Journal of the American Association for Laboratory Animal Science
Copyright 2011
by the American Association for Laboratory Animal Science

Vol 50, No 1
January 2011
Pages 79–83

# Harmonic Analysis of Noninvasively Recorded Arterial Pressure Waveforms in Healthy Bonnet Macaques (*Macaca radiata*)

**Oladipupo Olafiranye,[1] Louis Salciccioli,[1] Haroon Kamran,[1] Mark Stewart,[2] John Carter,[1] and Jason M Lazar[1,3,*]**

**To characterize primate arterial waveforms, we prospectively studied 38 bonnet macaques (*Macaca radiata*; 25 female, 13 ± 4 y). Brachial artery waveforms were recorded from these animals by applanation tonometry and were decomposed into harmonics by using Fourier analysis. The ratio of individual to total harmonic amplitude (H:T) was derived from frequency spectra. Left ventricular (LV) mass, ejection fraction, fractional shortening, septal wall thickness, posterior wall thickness, LV end-diastolic diameter, and LV end-systolic diameter were obtained by echocardiography in all 38 monkeys. Blood pressure was obtained by sphygmomanometry. The fundamental frequency was 2.76 cycles/s. Harmonics ranged from 5 to 14. Indexed LV mass was inversely correlated with third H:T and second H:T but not with systolic or diastolic blood pressure. In addition, the third H:T was inversely correlated with septal wall thickness, posterior wall thickness, and LV end-diastolic diameter, whereas second H:T was inversely correlated with LV end-diastolic diameter. Heart rate was inversely correlated with eighth H:T. On multivariate analysis adjusting for age, gender, weight, and length, only third H:T was an independent predictor of LV mass. Harmonic analysis of arterial waveforms may provide information pertaining to LV mass. Lower H:T ratios (second and third) are related to LV mass, whereas higher H:T (eighth) is related to heart rate.**

**Abbreviations:** H:T, ratio of the individual harmonic to the total harmonic amplitude; LV, left ventricular.

Nonhuman primates have long served as models for human cardiovascular and metabolic diseases.[9,40,43] Most studies have been performed under specific laboratory conditions such as single housing, with limited access to physical activity or dietary manipulations intended to cause diseases such as atherosclerosis or obesity. Macaques are one of the most widely studied species because they are anatomically similar to humans and exhibit similar cardiovascular physiology and metabolism. Macaques have been used in studies pertaining to aging, diabetes, obesity, and cardiac regeneration.[21,32,36,37]

In recent years, the growing use of applanation tonometry has revived interest in deriving qualitative and quantitative information from noninvasively obtained arterial waveforms.[28,29] Arterial applanation tonometry allows noninvasive and continuous recording of the arterial pressure waveform by using an external transducer to applanate (flatten) a superficial artery supported by bone. This technology commonly involves the application of mathematical transfer function to a peripheral waveform in order to derive the central aortic pressure waveform.[3,16] The transfer function, which is based on harmonic analysis, has been validated for humans but not nonhuman primates. Multiple studies performed over the past several decades have found the contour of the arterial waveform to provide information about the cardiovascular system.[1,2,5,6,8] Specifically, the harmonic components of arterial waveforms obtained from the cardiovascular, cerebrovascular, respiratory, peripheral, and ophthalmic beds provide physiologic information beyond that of blood pressure measurement alone.[1,2,5,6,8,14,24,31,35,38] Various harmonic amplitudes obtained by Fourier transfer are associated with several cardiovascular abnormalities.[10,25,33,39,42] Fast Fourier transformation is a mathematical algorithm that recreates the original pressure wave by summing a series of simple sine waves of various amplitudes and frequencies (that is, harmonics).[5] Fourier analyses converts the conventional arterial waveform in the time domain to harmonics in the frequency domain, which typically are displayed as spectra of amplitude plotted as a function of frequency. This analytical technique also has been used to calculate impedance from simultaneously recorded blood pressure and arterial flow.[28] Frequency domain analysis takes into account systemic vascular impedance, blood viscosity, vascular compliance, blood volume, and heart rate because these parameters determine the shape of the arterial pressure waveform. Therefore, the amplitudes of various harmonics would change in response to ventricular and arterial related factors that alter the arterial waveform.

Hypertension is uncommon in nonhuman primates.[11,26] In most primate species, blood pressure remains low. However, the significance of the arterial wave morphology is unknown in primates. Accordingly, the objective of the present study was to characterize noninvasively recorded arterial waveforms in apparently healthy, socially raised and housed bonnet macaques (*Macaca radiata*) and to assess relations between harmonics and cardiovascular variables.

## Materials and Methods

Characteristics of the State University of New York Downstate Medical Center primate colony have been described previously.[17] The colony currently consists of 125 laboratory-born and raised bonnet macaques (*Macaca radiata*) living in social groups of 6 to 10 and maintained on standard commercial monkey chow. All procedures were performed in careful conformance

*Received: 03 Feb 2010. Revision requested: 12 Mar 2010. Accepted: 24 May 2010.*
*[1]Division of Cardiovascular Medicine, [2]Department of Physiology and Pharmacology, and [3]Primate Behavior Laboratory, Department of Psychiatry, State University of New York, Downstate Medical Center, Brooklyn, New York.*
*[*]Corresponding author. Email: jason.lazar@downstate.edu*

with the *Guide for the Care and Use of Laboratory Animals*.[13] The State University of New York Downstate Medical Center Division of Laboratory Animal Research approved this prospective study. We studied 38 bonnet macaques (25 female, 13 male; mean age, 13 ± 4 y) that had no recent or ongoing participation in physiologic or pharmacologic studies.

**Laboratory methods.** ***Morphometry.*** Anesthesia was administered by using intramuscular ketamine (15 mg/kg) as clinically indicated to achieve sedation throughout the procedure. Immediately after sedation, each monkey was weighed; crown–rump length was measured; and heart rate, systolic blood pressure, and diastolic blood pressure were recorded by sphygmomanometry of the right lower extremity. Body mass index was calculated for all monkeys by dividing weight in kilograms by the square of the crown–rump length in meters.[15] The body surface area of each monkey was calculated by using a previously published formula.[22]

***Arterial tonometry.*** Applanation tonometry was performed in all 38 monkeys according to previously published techniques[13] by using a pulse-wave analysis system (SphygmoCor applanation tonometer interfaced with SphygmoCor software, version 81; AtCor Medical, New South Wales, Australia). The tonometry transducer was applied to the brachial artery of all monkeys studied, and continuous arterial waveforms were displayed instantaneously on a laptop connected to the pulse wave analysis system. Arterial waveforms were considered technically adequate if all of the following criteria were met: consistency and large amplitude of pulse height, presence of diastolic decay, and morphology maintained for 10 s. For each monkey, arterial waveforms were recorded for 10 s, corresponding to an average of 28 arterial waveforms per monkey given the average heart rate of 166 bpm in the cohort. The signal from the probe was amplified, filtered and digitized to 12 bits at a frequency of 128 samples per second, and transferred by USB interface to a laptop. The applanation tonometer uses a 0.67- to 40-Hz bandpass filter to minimize both group delay and distortion. The highest frequencies we recorded were an octave lower than the upper end of the tonometer's passband. For this reason, the filter settings did not affect the waveform morphology or harmonic components. The data were stored as a set of vectors in an Excel (Microsoft, Redmond, WA) file for later processing. Signal processing was performed by using a program running under MATLAB (MathWorks, Natick, MA). The program reads the Excel (Microsoft) file, displays the original waveforms, and calculates the amplitude spectrum. The determination of the spectrum was made by performing discrete Fourier transform individually on each signal vector and calculating the absolute value of the transform. The amplitude spectrum is the original signal in the frequency domain and contains the signals' constituent frequencies and their amplitudes. In addition, the relative amplitudes of the first 7 harmonics were tabulated and displayed. The amplitude of additional harmonics was measured by moving a cursor over the harmonic's peak in the displayed spectrum. The ratio of individual harmonic amplitude to the total amplitude (H:T) was derived for each decomposed wave.

***Echocardiography.*** Echocardiography (model Sonos 5500 machine with a 3.5- to 5.5-MHz transducer, Phillips, Andover, MA) was performed in all 38 monkeys by an experienced echocardiographer. Each study was inspected carefully to assure optimal imaging and was recorded on high-definition video tapes. Standard echocardiographic images were obtained. Left ventricular (LV) dimensions were measured from M-mode and 2-dimensional parasternal long-axis and apical 4-chamber axis images according to American Society of Echocardiography standards.[19,21] Three measurements were taken, and average values were recorded. LV mass and ejection fraction were calculated by the American Society of Echocardiography-corrected cube formula.[19,21] LV mass indexed by body surface area, fractional shortening, septal wall thickness, posterior wall thickness, LV end-diastolic diameter, and LV end-systolic diameter were determined for each monkey.

**Statistics.** Continuous variables were expressed as mean ± 1 SD. Univariate associations between variables were analyzed by using Spearman univariate correlation coefficients. Multiple linear regression analysis adjusted for significant univariate predictors was used to determine independent correlates of LV mass. All analyses were performed by using Statistical Package for Social Sciences (SPSS) version 16.0 (SPSS, Chicago, IL). A $P$ value less than 0.05 was considered to be statistically significant.

## Results

Clinical and echocardiographic values for all the monkeys are presented in Figure 1. The colony studied was a predominantly female (66%) population of adult bonnet macaques. The total number of harmonics ranged from 5 to 14 harmonics, with an interquartile range of 7 to 10. Whereas 53% of the total amplitude of the harmonics was contained in the fundamental frequency, an additional 21% and 8% were in the first and second harmonics, respectively; 95% of the total amplitude was contained within the fundamental and first 5 harmonics. The arterial pressure waveform in the time domain and its harmonic components in the frequency domain of a 10-y-old monkey are shown in Figure 2.

Unadjusted LV mass was inversely correlated with third H:T ($r = -0.52$, $P = 0.001$; Figure 3) and second H:T ($r = -0.38$, $P = 0.02$). LV mass index was inversely correlated with third H:T ($r = -0.53$, $P = 0.001$) and second H:T ($r = -0.35$, $P = 0.048$) but not with systolic blood pressure ($r = -0.04$, $P = 0.84$) or diastolic blood pressure ($r = 0.04$, $P = 0.83$). The third H:T also was inversely correlated with septal wall thickness ($r = -0.41$, $P = 0.01$), posterior wall thickness ($r = -0.41$, $P = 0.01$), and LV end-diastolic diameter ($r = -0.49$, $P = 0.002$), whereas second H:T was inversely correlated with LV end-diastolic diameter ($r = -0.38$, $P = 0.02$; Table 1). Heart rate was inversely correlated with the eighth H:T ($r = -0.42$, $P = 0$ 0.035) but not the total number of harmonics ($r = 0.00$, $P = 1.0$). On multivariate analysis adjusting for age, gender, weight, and crown–rump length, third H:T was an independent predictor of LV mass ($\beta = -54.14$, $P = 0.03$).

## Discussion

In the present study, we performed harmonic analysis of noninvasively recorded brachial arterial waveforms by using applanation tonometry. Given that 95% of the total harmonic amplitude is contained within the first 5 harmonics, the frequency spectra of nonhuman primates appears to be similar to that previously reported in humans.[23] By using Fourier analysis, the arterial blood pressure waveform can be decomposed into its fundamental and its harmonics. Because the LV ejects blood into the arterial system, it seemed likely to us that various harmonics would reflect LV structure and function. We found that the ratios of lower harmonics amplitude to total harmonic amplitude (second and third H:T) were related to LV mass, whereas the higher harmonics amplitude ratio (eighth H:T) was related to heart rate. In addition, LV mass was unrelated to blood pressure measured by sphygmomanometry.

| | |
|---|---|
| Age (y) | 13 ± 4 |
| Weight (kg) | 8.5 ± 3.8 |
| Body surface area (m$^2$) | 0.29 ± 0.07 |
| Crown–rump length (m) | 0.47 ± 0.04 |
| Body mass index (kg/m$^2$) | 38 ± 11 |
| Systolic blood pressure (mm Hg) | 109 ± 16 |
| Diastolic blood pressure (mm Hg) | 62 ± 5 |
| Heart rate (beats/min) | 166 ± 34 |
| Left ventricular mass (g) | 12.3 ± 4.4 |
| Septal wall thickness (cm) | 0.40 ± 0.06 |
| Posterior wall thickness (cm) | 0.39 ± 0.06 |
| Left ventricular end-diastolic diameter (cm) | 1.78 ± 0.28 |
| Left ventricular end-systolic diameter (cm) | 0.91 ± 0.28 |
| Fractional shortening (%) | 49 ± 11 |
| Left ventricular ejection fraction (%) | 73 ± 12 |

**Figure 1.** Clinical and echocardiographic measurements (mean ± 1 SD) in adult bonnet macaques.

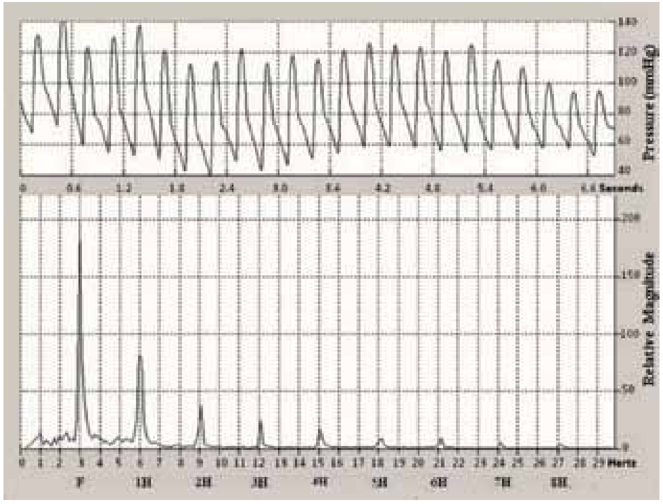


**Figure 2.** The arterial pressure waveform (above) and its harmonic (below) of a 10-y-old monkey.

Although the use of applanation tonometry to measure arterial stiffness and wave reflection has grown in recent years, we are aware of only 2 prior studies using this technique to assess arterial stiffness in monkeys.[20,40] In one,[40] the carotid artery in 6 older rhesus monkeys was assessed to determine the effects of a thiazolium on arterial properties in old, healthy *Macaca mulatta* primates. In the other study,[20] our group found applanation tonometry feasible for recording pressure waveforms from the carotid, brachial, and axillary arteries in 61 bonnet macaques. Although the augmentation index, a measure of arterial wave reflection and compliance, was found to correlate with LV mass, the transfer function by which this index was derived has been validated in humans but not in primates.[20] In addition, augmentation index was largely determined by heart rate, which varies greatly in nonhuman as compared with human primates. Neither study assessed the harmonic components directly. Consequently, we here performed harmonic analysis of the arterial waveform in a similar manner to that performed in humans over the past several decades,[5,35] to provide information about the cardiovascular system beyond blood pressure measurement alone.

We recorded arterial waveforms from the macaque brachial artery because of its close proximity to the aortic arch and because of the high yield of technically adequate waveforms.[20] Decomposition of the brachial artery pressure waveform yielded 5 to 14 harmonics, with an interquartile range of 7 to 10; 95% of

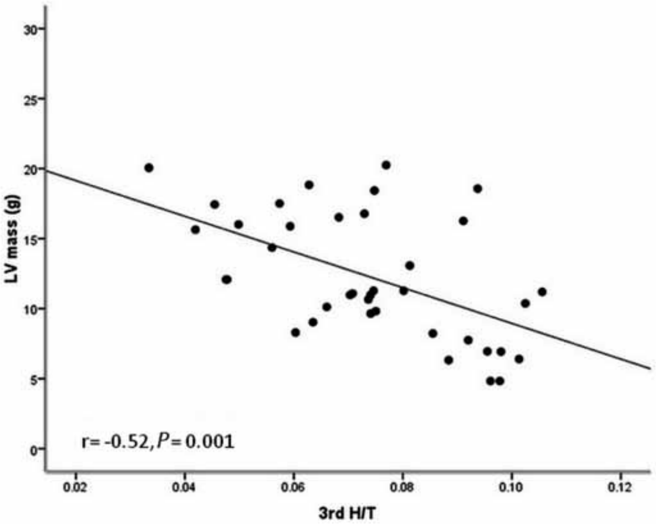


**Figure 3.** Relation between LV mass and the ratio of third over total harmonic amplitude (third H:T).

the total amplitude was represented by the first 5 harmonics. This finding is similar to that previously found in humans,[23] although the number of harmonics analyzed was limited to the first 10 in that earlier study. Therefore, despite differences in size, heart rate, and hip flexion, which all may affect arterial waveform reflection, the overall distribution of harmonics appears similar in human and nonhuman primates.

Harmonic analysis has been used once in primates to assess LV pressure waveforms derived by cardiac catheterization.[25] Among 37 rhesus monkeys, various harmonic contents were correlated with contractility indices whereas others correlated with LV loading indices.[25]

Several lines of evidence suggest that the third harmonic represents arterial compliance. In a rat model, bending the aorta to yield transverse displacement decreased blood pressure with a maximal drop in the second and third harmonics.[12] Similarly, in another study,[7] clamping the femoral artery produced large variations in only the third harmonic of the pressure wave. In studies of dogs and wombats,[34] the third harmonic was determined to be the dominant harmonic of the flow wave, given that it corresponded to the pronounced diastolic flow wave, and the authors proposed the frequency of the third harmonic to be the natural frequency of arterial waveform. In a study of 94 human patients with suspected peripheral arterial disease, only the third harmonic derived from electrical impedance rheographic signals was predictive of significant obstructive disease.[38] Among 10 survivors of acute myocardial infarction, changes in effective renal plasma flow over 1 wk were correlated strongly with changes in the third harmonic.[4] Moreover, among 59 patients with hypertension, the ratio of the change in the third harmonic relative to the change in the first harmonic was related to LV mass reduction after 1 y of antihypertensive therapy;[10] of note, LV mass reduction was not related to the drop in blood pressure in that study. The dominance of the third harmonic in these studies may relate to its relation with forward (LV ejection) as well as reflected (arterial) pressure waves. Indeed, although most of the spectral power is contained in the fundamental and first harmonic, the second and third harmonics have long been considered the main accumulators of energy of the pulse wave.[30]

There was no significant correlation between LV ejection fraction or fractional shortening and any of the harmonic ratios. This finding was surprising, given that the arterial waveform

**Table 1.** Correlations between echocardiographic indices and harmonic amplitude ratios

| | | 1st H:T | 2nd H:T | 3rd H:T | 4th H:T | 5th H:T | 6th H:T | 7th H:T | 8th H:T |
|---|---|---|---|---|---|---|---|---|---|
| Left ventricular mass | *r* | 0.15 | –0.38 | –0.52 | 0.05 | –0.32 | 0.05 | 0.18 | 0.16 |
| | *P* | 0.36 | 0.02[a] | 0.001[a] | 0.75 | 0.051 | 0.77 | 0.35 | 0.45 |
| Left ventricular mass index | *r* | 0.12 | –0.35 | –0.53 | –0.26 | –0.28 | –0.21 | –0.07 | 0.05 |
| | *P* | 0.49 | 0.048[a] | 0.001[a] | 0.15 | 0.12 | 0.24 | 0.73 | 0.82 |
| Septal wall thickness | *r* | 0.25 | –0.24 | –0.41 | –0.08 | –0.26 | 0.02 | –0.01 | –0.09 |
| | *P* | 0.13 | 0.15 | 0.01[a] | 0.64 | 0.11 | 0.90 | 0.97 | 0.69 |
| Posterior wall thickness | *r* | 0.11 | –0.24 | –0.41 | 0.05 | –0.23 | 0.08 | 0.17 | –0.07 |
| | *P* | 0.53 | 0.15 | 0.01[a] | 0.75 | 0.16 | 0.60 | 0.36 | 0.73 |
| Left ventricular end–diastolic diameter | *r* | 0.05 | –0.38 | –0.49 | 0.07 | –0.29 | 0.01 | 0.14 | 0.28 |
| | *P* | 0.76 | 0.02[a] | 0.001[a] | 0.68 | 0.08 | 0.95 | 0.48 | 0.19 |
| Left ventricular end–systolic diameter | *r* | 0.05 | –0.31 | –0.24 | 0.03 | 0.18 | –0.08 | 0.25 | 0.22 |
| | *P* | 0.77 | 0.06 | 0.14 | 0.88 | 0.28 | 0.63 | 0.19 | 0.30 |
| Fractional shortening | *r* | 0.10 | 0.19 | 0.02 | 0.09 | 0.11 | 0.09 | –0.12 | 0.18 |
| | *P* | 0.56 | 0.27 | 0.92 | 0.60 | 0.50 | 0.60 | 0.31 | 0.51 |
| Left ventricular ejection fraction | *r* | –0.10 | 0.18 | 0.02 | 0.08 | 0.11 | 0.09 | –0.12 | –0.21 |
| | *P* | 0.55 | 0.27 | 0.92 | 0.64 | 0.51 | 0.60 | 0.52 | 0.33 |
| Heart rate | *r* | 0.03 | 0.24 | 0.29 | –0.11 | 0.19 | –0.26 | –0.18 | –0.46 |
| | *P* | 0.88 | 0.13 | 0.09 | 0.55 | 0.29 | 0.14 | 0.37 | 0.035[a] |

H:T, ratio of individual harmonic amplitude to total amplitude
[a]*P* values of ≤ 0.05 are significant.

is composed of a primary wave generated by LV contraction and secondary wave due to waveform reflection. Whether other indices of LV function including change in pressure relative to time are related to various arterial harmonics remains unclear. The finding that LV mass index was unrelated to blood pressure is consistent with prior studies[21,27] and may relate to the narrow range of blood pressure in bonnet macaques.

The present study is associated with various limitations. This study is a cross-sectional study of apparently healthy bonnet macaques. All measurements were obtained during sedation with ketamine. Although anesthetic agents are known to influence LV performance, ketamine has been shown to have minimal effects on cardiac contractility and heart rate.[18] The mean heart rate of our macaques was similar to that observed in other monkey experiments. Similar LV wall thicknesses have been obtained from rhesus monkeys sedated with ketamine and with a combination of Telazol and isoflurane.[18] LV mass was based on measurements from the parasternal view, which was easily obtained in all of the animals. Other indices derived from applanation tonometry reflecting cardiac workload were not assessed. Arterial flow was not measured, and therefore impedance indices (the ratios of the harmonics of pressure to the harmonics of flow) could not be calculated. Respiratory variations in the arterial pressure waveforms could not be avoided completely, but arterial waveforms were considered technically adequate and were captured if all of the following criteria were met: consistency and large amplitude of pulse height, presence of diastolic decay, and morphology maintained for 10 s. Arterial properties were not assessed by a different technique, such as biopsy, to determine the direct effects of arteriopathy on specific harmonics. These results may not be referable to other arterial sites, given that the frequency spectra of different arterial beds can vary significantly.[7,41,44]

Harmonic analysis of noninvasively recorded arterial waveform may provide information pertaining to LV mass. Although the ratios of lower harmonics amplitude to total power (second and third H:T) were related to LV mass, higher harmonics amplitude ratio (eighth H:T) was related to heart rate. This study is the first to have evaluated harmonic analysis of noninvasively derived arterial waveform in bonnet macaques. The relative contribution of LV and arterial properties merits further study, as does extension of this approach to human subjects to derive information about LV mass. Subsequent studies might evaluate the utility of harmonic components of pressure and flow waveforms to derive impedance measures.

## References

1. **Attinger EO, Anne A, McDonald DA.** 1966. Use of Fourier series for the analysis of biological systems. Biophys J **6:**291–304.
2. **Burattini R, Campbell KB.** 1999. Assessment of aortic pressure power components and their link to overall elastic and resistive arterial properties. Med Biol Eng Comput **37:**366–376.
3. **Chen CH, Nevo E, Fetics B, Pak PH, Yin FCP, Maughan WL, Kass DA.** 1997. Estimation of central aortic pressure waveform by mathematical transformation of radial tonometry pressure. Validation of generalized transfer function. Circulation **95:**1827–1836.
4. **Chen CY, Wang WK, Kao T, Yu BC, Chiang BC.** 1993. Spectral analysis of radial pulse in patients with acute, uncomplicated myocardial infarction. Jpn Heart J **34:**131–143.
5. **Cooley JW, Tukey OW.** 1965. An algorithm for the machine calculation of complex Fourier series. Math Comput **19:**297–301.
6. **Dubin MJ, Magram G, Prasad AK.** 1998. Intracranial pressure waveform analysis: computation of pressure transmission and waveform shape indicators. Neurol Res **20:**533–541.
7. **Farrow RL, Stacy RW.** 1961. Harmonic analysis of aortic pressure pulses in the dog. Circ Res **9:**395–401.
8. **Grisk O, Stauss HM.** 2002. Frequency modulation of mesenteric and renal vascular resistance. Am J Physiol Regul Integr Comp Physiol **282:**R1468–R1476.
9. **Haider B, Yeh CK, Thomas G, Oldewurtel HA, Lyons MM, Regan TJ.** 1978. Altered myocardial function and collagen in diabetic rhesus monkeys on atherogenic diet. Trans Assoc Am Physicians **91:**197–203.
10. **Hashimoto J, Winter DC, Imai Y, O'Rourke MF**. 2008. Prediction of left ventricular mass reduction with antihypertensive therapy from harmonic content of the aortic waveform. J Clin Hypertens **10:**A38.

11. **Hollander W, Prusty S, Kemper T, Rosene DL, Moss MB.** 1993. The effects of hypertension on cerebral atherosclerosis in the cynomolgus monkey. Stroke **24:**1218–1226.
12. **Hsiu H, Jan MY, Lin Wang YY, Wang WK.** 2003. Effects of aorta bending and renal ligation on the blood pressure: a simulation on arterial stiffening. Biomed Eng Appl Basis Comm **15:**243–248.
13. **Institute for Laboratory Animal Research.** 1996. Guide for the care and use of laboratory animals. Washington (DC): National Academies Press.
14. **Jan MY, Hsiu H, Hsu TL, Wang WK, Wang Lin YY.** 2003. The physical conditions of different organs are reflected specifically in the pressure pulse spectrum of the peripheral artery. J Cardiovas Eng **3:**21–29.
15. **Jen KL, Hansen BC, Metzger BL.** 1985. Adiposity, anthropometric measures, and plasma insulin levels of rhesus monkeys. Int J Obes **9:**213–224.
16. **Karamanoglu M, O'Rourke MF, Avolio AP, Kelly RP.** 1993. An analysis of the relationship between central aortic and peripheral upper limb pressure waves in man. Eur Heart J **14:**160–167.
17. **Kaufman D, Smith EL, Gohil BC, Banerji M, Coplan JD, Kral JG, Rosenblum LA.** 2005. Early appearance of the metabolic syndrome in socially reared bonnet macaques. J Clin Endocrinol Metab **90:**404–408.
18. **Korcarz CE, Padrid PA, Shroff SG, Weinert L, Lang RM.** 1997. Doppler echocardiographic reference values for healthy rhesus monkeys under ketamine hydrochloride sedation. J Med Primatol **26:**287–298.
19. **Lang RM, Bierig M, Devereux RB, Flachskampf FA, Foster E, Pellikka PA, Picard MH, Roman MJ, Seward J, Shanewise JS, Solomon SD, Spencer KT, Sutton MS, Stewart WJ; Chamber Quantification Writing Group; American Society of Echocardiography's Guidelines and Standards Committee; European Association of Echocardiography.** 2005. Recommendations for chamber quantification: a report from the American Society of Echocardiography's Guidelines and Standards Committee and the Chamber Quantification Writing Group, developed in conjunction with the European Association of Echocardiography, a branch of the European Society of Cardiology. J Am Soc Echocardiogr **18:**1440–1463.
20. **Lazar J, Qureshi G, Kamran H, Rosenblum LA, Kral JG, Salciccioli L.** 2009. Characterization of arterial wave reflection in healthy bonnet macaques: feasibility of applanation tonometry. J Biomed Biotechnol **2009:**876093.
21. **Lazar JM, Qureshi G, Qureshi MR, Smith E, Scharf B, Rosenblum LA, Signaevsky M, Kral JG, Salciccioli L.** 2009. Left ventricular systolic and diastolic function in healthy adult bonnet macaques (*Macaca radiata*): new echocardiographic indices in Old World monkeys. Cardiology **113:**116–121.
22. **Liu CT, Higbee GA.** 1976. Determination of body surface area in the rhesus monkey. J Appl Physiol **40:**101–104.
23. **Maeshima M, Hiroe M, Taniguchi K, Marumo F.** 1991. Reduced high harmonic power spectra in patients with old myocardial infarction. Jpn Circ J **55:**41–52.
24. **Michelson G, Harazny J, Schmieder RE, Berendes R, Fiermann T, Wärntges S.** 2007. Fourier analysis of the envelope of the ophthalmic artery blood flow velocity: age- and blood-pressure–related impact. Hypertension **50:**964–969.
25. **Mirvis DM, Kopf GS, Potalla EW.** 1978. Harmonic analysis of the left ventricular pressure waveform of the primate. Cardiology **63:**79–93.
26. **Moore TL, Killiany RJ, Rosene DL, Prusty S, Hollander W, Moss MB.** 2002. Impairment of executive function induced by hypertension in the rhesus monkey (*Macaca mulatta*). Behav Neurosci **116:**387–396.
27. **Morita H.** 1995. Ventricular wall thickness and blood pressure values in normal cynomolgus monkeys. J Vet Med Sci **57:**1045–1048.
28. **Murgo JP, Westerhof N, Giolma JP, Altobelli SA.** 1980. Aortic input impedance in normal man: relationship to pressure waveforms. Circulation **62:**105–116.
29. **Nichols WW.** 2005. Clinical measurement of arterial stiffness obtained from noninvasive pressure waveforms. Am J Hypertens **18:**3S–10S.
30. **Nichols W, O'Rourke M.** 1990. Blood flow in arteries, p 270–281. Philadelphia (PA): Lea and Febiger.
31. **Njemanze PC, Beck OJ, Gomez CR, Horenstein S.** 1991. Fourier analysis of the cerebrovascular system. Stroke **22:**721–726.
32. **Norol F, Bonnet N, Peinnequin A, Chretien F, Legrand R, Isnard R, Herodin F, Baillou C, Delache B, Negre D, Klatzmann D, Vernant JP, Lemoine FM.** 2007. GFP-transduced $CD34^{+}$ and Lin-$CD34^{-}$ hematopoietic stem cells did not adopt a cardiac phenotype in a nonhuman primate model of myocardial infarct. Exp Hematol **35:**653–661.
33. **Oliva I, Geshwind H, Guttenbergerová K, Roztocil K, Laurent D.** 1978. Impedance of the arterial system in terms of Fourier harmonic analysis of the pulse wave. Physiol Bohemoslov **27:**333–340.
34. **O'Rourke MF.** 1967. Pressure and flow waves in systemic arteries and the anatomical design of the arterial system. J Appl Physiol **23:**139–149.
35. **Patel DJ, Mason DT, Ross J Jr, Braunwald E.** 1965. Harmonic analysis of pressure pulses obtained from the heart and great vessels of man. Am Heart J **69:**785–794.
36. **Reite M, Short R.** 1986. Behavior and physiology in young bonnet monkeys. Dev Psychobiol **19:**567–579.
37. **Sandhyamani S.** 1992. Vasculopathic and cardiomyopathic changes induced by low-protein high-carbohydrate tapioca-based diet in bonnet monkey. Vasculopathic and cardiomyopathic changes in induced malnutrition. Am J Cardiovasc Pathol **4:**41–50.
38. **Schuhfried O, Wiesinger G, Kollmitzer J, Mittermaier C, Quittan M.** 2003. Fourier analysis of impedance rheography for peripheral arterial occlusive disease. Eur J Appl Physiol **89:**384–386.
39. **Sherebrin MH, Sherebrin RZ.** 1990. Frequency analysis of the peripheral pulse wave detected in the finger with photoplethysmograph. IEEE Trans Biomed Eng **37:**313–317.
40. **Vaitkevicius PV, Lane M, Spurgeon H, Ingram DK, Roth GS, Egan JJ, Vasan S, Wagle DR, Ulrich P, Brines M, Wuerth JP, Cerami A, Lakatta EG.** 2001. A cross-link breaker has sustained effects on arterial and ventricular properties in older rhesus monkeys. Proc Natl Acad Sci USA **98:**1171–1175.
41. **Wang WK, Lo YY, Chiang Y, Hsu TL, Wang Lin YY.** 1989. Resonance of organs with the heart, p 259–268. In: Young WJ, editor. Biomedical Engineering—An International Symposium. Washington (DC): Hemisphere.
42. **Wang YY, Chang SL, Wu YE, Hsu TL, Wang WK.** 1991. Resonance.The missing phenomenon in hemodynamics. Circ Res **69:**246–249.
43. **Williams JK, Anthony MS, Clarkson TB.** 1991. Coronary heart disease in rhesus monkeys with diet-induced coronary artery atherosclerosis. Arch Pathol Lab Med **115:**784–790.
44. **Young ST, Wang WK, Chang LS, Kuo TS.** 1989. Specific frequency properties of the renal and the superior mesenteric arterial beds in rats. Cardiovasc Res **23:**465–467.