Sections 3 and 4 present the experimental results and discussion demonstrating the efficiency of the proposed methods and the conclusions, respectively.

2. Methodology

2.1. Experimental setup

The MCL system was established to simulate the pulmonary circulation system, consisting of an artificial right ventricle, a primary