Reduction in Pulse Wave Velocity and Improvement of Aortic Distensibility Accompanying Regression of Atherosclerosis in the Rhesus Monkey

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SUMMARY Subclavian-to-femoral artery pulse wave velocity, as a measure of aortic stiffness, was determined in 31 rhesus monkeys (Macaca mulatta) which were divided into three groups on atherogenic progression or regression diets: nine monkeys (IIA) were fed a high cholesterol diet for 38 months, resulting in an average plasma cholesterol concentration of 638 mg/dl; and 10 (IIBi) and 12 (IICi) monkeys were fed the same progression diet followed by 24-month regression diets which were manipulated to maintain plasma cholesterol concentrations as close as possible to 300 and 200 mg/dl, respectively. Average pulse wave velocity at a diastolic blood pressure of 70 mm Hg was significantly greater (9.4 ± 1.0 (mean ± SEM) m/sec) in the IIA group than in the IIBi (6.3 ± 0.3) or IICi (6.6 ± 0.3) groups, although four of the IIA monkeys had pulse wave velocities that were not significantly higher than the regression monkeys. Total thoracic plus abdominal aortic cholesterol concentration was significantly reduced from 10.2 ± 1.4 mg/g wet weight in the IIA group to 5.7 ± 0.8 (IIBi) and 4.6 ± 0.6 mg/g wet weight (IICi). The total percentage of thoracic plus abdominal aortic intimal surface covered with fibrous plus fatty plaque averaged 56.9 ± 9.2% (IIA) vs. 33.5 ± 6.7 (IIBi) and 35.0 ± 7.4% (IICi). Collagen content beneath a given intimal square surface significantly increased from 4.59 ± 0.31 mg/cm² (IIA) to 6.46 ± 0.33 (IIBi) and 6.49 ± 0.48 mg/cm² (IICi), whereas elastin content decreased from 9.47 ± 1.56 (IIA) to 6.58 ± 0.73 (IIBi) and 6.01 ± 0.39 mg/cm² (IICi). There was no significant difference in any parameter between the two regression groups. These studies suggest a functional improvement of aortic elastic properties with regression of atherosclerosis. When comparing groups, the improvement appears to follow the reductions in total aortic cholesterol concentrations and in the extent of total atherosclerotic plaque rather than alterations in the collagen: elastin ratio which, in fact, increased when arterial stiffness decreased with regression. Circ Res 47: 425-432, 1980.

REGRESSION of atherosclerosis has been demonstrated in several studies in which laboratory animals were fed cholesterol-containing atherogenic diets for a period of time followed by diets with reduced cholesterol content (reviewed by Armstrong, 1976; Stary, 1979). These studies have shown that regression can result in reductions in the size of certain kinds of plaques and in the amount of lipids they contain, thus demonstrating morphological and biochemical improvement of the arterial wall. Others have provided angiographic evidence of regression of atherosclerosis, or at least increases in lumen diameter, in human subjects (Blankenhorn, 1977, 1978). However, we know of no controlled investigations of regression of atherosclerosis that have shown functional improvement of the circulatory system in terms of either improved blood flow or improved arterial elastic properties.

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This investigation was supported in part by HL00487 and SCOR Grant HL14164.

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Received October 26, 1979; accepted for publication April 3, 1980.

Altered circulatory function with atherosclerosis usually is thought of in terms of stenotic lesions which impair blood flow, and reductions in the severity of stenosis certainly would be important for improving symptoms associated with atherosclerosis. However, complications of atherosclerosis also include arterial stiffening which can increase systolic blood pressure, vascular impedance, and the load on the heart (Milnor, 1975; O'Rourke, 1967; Taylor, 1967; Urschel et al., 1968). Altered arterial elastic properties also have been shown to affect baroreceptor function (Aars, 1969; Angell-James and Lumley, 1974) and blood pressure and flow pulse wave transmission (O'Rourke, 1968, 1970).

Previous work from this laboratory has shown that arterial pulse wave velocity, which is related to the square root of arterial stiffness, was significantly higher in cynomolgus monkeys (Macaca fascicularis) fed a high cholesterol atherogenic diet for 3 years compared to control monkeys (Farrar et al. 1978). The present study demonstrates that regression of diet-induced atherosclerosis in different nonhuman primate model, the rhesus monkey (Macaca mulatta), results in a reduction of pulse wave velocity and arterial stiffness and therefore results in an improvement of arterial function. In
addition, no further improvement was found in monkeys that underwent lesion regression with serum cholesterol concentrations averaging 200 mg/dl vs. those at 300 mg/dl.

Methods

Experimental Animals

Thirty-one male rhesus monkeys (M. mulatta) were fed for 38 months a semipurified diet containing 45% of the calories from lard and 1 mg of cholesterol/Cal. At the end of this progression phase, nine of these monkeys, which were mature adults approximately 7 years old, were killed for baseline observations (group IIA). The remaining monkeys were divided into two regression groups: 10 (group IIBi) and 12 (group IICi) monkeys which were fed, for the next 24 months, regression diets with varying amounts of added cholesterol manipulated to maintain total mean plasma cholesterol concentration as close as possible to 300 and 200 mg/dl, respectively. These monkeys were approximately 9 years old at the end of the diet period. The mean plasma cholesterol concentrations for these groups during the progression phase were 638 ± 34 (mean ± SEM), 652 ± 47, 632 ± 46 mg/dl for the IIA, IIBi, and IICi groups, respectively. Mean plasma cholesterol concentrations during the regression phase were 324 ± 14 and 201 ± 7 mg/dl for the IIBi and IICi groups, respectively. Mean plasma cholesterol concentrations for these groups during the regression phase were 638 ± 34 (mean ± SEM), 652 ± 47, 632 ± 46 mg/dl for the IIA, IIBi, and IICi groups, respectively. Mean plasma cholesterol concentrations during the regression phase were 324 ± 14 and 201 ± 7 mg/dl for the IIBi and IICi groups, respectively. These animals were a subset of a much larger colony of monkeys, and additional information on the experimental design and lesion induction can be found elsewhere (Clarkson et al., 1979).

Determination of Pulse Wave Velocity

After the 38-month dietary period for the progression phase (group IIA) and after the 38-month progression plus the 24-month regression phase for the IIBi and IICi groups, subclavian-to-femoral artery pulse wave velocity was determined in each monkey after it had been anesthetized with sodium pentobarbital (30 mg/kg, iv). Additional anesthesia was administered intravenously as required during the experiment. Arterial pressure was measured with a Statham P23Db pressure transducer through a 15-cm catheter which was positioned to allow measurement of subclavian artery pressure near the aortic arch. The exact catheter placement was determined at necropsy. A femoral artery pulse was measured noninvasively with an air-filled cup 1.7 cm in diameter covered with a rubber membrane and connected to a Statham P23BB venous pressure transducer. The cup was held in place over the femoral artery with clamps and adjusted for a maximum arterial pulse. The frequency response of each pulse detection recording system was determined with a variable frequency sinusoidal pump or with the “pop” method (McDonald, 1974). Each transducer system was found to be flat to 20 Hz with negligible phase shift. All transducers were connected to a Grass polygraph recorder with identical amplitude response (~6 dB at 60 Hz) and time delay (4.5 msec in the frequency range of 0–20 Hz) in each channel so that the possible error in computing transit time due to the delay through the amplifiers was eliminated. Further information concerning the validity of the noninvasive femoral pulse measurement can be found in a previous report (Farrar et al., 1978).

The outputs of the Grass recorder were sent to a Classic LINC computer which digitized each channel simultaneously at 500 samples/sec. In each experiment, 10–20 individual cardiac cycles, triggered by the R wave of the ECG, were stored for later analysis.

It is assumed for this study that there are two parameters which have a major effect on pulse wave velocity: diastolic blood pressure and severity of atherosclerosis. To compare animals only in terms of atherosclerosis, one needs either to measure all pulse wave velocities in the same pressure range or to correct for the effects of blood pressure. Since it was not always possible to do the former, we adjusted for blood pressure using a linear regression equation which describes the relationship between pulse wave velocity and diastolic blood pressure in control M. fascicularis monkeys (Farrar et al., 1978). This procedure assumes that the pulse wave velocity-diastolic blood pressure relationship in all monkeys, test or control, has the same slope as in these controls. Using this assumption, all data points are moved parallel to this line and averaged at a single diastolic pressure of 70 mm Hg.

In approximately one-half of the regression animals, measurements were possible at two different blood pressures. In these monkeys, data were taken before and after intravenous infusion of sodium nitroprusside at an average rate of 4.6 ± 0.9 (SEM) μg/kg per min, which lowered diastolic pressure by 36.2 ± 4.2 mm Hg from the predrug pressure. In addition, spontaneously varying blood pressure in a single IIA monkey allowed for pulse wave velocity measurements at two pressures.

Pulse wave velocities were determined on the computer by dividing the distance between the transducers by the pulse transit time. The computer program determined the time between the maximum second derivatives of the subclavian and femoral pulses, which corresponded to the velocity of the initial steep rise of the pulse wave immediately after the foot of the pulse. This velocity is the wave front velocity which, like the foot-to-foot velocity, has been shown to be the velocity in the absence of reflections and thus related to the square root of arterial stiffness (McDonald, 1968, 1974). For the purpose of this study, the term aortic pulse wave velocity will represent the velocity over all the arterial segments between the transducers, which
includes the thoracic and abdominal aortas and the iliac artery.

**Anatomical Pathology**

At the time of necropsy, a midline abdominal incision was made, and each monkey was killed by exsanguination through the posterior vena cava. The aorta was dissected from the level of the first intercostal arteries to the iliac bifurcation. This artery then was opened longitudinally along the anterior midline and divided into thoracic and abdominal segments immediately superior to the origin of the celiac artery. Each individual segment then was divided longitudinally along the posterior midline. The left half of each segment was retained for chemical analysis and the right side was fixed flat in 10% neutral buffered formalin. After fixation was complete, the arteries were stained overnight in a saturated solution of Sudan IV in isopropanol. Each segment then was graded for the percentage of intimal surface that contained fatty streaks (flat red-staining lesions), diffuse intimal thickening (flat opaque or white lesions), fatty plaques (raised red-stained lesions), and fibrous plaques (raised opaque or white pearly lesions). The percentage of surface area affected with each of the above lesions was estimated visually with a dissection microscope, by the consensus of two experienced pathologists.

**Angiochemical Evaluation**

Biochemical methods have been described previously in detail (Clarkson et al., 1979). Briefly, arteries were homogenized in chloroform-methanol, and lipids were extracted according to the method of Folch et al. (1957). An aliquot of the lipid extract was used to determine total phospholipid phosphorus. The lipids from another aliquot were separated by chromatography on silica gel G, and nonesterified and esterified cholesterol were quantified. Arterial calcium concentrations were determined by atomic absorption spectrophotometry using 0.1 N HCl extracts of the lipid-free dried arteries. Collagen and elastin were separated by treating the lipid- and mineral-free artery with 0.1 N sodium hydroxide at 98°C for 50 minutes. The alkali-soluble material containing the collagen was hydrolyzed in 6 N HCl for 18 hours and analyzed for the concentration of hydroxyproline by the method of Bergman and Loxley (1963). Collagen concentrations were calculated by assuming that arterial collagen contained 12.9% hydroxyproline (Jackson and Cleary, 1967). Elastin was determined by weighing the alkali-insoluble residue. The results of all angiochemical observations were expressed as concentration (mass per unit weight) and content (mass per unit area).

**Statistical Analysis**

Statistical comparisons between groups were done by analysis of variance followed by Scheffe's method for multiple comparisons of population means (Bancroft, 1968).

**Results**

**Pulse Wave Velocity and Blood Pressure**

Measurement of pulse wave velocity as a function of diastolic blood pressure for the monkeys in all three groups shows that values for five of the nine monkeys in the IIA group were clearly greater than those of any of the animals from either the IIBi or IICi groups (Fig. 1). However, pulse wave velocities from the remaining four IIA animals were indistinguishable from those of the IIBi or IICi animals. No control rhesus monkeys were available, but to put these data in perspective with data from other experiments, the linear regression line representing the control relationship between pulse wave velocity and blood pressure is shown for another species of macaque, *M. fascicularis* (Farrar et al., 1978). All IIBi and IICi animals under either nitroprusside or predrug conditions were in the range of these control data, and the pulse wave velocity data from the rhesus animals also exhibited a correlation with diastolic blood pressure.

Without adjustment for blood pressure, the IIA group pulse wave velocity averaged 10.6 ± 1.2 m/
sec at a diastolic pressure of 97.8 ± 7.1 mm Hg, compared to prenitroprusside averages of 7.2 ± 0.4 m/sec at 92.9 ± 5.0 mm Hg for the IIBi group and 7.2 ± 0.5 m/sec at 88.3 ± 6.5 mm Hg for the IICi group. Pulse wave velocity was significantly (P < 0.01) lower in the IIBi and IICi groups than in the IIA group, whereas there was no difference in diastolic blood pressure. The data adjusted to a diastolic pressure of 70 mm Hg (Fig. 2) also show that monkeys in the IIBi group (6.3 ± 0.3 m/sec) and IICi group (6.6 ± 0.3 m/sec) had significantly lower pulse wave velocities than the IIA group (9.4 ± 1.0 m/sec). No differences were found between monkeys that underwent lesion regression with plasma cholesterol concentrations of 300 mg/dl (IIBi) or 200 mg/dl (IICi).

Blood pressure measurements taken approximately 1 hour after the initial anesthetic dose of pentobarbital did not reveal any significant differences for mean or diastolic blood pressures between any of the groups of monkeys. Systolic blood pressure in the IIA group averaged 158 ± 12 mm Hg compared to the IIBi (127 ± 7) and IICi (128 ± 10) groups, but these differences were also not significant (0.05 < P < 0.10). However, the pulse pressure was significantly greater in the IIA animals (60.0 ± 6.1 mm Hg) than in the IIBi (34.0 ± 2.7) or IICi (39.5 ± 3.0) animals (Fig. 3).

**Angiochemical Findings**

Total cholesterol in the thoracic and abdominal aortic walls, whether expressed on a content or concentration basis, was significantly less in the IIBi and IICi groups, compared to the IIA group (Fig. 4). Average thoracic and abdominal aortic collagen was significantly greater in the two groups than underwent lesion regression than in the IIA group, whereas elastin was significantly reduced (Fig. 5). The collagen: elastin ratios for the combined thoracic plus abdominal aortas were significantly (P < 0.01) greater in the IIBi (1.38 ± 0.16) and IICi (1.48 ± 0.24) groups than in the IIA (0.62 ± 0.07) group. No significant difference was found between the IIBi and IICi animals in either cholesterol, collagen, or elastin.

**Morphological Findings**

The percentage of the intimal surface covered with atherosclerotic lesions revealed no significant differences among the groups except for a smaller (P < 0.05) amount of fatty plaque in the IICi group compared to the IIA group (Fig. 6). In general, however, the total amount of fibrous plus fatty plaque (total raised lesions) was less in the IIBi and
Discussion

This study suggests that there is a functional improvement of aortic elastic properties with regression of atherosclerosis in the rhesus monkey. Pulse wave velocity was reduced on the average by approximately 30–35% with regression, which implies a 50–55% reduction in arterial stiffness since pulse wave velocity is related to the square root of stiffness. This improvement also resulted in a 35–45% reduction in pulse pressure which is a logical consequence of reduced arterial stiffness assuming constant stroke volume. The changes in elasticity accompanied reductions in total cholesterol in the arterial wall with increases in collagen and decreases in elastin. No further improvement was found in the monkeys which underwent atherosclerosis regression with plasma cholesterol levels at 200 mg/dl vs. those at 300 mg/dl.

The exact relationship between changes in the severity of atherosclerosis and resultant changes in pulse wave velocity and arterial stiffness still is not clear. Previous studies have shown that increases in stiffness with atherosclerosis in cynomolgus monkeys appeared to be due mainly to increases in wall thickness and not to measurable changes in the elastic modulus (Farrar et al., 1978). However, others have found increases in the tangential elastic modulus with atherosclerosis in rabbits (Band et al., 1973) and a correlation between tangential elastic modulus and increased cholesterol esters also in rabbits (Pynadath and Mukharjee, 1977). Newman et al. (1971) provided evidence in cockerels that arteries may become more compliant in the earliest stages of the disease and then become stiffer later on due to increased calcification and fibrosis. However, a study by Nakashima and Tanikawa (1971) suggested that arterial stiffening in humans increases with age but is independent of the severity of atherosclerosis.

The ratio of collagen to elastin has been proposed as an index of the relative stiffness of functionally different arteries (Fischer and Llaurado, 1966). Indeed, increases in arterial stiffness with distance from the heart appear to follow closely the corresponding increases in the collagen: elastin ratio. Other studies also have found close relationships between changes in the collagen: elastin ratio and passive mechanical properties with age and growth in rat carotid arteries (Cox, 1977, 1978). However, Cox (1979) found no difference in the collagen: elastin ratio in spontaneously hypertensive and normotensive rats even though the arteries from the hypertensive rats were stiffer. In addition, atherosclerotic dog arteries were found to be stiffer than
controls even though the collagen: elastin ratio was decreased in the carotid and slightly increased in the iliac arteries (Cox and Detweiler, 1979).

The present study also suggests that the collagen: elastin ratio as an index of arterial stiffness does not apply to atherosclerotic arteries that have undergone regression. In this study, the collagen: elastin ratio of the combined thoracic and abdominal aortas increased from approximately 0.6 in the atherosclerotic aortas of rhesus monkeys to 1.4 after regression, when pulse wave velocity decreased from approximately 9.4 to 6.5 m/sec with regression. Some of the increase in collagen may be due to the 2 years of aging during the regression period. However, since all the monkeys were mature adults, most of the increase must be attributed to regression of atherosclerosis. This increase compares with results of our previous studies in M. fascicularis in which the combined thoracic and abdominal aortic collagen: elastin ratio was only slightly larger in the atherosclerotic aortas (0.7) than in the control aortas (0.6), whereas the aortic pulse wave velocities were much higher (11.7 vs. 7.1 m/sec) (Farrar et al., 1978). Therefore, no clear relation between the collagen: elastin ratio and aortic stiffness was found in either atherosclerotic M. mulatta or M. fascicularis. As was noted in our earlier report, new collagen and elastin with atherosclerosis probably do not result in a functional network of connective tissue which contributes in a consistent manner to arterial elasticity. In addition, the large amount of type I collagen that is synthesized in plaques (McCullagh and Balian, 1975) may contribute differently from the normal type III collagen to arterial elastic properties. Therefore, the total content or concentration of these proteins appears to have little direct relationship with arterial stiffness during the progression and regression of atherosclerosis.

The rhesus (M. mulatta) monkeys in the present study and the cynomolgus (M. fascicularis) monkeys from our previous study were fed the same atherogenic diet for 3 years. The extent and severity of aortic atherosclerosis were greater in the cynomolgus monkeys than in the rhesus monkeys, both in terms of morphological and angiochemical findings. Approximately 90% of the aortic intimal surface of cynomolgus macaques was covered with fatty or fibrous plaque, compared with roughly 55% in the rhesus monkeys. Total cholesterol concentration was approximately 200 mg/g wet weight for the cynomolgus monkeys compared to 10 mg/g wet weight for the rhesus monkeys. The species difference also was detected in pulse wave velocity which averaged 11.7 m/sec in the cynomolgus macaques compared to 9.4 m/sec in the rhesus monkeys. All of the cynomolgus monkeys had pulse wave velocities greater than the controls, whereas pulse wave velocities from only five out of nine rhesus monkeys were greater than that from any of the animals that underwent lesion regression. The pulse wave velocity of about 6.5 m/sec in the two rhesus groups after regression for 24 months was in the same range as the cynomolgus control monkeys of about 7 m/sec. Even though there were no pulse wave velocity data from control rhesus monkeys, it is unlikely that they would be much different from control data from other macaques such as M. fascicularis. It would appear then that pulse wave velocity and thus arterial stiffness in the atherosclerosis regression groups have returned to control levels in spite of (1) altered collagen and elastin, (2) a still-elevated thoracic and abdominal aortic total cholesterol concentration of 5 mg/g wet weight compared to M. fascicularis controls of roughly 1.4 mg/g and M. mulatta controls of 1.7 mg/g (Clarkson et al., 1979), and (3) fatty and fibrous plaques still covering approximately 35% of the intimal surface area.

No further change in arterial stiffness was found in the monkeys with plasma cholesterol concentrations during the atherosclerosis regression phase of 200 mg/dl vs. those at the higher level of 300 mg/dl. However, in a similar study in monkeys with less severe atherosclerosis (19-month, rather than 38-month, progression but with the same 24-month regression period), there were detectable differences in total aortic cholesterol in animals at 200 mg/dl vs. those at 300 mg/dl (Wagner and St. Clair, 1979). This would imply that less severe lesions are more likely to improve at the lower plasma cholesterol concentration of 200 mg/dl, whereas more advanced lesions may not respond selectively to the different regression diets. However, pulse wave velocity and arterial stiffness probably would not be any lower in these other monkeys than in those in the present study since the pulse wave velocity already had returned to control levels in both the II B1 and II C groups.

We are not certain why four of the II A rhesus monkeys did not have elevated pulse wave velocities since, in angiochemical and morphological terms, the aortas from these monkeys were similar to the other five with elevated pulse wave velocities. One possibility is that, since the rhesus monkeys do not develop as much atherosclerosis and as much medial damage underlying the lesion as the cynomolgus monkeys, there may be more variability in the rhesus monkeys in the amount of stiffening that affects the whole arterial segment. For example, a major focal lesion on an otherwise normal vessel may have little effect on the overall pulse wave velocity, although it may increase the vessel stiffness at that one location. On the other hand, more diffuse atherosclerosis affecting the whole artery may indeed increase pulse wave velocity. Thus, normal pulse wave velocity does not necessarily indicate the absence of disease, but elevated pulse wave velocity strongly suggests abnormal stiffening associated with atherosclerosis.

Although we still are not certain of the exact
mechanisms involved in producing elevated stiffness and pulse wave velocity with atherosclerosis, our studies in two nonhuman primate models (M. mulatta in the present study and M. fascicularis in Farrar et al., 1978) suggest that a certain amount of disease must be present before any changes can be detected. These studies also suggest that pulse wave velocity appears to be related best to the extent of atherosclerotic plaque involvement, to the concentration of cholesterol in the arterial wall, and to arterial wall thickness. If we assume that the functional properties of regressed atherosclerotic plaques are similar to those from progressed lesions, which may not be the case, then we can speculate that subclavian-to-femoral artery pulse wave velocity stays roughly constant until the total amount of fibrous plus fatty plaques reaches about 35% of the intimal surface and the total cholesterol concentration of the thoracic and abdominal aorta reaches about 6 mg/g (Figs. 8 and 9). Then, as the extent of the disease increases with more plaque and more arterial wall cholesterol, pulse wave velocity increases above these control values. Conversely, with regression of atherosclerosis, total plaque and total cholesterol are reduced along with concomitant reductions in, or “regression” of, pulse wave velocity. Further information is needed to fill in the missing data on progressing atherosclerosis to determine if this speculative relationship is correct. Since pulse wave velocity can be determined noninvasively as well as invasively, this technique provides a method of following the progression and regression of atherosclerosis in animal models and in humans in response to dietary, pharmacological, or other therapeutic intervention.

Acknowledgments

We acknowledge the valuable technical assistance of Betsy Vestal with the computer programs, the assistance of Jim Riveneaux, Rick Mackenzie, Dr. Roberto Gobbee, Bob Cook, and Janet Taxis with the experiments and the analysis of the data, and that of Thelma Reid with typing and preparation of the manuscript.

References

Band W, Goedhard WJA, Knoop AA (1973) Comparison of effects of high cholesterol intake on viscoelastic properties of the thoracic aorta in rats and rabbits. Atherosclerosis 18: 163–171
Farrar DJ, Green HD, Bond MG, Wagner WD, Gobbee RA (1978) Aortic pulse wave velocity, elasticity, and composition

FIGURE 8  Relationship between subclavian-to-femoral artery pulse wave velocity at 70 mm Hg and total cholesterol concentration in the thoracic plus abdominal aorta (mean ± SEM). See legend, Figure 8.
Fischer GM, Llaurado JG (1966) Collagen and elastin content in
canine arteries selected from functionally different vascular
Folch J, Lees M, Stanley GHS (1957) A simple method for the
isolation and purification of total lipids from animal tissues. J
Biol Chem 226: 497–509
Jackson DS, Cleary EG (1967) The determination of collagen
and elastin. Methods Biochem Anal 50: 25–76
McCullagh KA, Balian G (1975) Collagen characterisation and
75
McDonald DA (1968) Regional pulse wave velocity in the arterial
McDonald DA (1974) Blood Flow in Arteries. Baltimore, the
Williams & Wilkins Co.
Milnor WR (1975) Arterial impedance as ventricular afterload.
Circ Res 36: 565–570
distensibility with relation to atherosclerosis and aging. An-
giology 22: 477–490
Newman DL, Gosling RG, Bowden, NLR (1971) Changes in
aortic distensibility and area ratio with the development of
atherosclerosis. Atherosclerosis 14: 231–240
O'Rourke MF (1967) Steady and pulsatile energy losses in the
systemic circulation under normal conditions and in simulated
Circ Res 27(suppl II): 123–133
O'Rourke MF, Blazek JV, Morreels CL, Krovetz LJ (1968)
Pressure wave transmission along the human aorta: Changes
with age and in arterial degenerative disease. Circ Res 23:
567–579
Pynadath TL, Mukherjee DP (1977) Dynamic mechanical prop-
erties of atherosclerotic aorta: A correlation between the cho-
lesterol ester content and the viscoelastic properties of the
atherosclerotic aorta. Atherosclerosis 26: 311–318
Stary HC (1979) Regression of atherosclerosis in primates. Vir-
Taylor MG (1967) The elastic properties of arteries in relation
to the physiological function of the arterial system. Gastro-
enterology 52: 358–364
Urschel CW, Covell JW, Sonnenblick EH, Ross J Jr, Brauwald
E (1968) Effects of decreased aortic compliance on perform-
ance of the left ventricle. Am J Physiol 214: 288–304
Wagner WD, St. Clair RW (1979) A comparison of the regression
of moderate and more advanced atherosclerosis in monkeys
at plasma cholesterol concentrations of 200 or 300 mg/dl
(abstr). Fed Proc 38: 1347
Reduction in pulse wave velocity and improvement of aortic distensibility accompanying regression of atherosclerosis in the rhesus monkey.
D J Farrar, H D Green, W D Wagner and M G Bond

Circ Res. 1980;47:425-432
doi: 10.1161/01.RES.47.3.425

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7330. Online ISSN: 1524-4571

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