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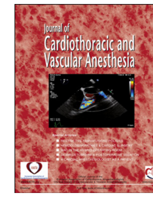

Original Article

Intraoperative Renal Resistive Index as an Acute Kidney Injury Biomarker: Development and Validation of an Automated Analysis Algorithm

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Objective: Intraoperative Doppler-determined renal resistive index (RRI) is a promising early acute kidney injury (AKI) biomarker. As RRI continues to be studied, its clinical usefulness and robustness in research settings will be linked to the ease, efficiency, and precision with which it can be interpreted. Therefore, the authors assessed the usefulness of computer vision technology as an approach to developing an automated RRI-estimating algorithm with equivalent reliability and reproducibility to human experts.
Design: Retrospective.
Setting: Single-center, university hospital.
Participants: Adult cardiac surgery patients from 7/1/2013 to 7/10/2014 with intraoperative transesophageal echocardiography-determined renal blood flow measurements.
Interventions: None.
Measurements and Main Results: Renal Doppler waveforms were obtained retrospectively and assessed by blinded human expert raters. Images (430) were divided evenly into development and validation cohorts. An algorithm for automated RRI analysis was built using computer vision techniques and tuned for alignment with experts using bootstrap resampling in the development cohort. This algorithm then was applied to the validation cohort for an unbiased assessment of agreement with human experts. Waveform analysis time per image averaged 0.144 seconds. Agreement was excellent by intraclass correlation coefficient (0.939; 95% confidence interval [CI] 0.921 to 0.953) and in Bland-Altman analysis (mean difference [human–algorithm] -0.0015; 95% CI –0.0054 to 0.0024), without evidence of systematic bias.
Conclusion: The authors confirmed the value of computer vision technology to develop an algorithm for RRI estimation from automatically processed intraoperative renal Doppler waveforms. This simple-to-use and efficient tool further adds to the clinical and research value of RRI, already the "earliest" among several early AKI biomarkers being assessed.

Key Words: cardiac surgery; acute kidney injury; Doppler echocardiography; computer vision; image processing; algorithms

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DOPPLER-DETERMINED renal resistive index (RRI), an index of renal arterial pulsatility, is an emerging novel biomarker for acute kidney injury (AKI) that adds value to a routine cardiovascular ultrasound examination (eg, intraoperative transesophageal echocardiography [TEE] or transabdominal ultrasound).[1–3] RRI is calculated using Doppler velocity measurements of intrarenal arterial blood flow (Fig 1). Emerging evidence highlights the applications of RRI as significant in both clinical and research settings; these require that waveform interpretation be precise, reproducible, and consistent among raters. This is particularly important given high-acuity situations in which RRI may play an important role (eg, intraoperative and critical care settings). Furthermore, as the value of RRI becomes more validated, its use in clinical practice will be linked directly to the ease and efficiency with which it can be obtained and interpreted.

Importantly, traditional AKI diagnosis and therapy often is delayed due to reliance on serum creatinine accumulation (ie, up to 48 hours). This has prompted a highly publicized search for early AKI biomarkers, among which an abnormally high RRI appears to be, by several hours, the earliest potential marker of AKI. This early advantage may be explained mechanistically: It has been proposed that RRI elevation may reflect increased intracapsular pressure (ie, injury-related renal "compartment syndrome").[4–6] In cardiac surgery patients, the apparent intraoperative timing of primary renal insult has facilitated research into the promptness of RRI as an early AKI biomarker.[2,7] An elevated *intraoperative* (post-cardiopulmonary bypass) RRI by TEE in cardiac surgery patients is associated with subsequent AKI diagnosis.[1,2] Similarly, elevated RRI is associated with AKI in critically ill patients *soon after* various surgical procedures.[3,8–10] The hope is that this earliest knowledge of AKI risk based on RRI elevation (before other biomarkers become positive) will translate into the future development of renoprotective interventions in both surgical and nonsurgical patients.

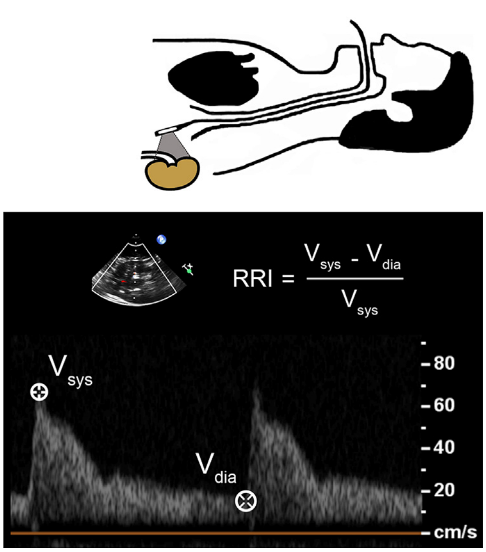

Fig 1. Calculation of the renal resistive index (RRI) using transesophageal echocardiography. V_{sys} = peak systolic velocity; V_{dia} = trough diastolic velocity.

Furthermore, the utility of RRI as a biomarker is not limited to AKI episodes, nor is it limited to renal pathology alone. For example, elevated RRI in patients with congestive heart failure has prognostic value for mortality risk and the future decline of both cardiac and renal function.[11–13] Moreover, in the setting of chronic kidney disease, RRI elevation correlates with mortality risk.[14] As this intriguing biomarker continues to be tested for its potential mainstream clinical utility, using a development-validation approach the authors sought to assess the value of computer vision technology (ie, the computerized processing and analysis of digital images) to develop an automated algorithm for processing renal Doppler waveforms to more easily and reproducibly estimate RRI.

Methods

Study Population

After institutional review board approval, a retrospective review of the authors' institutional TEE database was performed. Subjects included patients ≥18 years old who underwent cardiac surgery between 7/1/2013 and 7/10/2014 at the authors' institution for whom renal blood flow measurements obtained via TEE were documented. Renal Doppler images were excluded *a priori* if they were deemed to be of insufficient quality for automated analysis (eg, significant artifact, distortion due to masking, partial waveforms).

Intraoperative Ultrasound Imaging

A comprehensive examination using a multiplane TEE probe (Philips X7-2t, iE33; Philips Healthcare, Inc., Andover, MA) is routine both before and after cardiopulmonary bypass at the authors' institution. Acquisition of renal blood flow measurements is encouraged during examination, and images from each examination are saved in an institutional database for future reference. The examination is performed by an adult cardiothoracic anesthesiology fellow along with an attending anesthesiologist certified in advanced perioperative TEE by the National Board of Echocardiography (Advanced PTEeXAM). Left renal artery Doppler velocity images were obtained using a transgastric approach. Briefly, a midpapillary transgastric short-axis view first is obtained. The probe then is rotated approximately 180 degrees to the left to obtain a short-axis view of the descending aorta and then advanced to the origin of the left renal artery. This artery is followed by rotating the probe to the right until visualization of the left kidney occurs.[15]

Human Assessment of RRI

Seven cardiothoracic anesthesiologists certified in TEE reviewed deidentified renal Doppler images to determine RRI values. Inter-rater reliability for RRI determination among the investigators was assessed previously through evaluation of 78 images (intraclass correlation coefficient [ICC] 0.77).[2] Renal arterial peak systolic and trough diastolic velocities were