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Letter to the Editor

Fractional flow reserve derived from conventional coronary angiograms and computational fluid dynamics

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The assessment of the functional severity by fractional flow reserve (FFR) provides a physiologic adjunct to invasive coronary angiography by accurately detecting hemodynamically significant coronary artery stenoses associated with reduced coronary blood flow [1]. FFR-guided intervention has been documented to offer improved clinical outcomes [2]. Despite these benefits, less than 10% of percutaneous coronary intervention procedures use adjunctive intracoronary measurements, and even in fewer diagnostic cases FFR is utilized in order to guide management [3]. This is mainly due to the inherent limitations of the technique, such as the requirement of invasive cardiac catheterization, an expensive coronary pressure wire and intracoronary or intravenous adenosine infusion. Advances in coronary imaging and computational fluid dynamics enable calculation of coronary flow and pressure fields from anatomic image data [4]. Computational fluid dynamics (CFD) is a general term used to account for the numerical reconstruction of the targeted topology, the discretization of the control volume and the solution of the governing equations of fluid flow on the volume mesh nodes with the use of proper boundary conditions. Typically, at a CFD problem the vessel model is reconstructed and discretized into a number of smaller entities (finite volumes) which form the nodes of a computational mesh, on which the unknowns of flow (e.g., pressure and velocity) are calculated. The discretization of the governing differential equations results in systems of algebraic equations, the iterative solution of which gives the problem unknowns at the mesh nodes. In order to perform a CFD simulation of flow in a coronary vessel and to computationally determine FFR, a three-dimensional (3D) description of the vessel lumen and boundary flow conditions at the entrance and exit of the vessel model are required.

The aim of the current study was to explore the accuracy of FFR determination by employing a simple and rapid CFD methodology based on generic boundary flow conditions at coronary models obtained from conventional coronary angiography without any modification of the imaging acquisition protocol.

The coronary models were obtained from conventional coronary angiograms by an algorithm previously developed by our group based on the concept of epipolar geometry [5]. In brief, the algorithm uses two routine angiographic views and combines image software enhancement, automatic detection of the centerline of selected branches as well as automatic edge detection. An iterative procedure is used to estimate the 3D centerline of the selected arterial branches as well as their diameter (Fig. 1). Three cases of stenosed left anterior descending (LAD) coronary arteries were considered in which the functional severity of lesions has been assessed by invasive FFR (FFR_{INV}). These cases included a functionally insignificant lesion ($FFR_{INV1} = 0.93$), a moderate lesion ($FFR_{INV2} = 0.85$) and a severe lesion ($FFR_{INV3} = 0.70$). The LAD anatomies were reconstructed as previously described, meshed with an appropriate commercial package (ANSYS) and fed into a CFD solver (ANSYS Fluent) where realistic generic transient boundary flow conditions were applied [4]. FFR was estimated as the ratio of the calculated total mass flow rate of the stenosed model to that of the model in which the stenotic lesion has been computationally removed (Figs. 1 and 2).

Fig. 1a displays the angiographic views used for model reconstruction at the case of a moderately hemodynamic significant coronary stenosis ($FFR_{INV} = 0.85$). Two end-diastolic views have been used for the reconstruction of the 3D model of the main artery and side branches (Fig. 1b). Fig. 1c displays the coronary stenosis of the model

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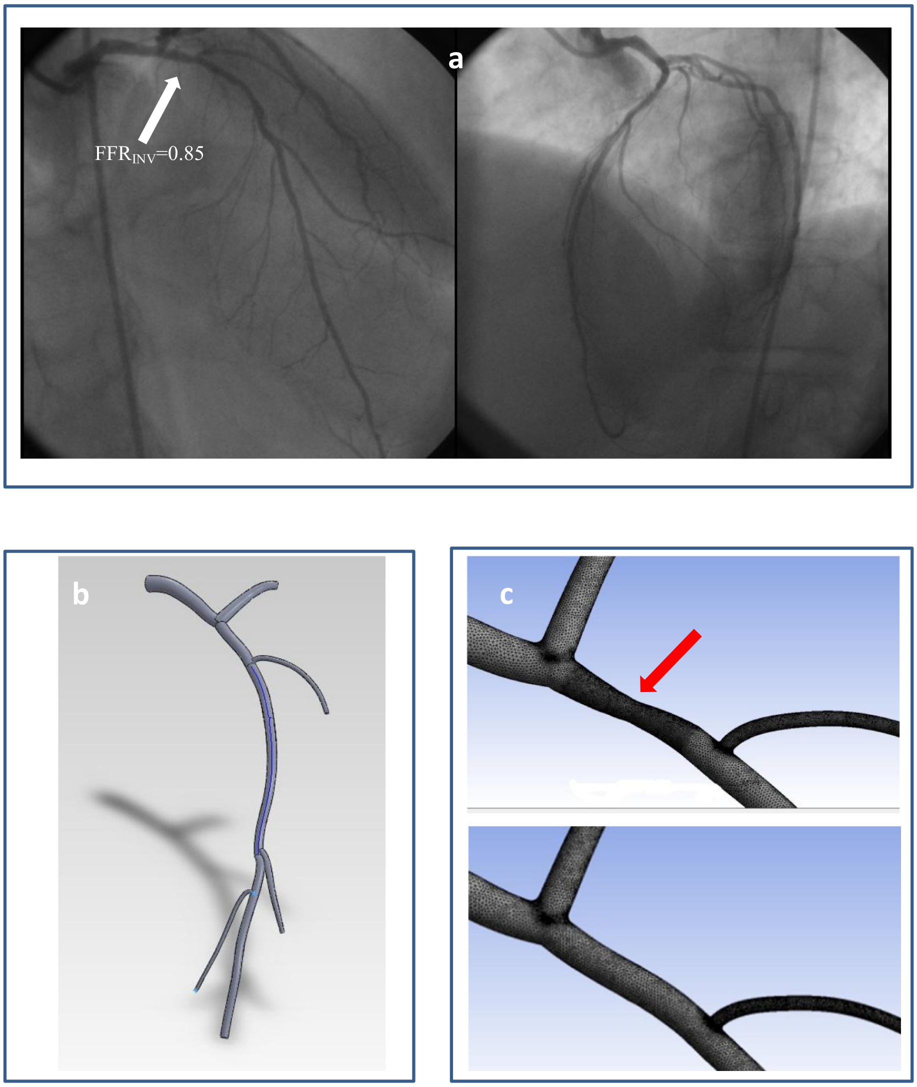

Fig. 1. (a) End diastolic angiographic views (RAO 12.9°/37°, LAO 39.3°/19.5°) used for coronary model reconstruction at the case of moderately significant coronary stenosis. The white arrow denotes the site that FFR was invasively measured, (b) the generated 3D model of the LAD and main branches, (c) the detail of the coronary stenosis (red arrow) and the "healthy" corresponding LAD anatomy in which the stenosis has been removed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and the "healthy" corresponding LAD model in which the coronary stenosis has been removed. In the case of the "healthy" anatomy the stenosis has been replaced by a vessel segment with proximal and distal diameters equal to the corresponding vessel reference diameters. Fig. 2 displays the transient calculated total mass flow rate of the three stenosed models and the calculated total mass flow rate of the model without arterial restriction ("healthy" model). The mass flow rate variation corresponds to one cardiac cycle. It is evident from the three diagrams that as the functional severity of the stenosis increases, the difference in mass flow rate between the "healthy" and stenosed model also increases. The difference in total mass flow rate between the two models can be graphically appraised by the area between the two lines (healthy/stenosed) of each graph. The computed value of FFR for each case was determined by the ratio of the time integral during two cardiac cycles of the mass flow rate of the stenosed model to that of the "healthy" model. The computationally determined values of FFR (FFR_{CFD}) for the three cases of coronary stenoses were $FFR_{CFD1} = 0.95$, $FFR_{CFD2} = 0.85$ and $FFR_{CFD3} = 0.72$ thus differences with the invasively measured values were 0.02, 0.00 and 0.02 respectively.

Comprehensive noninvasive anatomical and functional imaging would be desirable to identify patients who are likely to benefit from revascularization. By employing various modalities of coronary imaging coupled with CFD methodologies, various investigators have presented alternative methods of FFR calculation. In these studies the imaging modality, either a multislice computed tomography (MDCT) scanner [6,7], a conventional angiography unit [8,9] or an angiography unit capable of rotational coronary angiography [3] were employed for the acquisition of vessel models of diseased coronary arteries. In these studies FFR calculations by CFD methodologies is rather demanding, either requiring the acquisition of patient specific boundary flow conditions or requiring coronary image data to be sent to an off-site core laboratory for processing and result extraction. Moreover, in the cases that the coronary model is derived by a MDCT scanner, an additional imaging procedure is required which adds discomfort, risks and cost. The developed methodology enables the virtual assessment of the functional severity of atherosclerotic lesions by routine angiography and without requiring invasive measurements or hyperemia induction. This "less invasive" approach when validated to larger patient cohorts could have important implications for patient management and cost.

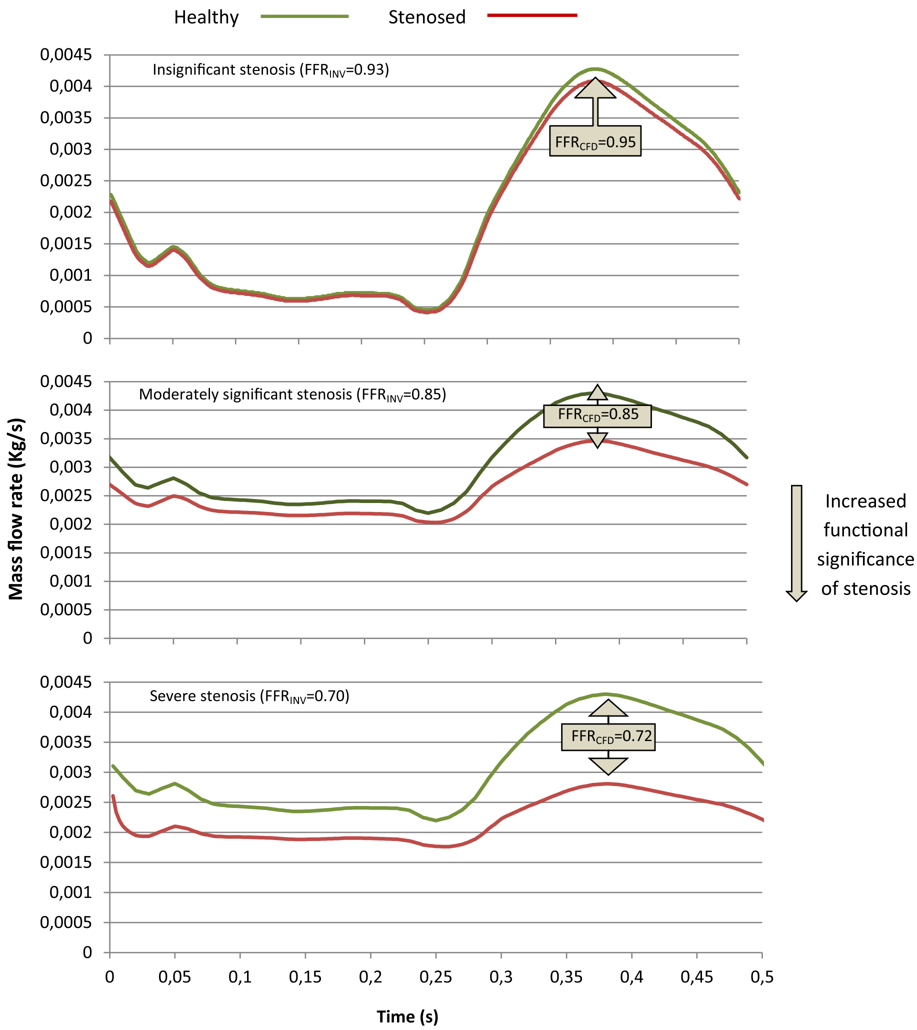

Fig. 2. Calculated total mass flow rate of the three stenosed models (insignificant, moderate and severe) and the calculated total mass flow rate of the model without arterial restriction ("healthy" model).

Conflict of interest

The authors report no relationships that could be construed as a conflict of interest.

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References

[1] N. Melikian, P. De Bondt, P. Tonino, O. De Winter, E. Wyffels, J. Bartunek, G.R. Heyndrickx, W.F. Fearon, N.H. Pijls, W. Wijns, B. De Bruyne, Fractional flow reserve and myocardial perfusion imaging in patients with angiographic multivessel coronary artery disease, JACC Cardiovasc. Interv. 3 (2010) 307–314.

[2] P.A. Tonino, B. De Bruyne, N.H. Pijls, U. Siebert, F. Ikeno, M. van't Veer, V. Klauss, G. Manoharan, T. Engstrom, K.G. Oldroyd, P.N. Ver Lee, P.A. MacCarthy, W.F. Fearon, Fractional flow reserve versus angiography for guiding percutaneous coronary intervention, N. Engl. J. Med. 360 (2009) 213–224.

[3] P.D. Morris, D. Ryan, A.C. Morton, R. Lycett, P.V. Lawford, D.R. Hose, J.P. Gunn, Virtual fractional flow reserve from coronary angiography: modeling the significance of coronary lesions: results from the VIRTU-1 (VIRTUal Fractional Flow Reserve From Coronary Angiography) study, JACC Cardiovasc. Interv. 6 (2013) 149–157.

[4] H.J. Kim, I.E. Vignon-Clementel, J.S. Coogan, C.A. Figueroa, K.E. Jansen, C.A. Taylor, Patient-specific modeling of blood flow and pressure in human coronary arteries, Ann. Biomed. Eng. 38 (2010) 3195–3209.

[5] A. Andriotis, A. Zifan, M. Gavaises, P. Liatsis, I. Pantos, A. Theodorakakos, E.P. Efstathopoulos, D. Katritsis, A new method of three-dimensional coronary artery reconstruction from X-ray angiography: validation against a virtual phantom and multislice computed tomography, Catheter. Cardiovasc. Interv. 71 (2008) 28–43.

[6] J.K. Min, J. Leipsic, M.J. Pencina, D.S. Berman, B.K. Koo, C. van Mieghem, A. Erglis, F.Y. Lin, A.M. Dunning, P. Apruzzese, M.J. Budoff, J.H. Cole, F.A. Jaffer, M.B. Leon, J. Malpeso, G.B. Mancini, S.J. Park, R.S. Schwartz, L.J. Shaw, L. Mauri, Diagnostic accuracy of fractional flow reserve from anatomic CT angiography, JAMA 308 (2012) 1237–1245.

[7] B.K. Koo, A. Erglis, J.H. Doh, D.V. Daniels, S. Jegere, H.S. Kim, A. Dunning, T. DeFrance, A. Lansky, J. Leipsic, J.K. Min, Diagnosis of ischemia-causing coronary stenoses by noninvasive fractional flow reserve computed from coronary computed tomographic angiograms. Results from the prospective multicenter DISCOVER-FLOW (Diagnosis of Ischemia-Causing Stenoses Obtained Via Noninvasive Fractional Flow Reserve) study, J. Am. Coll. Cardiol. 58 (2011) 1989–1997.

[8] S. Tu, E. Barbato, Z. Koszegi, J. Yang, Z. Sun, N.R. Holm, B. Tar, Y. Li, D. Rusinaru, W. Wijns, J.H. Reiber, Fractional flow reserve calculation from 3-dimensional quantitative coronary angiography and TIMI frame count: a fast computer model to quantify the functional significance of moderately obstructed coronary arteries, JACC Cardiovasc. Interv. 7 (2014) 768–777.

[9] M.I. Papafaklis, T. Muramatsu, Y. Ishibashi, L.S. Lakkas, S. Nakatani, C.V. Bourantas, J. Ligthart, Y. Onuma, M. Echavarria-Pinto, G. Tsirka, A. Kotsia, D.N. Nikas, O. Mogabgab, R.J. van Geuns, K.K. Naka, D.I. Fotiadis, E.S. Brilakis, H.M. Garcia-Garcia, J. Escaned, F. Zijlstra, L.K. Michalis, P.W. Serruys, Fast virtual functional assessment of intermediate coronary lesions using routine angiographic data and blood flow simulation in humans: comparison with pressure wire — fractional flow reserve, EuroIntervention 10 (2014) 574–583.