Backward Mitral Flow Assessment Based on Indicator-Dilution Measurements

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Indicator dilution technique has regained interest recently since the latest achievements in echocontrast cardiography and computerized angiography. Appearance of second generation of long-living echo-contrast agents, which can be used as a reliable indicator, makes echo-contrast ultrasonics a perfect candidate for noninvasive method of cardiac flow assessment with a perspective to substitute such traditional technique as nuclear radiography. This work is concerned with mitral flow assessment, however the algorithm we used here is general and can be implemented anywhere whenever two compartment model of indicator dilution is suitable. Consider a chamber with i inputs and k outputs. It is assumed that the condition of perfect mixing of an ideal indicator is permanently maintained in both chambers. Ideal indicator means that it does not interfere with the flow of host liquid and its velocity field is identical to that of the host liquid. Designating by Fi , Fk ,V, ci and c incoming, outgoing flows, chamber volume, incoming concentrations and existing at the present moment in the chamber indicator concentration respectively, one obtains the following system of equations:

$$\begin{cases} \dfrac{d(Vc)}{dt} = \sum_i F_i c_i - c\sum_k F_k \\ \dfrac{dV}{dt} = \sum_i F_i - \sum_k F_k \end{cases} \quad (1)$$

$$\frac{dc}{dt} = \frac{1}{V}\left(\sum_i F_i c_i - c\sum_i F_i\right) \quad (2)$$

Assuming: a)Fin(t)-left atrium input flow; Va(t) - atrium volume; ca(t)- atrium contrast agent concentration; b)FM+(t)- mitral forward flow; FM-(t)- mitral backward flow; c)there is no aortic backward flow; d)Vv(t)-ventricular volume; cv(t)- ventricular contrast agent concentration; e)ED, ES end diastolic and end systolic points of time respectively, and applying (1), (2) one gets for the ventricle at diastole:

$$\begin{aligned} & V_v \frac{dc_v}{dt} = F_{M+}(c_a - c_v) \Rightarrow \frac{d(V_v)}{V_v} = \frac{1}{c_a - c_v}\frac{dc_v}{dt} \\ & \Rightarrow V_v(ES+t) = V_v(ES)\exp\left(\int_{ES}^{ES+t} \frac{1}{c_a - c_v}\frac{dc_v}{d\tau}d\tau\right) \end{aligned} \quad (3)$$

For the atrium at initial part of ventricle systole when FM->0 and Fin<<FM-

$$V_a \frac{dc_a}{dt} = F_{M-}(c_v - c_a) \Rightarrow \frac{dV_a}{V_a} = \frac{1}{c_v - c_a}\frac{dc_a}{dt}$$
$$\Rightarrow V_a(ED+t) = V_a(ED)\frac{c_a(ED+t) - c_v(ED+t)}{c_a(ED) - c_v(ED)} \qquad (4)$$

Computer model of cardiovascular circulation was built based on lumped, constant-segment approach, previously developed by O.Barnea et al. 1990, O.Barnea and N.Sheffer 1993, in which mitral valve parameters were made variable to mimic different degree of mitral regurgitation. This model was used in conjunction with another computer model of first pass indicator dilution, developed on the basis of equations (1)-(2) to yield right and left heart concentration vs. time curves. These in turn were used to solve backward problem of finding mitral flow in accordance with the equations (3)-(4).

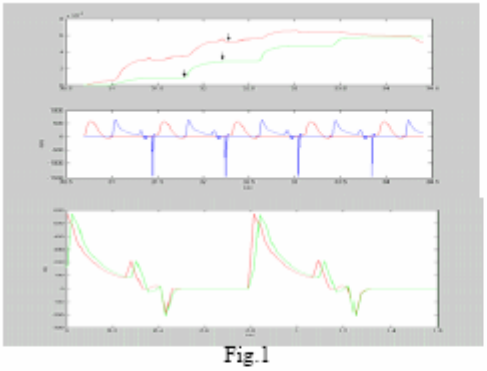

Fig.1
Results of backward solved problem for minimal MV regurgitation Upper half-LA (red) and LV (green) indicator concentrations along with aortic (red) and mitral (blue) flow; Lower half- backward problem solution for mitral flow (red) and initial mitral flow (green)

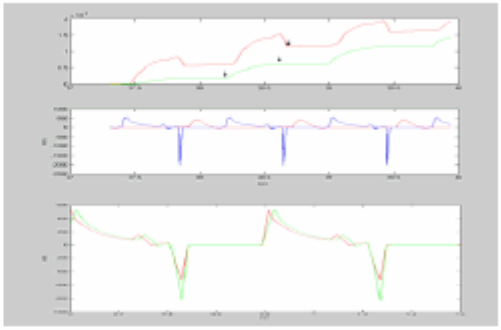

Fig.2
Results of backward solved problem for severe MV regurgitation: Upper half-LA (red) and LV (green) indicator concentrations along with aortic (red) and mitral (blue) flow; Lower half- backward problem solution for mitral flow (red) and initial mitral flow (green)

Some results are presented in Fig1-3. As can be seen from Fig 1-2 good agreement exists between initial flows and backward calculated ones. The accuracy is determined by the accuracy of the estimation of the multiplying constants in equations 3-4. In computer model these were calculated as maximum and minimum over one cycle of the ventricle and atrium volumes respectively. Good agreement between mitral flow and mitral flow estimation derived from concentration data is not surprising, since both, concentration and flow, are related to each other via the same equations (1). Much more meaningful result is the fact that computer model confirms our and others experimental observation, that mitral and ventricle concentration-time curves have characteristic flow dependent modulation. We have varied $\tau = F/V$ in the interval 1.5-3s with no principal change in the results. It can

be inferred therefore, that despite, that τ most probably varies along the vascular tract; this makes no principle difference on right and left heart indicator concentration patterns. We have also checked the influence of picking up erroneous end diastolic, end systolic and end mitral regurgitation timing points on accuracy of the suggested model of mitral flow calculation. The algorithm is insensitive to erroneous determination of end mitral regurgitation timing point, so that neglecting of incoming to atrium flow at ventricle systole made at derivation of the equation (4), does not introduce any significant errors into
the calculations. Wrong determination of end diastole timing leads to an inaccurate estimation of the part of a mitral flow curve associated with the contribution of atrium systole, so called A peak, preserving its main peak (E peak), deceleration slope of the curve and backward flow pattern. Wrong, more precisely late, end systolic timing is most critical since it causes significant mitral flow underestimation, that is decreased values of E peak and, as a result, of deceleration slope, which is quite conceivable because late end systolic timing means throwing away initial phase of diastolic filling where mitral flow starts to grow very fast. Finally, we have checked the influence of aortic regurgitation in combination with mitral regurgitation on applicability of the model. For the worst case of mitral regurgitation we have increased average aortic backward leakage from 4.2 ml/s to 10.1ml/s, which constituted 8.5% and 21% respectively from cardiac output and still obtained good agreement between original and backward calculated mitral flow curves.

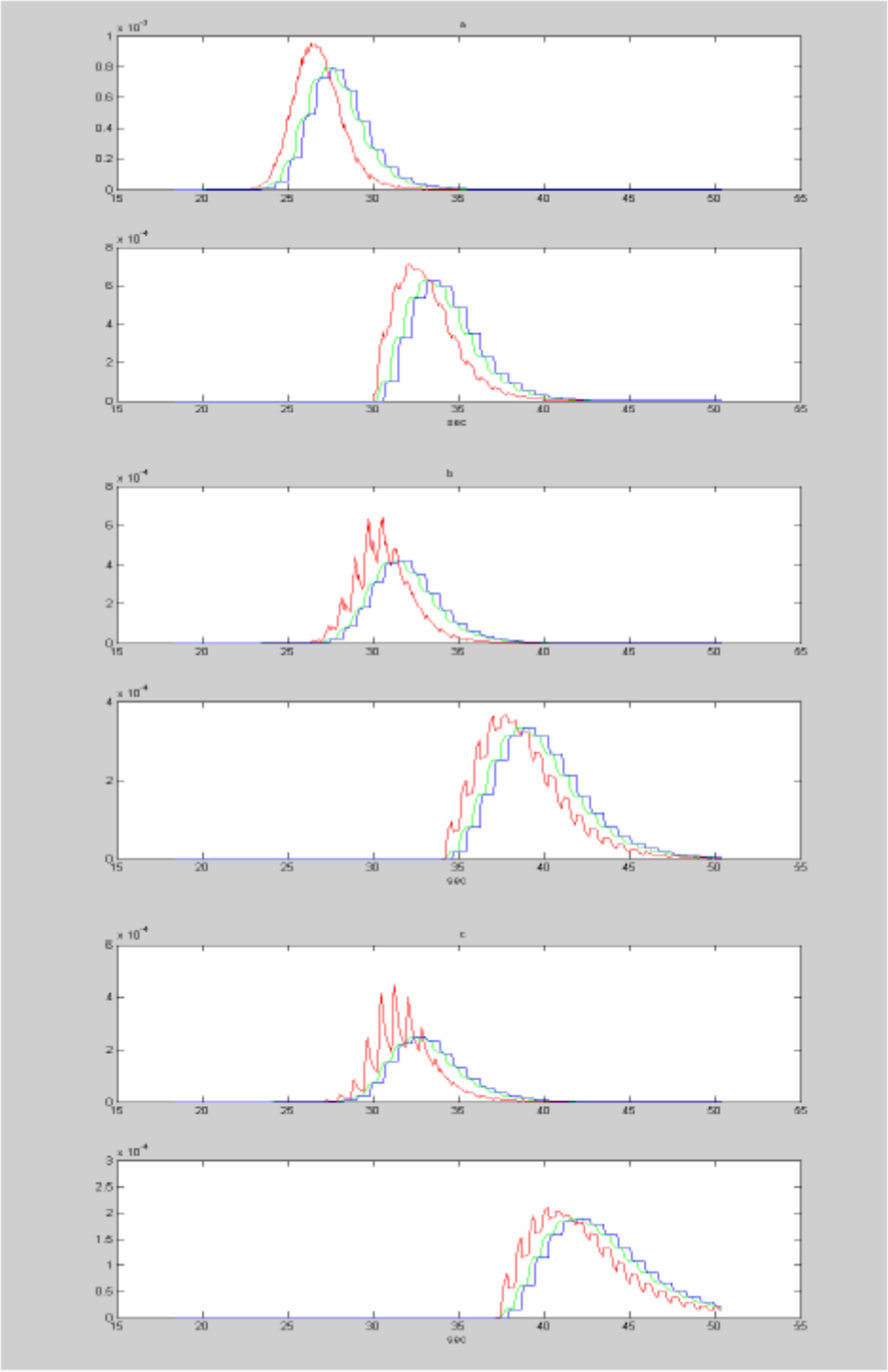

Fig 3

Impact of gradual increase of mitral regurgitation, from minimal – a, to more severe – c, on appearance of right (upper half) and left (lower half) heart indicator concentration curves.