Lin, W. J.; **Iafrati, M. D.**; **Peattie, R. A.**; **Dorfmann, L.**

Growth and remodeling with application to abdominal aortic aneurysms. (English)

Zbl 1408.74038
J. Eng. Math. 109, 113-137 (2018).

Summary: In this paper, we apply a mixture theory of growth and remodeling to study the formation and dilatation of abdominal aortic aneurysms. We adapt the continuum theory of mixtures to formalize the processes of production and removal of constituents from a loaded body. Specifically, we consider a mixture of elastin and collagen fibers which endow the material with anisotropic properties. An evolving recruitment variable defines the intermediate configuration from which the elastic stretch of collagen is measured. General formulations of the equations governing homeostatic state and aneurysm development are provided. In the homeostatic state, the idealized geometry of the aorta is a thick-walled tube subject to constant internal pressure and axial stretch. The formation of an aneurysm induces an increase of mass locally achieved via production of new material that exceeds the removal of old material. The combined effects of loss of elastin, degradation of existing and deposition of new collagen, as well as fiber remodeling results in a continuous enlargement of the aneurysm bulge. The numerical method makes use of a purposely written material subroutine, called UMAT, which is based on the constitutive formulation provided in the paper. Numerical results based on patient-based material parameters are illustrated.

MSC:

74L15 Biomechanical solid mechanics
92C30 Physiology (general)

Keywords:

AAA; abdominal aortic aneurysm; finite element analysis; growth; homeostatic state; mixture theory; remodeling

Full Text: DOI

References:

[1] Armentano, R; Barra, J; Levenson, J; Simon, A; Pichel, R, Arterial wall mechanics in conscious dogs: assessment of viscous, inertial and elastic moduli to characterize aortic wall behavior, Circ Res, 76, 468-478, (1995)

[2] Shadwick, R, Mechanical design in arteries, J Exp Biol, 202, 3305-3313, (1999)

[3] Raghavan, ML; Webster, M; Vorp, DA, Ex-vivo bio-mechanical behavior of AAA: assessment using a new mathematical model, Ann Biomed Eng, 24, 573-582, (1999)

[4] Sverdlik, A; Lanir, Y, Time dependent mechanical behaviour of sheep digital tendons, including the effects of preconditioning, J Biomech Eng, 124, 78-84, (2002)

[5] Sacks, MS, Incorporation of experimentally derived fiber orientation into a structural constitutive model for planar collagenous tissues, J Biomech Eng, 125, 280-287, (2003)

[6] Pancheri, FQ; Peattie, RA; Reddy, ND; Ahamed, T; Lin, W; Ouellette, TD; Iafrati, MD; Dorfmann, L, Histology and biaxial mechanical behavior of abdominal aortic aneurysm tissue samples, J Biomech Eng, 139, 031002, (2017)

[7] O'Leary, SA; Healey, DA; Kavanagh, EG; Walsh, MT; McGloughlin, TM; Doyle, BJ, The biaxial biomechanical behavior of abdominal aortic aneurysm tissue, Ann Biomed Eng, 42, 2440-2450, (2014)

[8] Tong, J; Cohnert, T; Regitnig, P; Holzapfel, GA, Effects of age on the elastic properties of the intraluminal thrombus and the thrombus-covered wall in abdominal aortic aneurysms: biaxial extension behaviour and material modelling, Eur J Vasc Endovasc Surg, 42, 207-219, (2011)

[9] Humphrey, JD, Remodelling of a collagenous tissue at fixed lengths, ASME J Biomech Eng, 121, 591-597, (1999)

[10] Nissen, R; Cardinale, GJ; Udenfriend, S, Increased turnover of arterial collagen in hypertensive rats, Proc Natl Acad Sci USA Med Sci, 75, 451-453, (1978)

[11] He, CM; Roach, M, The composition and mechanical properties of abdominal aortic aneurysms, J Vasc Surg, 20, 6-13, (1993)

[12] Cheheltani, R; Pichamuthu, JE; Rao, J; Weinbaum, JS; Kiani, MF; Vorp, DA; Pleshko, N, Fourier transform infrared spectroscopic imaging-derived collagen content and maturity correlates with stress in the aortic wall of abdominal aortic aneurysm patients, Cardiovasc Eng Technol, 8, 70-80, (2017)

[13] McGee, GS; Baxter, BT; Shively, VP; Chisholm, R; McCarthy, WJ; Flinn, WR; Yao, JST; Pearce, WH, Aneurysm or occlusive disease-factors determining the clinical course of atherosclerosis of the infrarenal aorta, Surgery, 110, 370-376, (1991)

[14] Choke, E; Cockerill, G; Wilson, WRW; Sayed, S; Dawson, J; Loftus, I; Thompson, MM, A review of biological factors implicated in abdominal aortic aneurysm rupture, Eur J Vasc Endovasc Surg, 30, 227-244, (2005)

[15] Vorp, DA, Biomechanics of abdominal aortic aneurysm, J Biomech, 40, 1887-1902, (2007)

[16] Fillinger, MF; Raghavan, ML; Marra, SP; Cronenwett, JL; Kennedy, FE, In vivo analysis of mechanical wall stress and abdominal aortic aneurysm rupture risk, J Vasc Surg, 36, 589-597, (2002)

[17] Dorfmann, A; Wilson, C; Edgar, ES; Peattie, RA, Evaluating patient-specific abdominal aortic aneurysm wall stress based on flow-induced loading, Biomech Model Mechan, 9, 127-139, (2010)

[18] Erhart, P; Grond-Ginsbach, C; Hakimi, M; Lasitschka, F; Dihlmann, S; Böckler, D; Alexander Hyhlik-Dürr, A, Finite element analysis of abdominal aortic aneurysms: predicted rupture risk correlates with aortic wall histology in individual patients, J Endovasc Ther, 21, 556-564, (2014)

[19] Ahamed, T; Dorfmann, L; Ogden, RW, Modelling of residually stressed materials with application to AAA, J Mech Behav Biomed, 61, 221-234, (2016)

[20] Rissland, P; Alemu, Y; Einav, S; Ricotta, J; Bluestein, D, Abdominal aortic aneurysm risk of rupture: patient-specific FSI simulations using anisotropic model, ASME J Biomech Eng, 131, 031001, (2009)

[21] Pierce, DM; Fastl, TE; Rodriguez-Vila, B; Verbrugghe, P; Fourneau, I; Maleux, G; Herijgers, P; Gomez, EJ; Holzapfel, GA, A method for incorporating three-dimensional residual stretches/stresses into patient-specific finite element simulations of arteries, J Mech Behav Biomed Mater, 47, 147-16, (2015)

[22] Joldes, GR; Miller, K; Wittek, A; Doyle, B, A simple, effective and clinically applicable method to compute abdominal aortic aneurysm wall stress, J Mech Behav Biomed Mater, 58, 139-148, (2016)

[23] Eriksson, T; Watton, P; Luo, X; Ventikos, Y, Modelling volumetric growth in a thick walled fibre reinforced artery, J Mech Phys Solids, 73, 134-150, (2014) · Zbl 1349.74260

[24] Raghavan, ML; Vorp, DA, Toward a biomechanical tool to evaluate rupture potential of abdominal aortic aneurysm: identification of a finite strain constitutive model and evaluation of its applicability, J Biomech, 33, 475-482, (2000)

[25] Maier, A; Gee, MW; Reeps, C; Pongratz, J; Eckstein, HH; Wall, WA, A comparison of diameter, wall stress, and rupture potential index for abdominal aortic aneurysm rupture risk prediction, Ann Biomed Eng, 38, 3124-3134, (2010)

[26] Gasser, T; Auer, M; Labruto, F; Swedenborg, J; Roy, J, Biomechanical rupture risk assessment of abdominal aortic aneurysms: model complexity versus predictability of finite element simulations, Eur J Vasc Endovasc, 40, 176-185, (2010)

[27] Erhart, P; Hyhlik-Dürr, A; Geisbüsch, P; Kotelis, D; Müller-Eschner, M; Gasser, T; Tengg-, Kobligk H; Böckler, D, Finite element analysis in asymptomatic, symptomatic, and ruptured abdominal aortic aneurysms: in search of new rupture risk predictors, Eur J Vasc Endovasc, 49, 239-245, (2015)

[28] Watton, PN; Hill, NA; Heil, M, A mathematical model for the growth of the abdominal aortic aneurysm, Biomech Model Mech, 3, 98-113, (2004)

[29] Watton, PN; Hill, NA; Heil, M, Evolving mechanical properties of a model of abdominal aortic aneurysm, Biomech Model Mech, 8, 25-42, (2009)

[30] Humphrey, JD; Rajagopal, KR, A constrained mixture model for growth and remodeling of soft tissues, Math Models Methods Appl Sci, 12, 407-430, (2002) · Zbl 1021.74026

[31] Baek, S; Rajagopal, KR; Humphrey, JD, A theoretical model of enlarging intracranial fusiform aneurysms, ASME J Biomech Eng, 128, 142-149, (2006)

[32] Valentin, A; Cardamone, L; Baek, S; Humphrey, J, Complementary vasoactivity and matrix re-modelling in arterial adaptations to altered flow and pressure, J R Soc Interface, 6, 293-306, (2009)

[33] Valentin, A; Humphrey, J, Evaluation of fundamental hypotheses underlying constrained mixture models of arterial growth and remodelling, Philos Trans R Soc A, 367, 3585-3606, (2009) · Zbl 1185.74069

[34] Wilson, JS; Baek, S; Humphrey, JD, Parametric study of effects of collagen turnover on the natural history of abdominal aortic aneurysms, Proc R Soc A Math Phys Eng Sci, 469, 20120556, (2013) · Zbl 1371.92069

[35] Valentin, A; Humphrey, J; Holzapfel, GA, A multi-layered computational model of coupled elastin degradation, vasoactive dysfunction, and collagenous stiffening in aortic aging, Ann Biomed Eng, 39, 2027-2045, (2011)

[36] Valentin, A; Humphrey, J; Holzapfel, GA, A finite element-based constrained mixture implementation for arterial growth, remodeling, and adaptation: theory and numerical verification, Int J Numer Methods Biomed Eng, 29, 822-849, (2013)

[37] Spencer, AJM; Rivlin, RS, Finite integrity bases for five or fewer symmetric $3× 3$ matrices, Arch Ration Mech Anal, 2, 435-446, (1959) · Zbl 0095.25102

[38] Spencer, AJM; Eringen, AC (ed.), Theory of invariants, No. 1, 239-353, (1971), New York

[39] Flory, PJ, Thermodynamic relations for highly elastic materials, Trans Faraday Soc, 57, 829-838, (1961)

[40] Ogden, RW, Nearly isochoric elastic deformations: application to rubberlike solids, J Mech Phys Solids, 26, 37-57, (1978) · Zbl 0377.73044

[41] Demirkoparan, H; Pence, TJ; Wineman, A, On dissolution and reassembly of filamentary reinforcing networks in hyperelastic materials, Proc R Soc A Math Phys Eng Sci, 465, 867-894, (2009) · Zbl 1186.74021

[42] Demirkoparan, H; Pence, TJ; Wineman, A, Chemomechanics and homeostasis in active strain stabilized hyperelastic fibrous microstructures, Int J Nonlinear Mech, 56, 86-93, (2013)

[43] Holzapfel, GA; Gasser, TC; Ogden, RW, A new constitutive framework for arterial wall mechanics and a comparative study of material models, J Elasticity, 61, 1-48, (2000) · Zbl 1023.74033

[44] Wang N, Butler JP, Ingber DE (1993) Mechanotransduction across the cell-surface and through the cytoskeleton. Science 260:1124-1127

[45] Tözeren, A; Skalak, R, Interaction of stress and growth in a fibrous tissue, J Theor Biol, 130, 337-350, (1988)

[46] Kroon M, Holzapfel GA (2007) A model of saccular cerebral aneurysm growth by collagen fiber remodeling. J Theor Biol 247:775-787

[47] Kroon, M; Holzapfel, GA, Modeling of saccular aneurysm growth in a human middle cerebral artery, ASME J Biomech Eng, 130, 051012, (2008)

[48] Rajagopal, K; Wineman, A, A constitutive equation for nonlinear solids which undergo deformation induced microstructural changes, Int J Plasticity, 8, 385-395, (1992) · Zbl 0765.73005

[49] Rodriguez, EK; Hoger, A; McCulloch, AD, Stress-dependent finite growth in soft elastic tissues, J Biomech, 27, 455-67, (1994)

[50] Cyron, CJ; Humphrey, JD, Growth and remodeling of load-bearing biological soft tissues, Meccanica, 52, 645-664, (2017)

[51] Rezakhaniha, R; Agianniotis, A; Schrauwen, JTC; Griffa, A; Sage, D; Bouten, CVC; Vosse, FN; Unser, M; Stergiopulos, N, Experimental investigation of collagen waviness and orientation in the arterial adventitia using confocal laser scanning microscopy, Biomech Model Mech, 11, 461-473, (2012)

[52] Frank, C; Shrive, N; Hiraoka, H; Nakamura, N; Kaneda, Y; Hart, D, Optimisation of the biology of soft tissue repair, J Sci Med Sport, 2, 190-210, (1999)

[53] Gurtner, GC; Werner, S; Barrandon, Y; Longaker, MT, Wound repair and regeneration, Nature, 453, 314-321, (2008)

[54] Adler, JH; Dorfmann, L; Han, D; MacLachlan, S; Paetsch, C, Mathematical and computational models of incompressible materials subject to shear, IMA J Appl Math, 79, 889-914, (2014) · Zbl 1299.74155

[55] Braeu, FA; Seitz, A; Aydin, RC; Cyron, CJ, Homogenized constrained mixture models for anisotropic volumetric growth and remodeling, Biomech Model Mech, 16, 889-906, (2016)

[56] Cyron, CJ; Wilson, JS; Humphrey, JD, Mechanobiological stability: a new paradigm to understand the enlargement of aneurysms?, J R Soc Interface, 11, 20140680, (2014)

[57] Cyron, CJ; Humphrey, JD, Vascular homeostasis and the concept of mechanobiological stability, Int J Eng Sci, 85, 203-223, (2014) · Zbl 06982878

[58] Wilson, JS; Baek, S; Humphrey, JD, Importance of initial aortic properties on the evolving regional anisotropy, stiffness and wall thickness of human abdominal aortic aneurysms, J R Soc Interface, 9, 2047-2058, (2012)

[59] Pancheri FQ (2014) Experimental and analytical aspects of biological and engineering materials subject to planar biaxial loading. PhD Thesis, Tufts University

[60] Langille, BL; Bevan, JA (ed.); Kaley, G (ed.); Rubanyi, GM (ed.), Blood flow-induced remodeling of the artery wall, (1995), New York

[61] Raghavan, ML; Vorp, DA; Federle, M; Makaroun, MS; Webster, MW, Wall stress distribution on three-dimensionally reconstructed models of human abdominal aortic aneurysm, J Vasc Surg, 31, 760-769, (2000)

[62] Wang, DHJ; Makaroun, MS; Webster, MW; Vorp, DA, Effect of intraluminal thrombus on wall stress in patient-specific models of abdominal aortic aneurysm, J Vasc Surg, 36, 598-604, (2002)

[63] Lu, J; Zhou, X; Raghavan, ML, Inverse elastostatic stress analysis in pre-deformed biological structures: demonstration using abdominal aortic aneurysms, J Biomech, 40, 693-696, (2007)

[64] Scotti, CM; Jimenez, J; Muluk, SC; Finol, EA, Wall stress and flow dynamics in abdominal aortic aneurysms: finite element analysis vs. fluid-structure interaction, Comput Methods Biomech Biomed Eng, 11, 301-322, (2008)

[65] Ogden RW (1997) Non-linear elastic deformations. Dover, Mineola

[66] Vande Geest, JP; Sacks, MS; Vorp, DA, The effects of aneurysm on the biaxial mechanical behavior of human abdominal aorta, J Biomech, 39, 1324-1334, (2006)

[67] Pancheri, FQ; Eng, CM; Lieberman, DE; Biewener, AA; Dorfmann, L, A constitutive description of the anisotropic response of the fascia lata, J Mech Behav Biomed, 30, 306-323, (2014)