BASIC SCIENCES

# Index of Pressure Wave Reflection Assessed from Radial Pulse Wave Analysis

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*Received:* 09/13/2007
*Accepted:* 05/13/2008

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## ABSTRACT

Systolic wave width, a parameter obtained from the record of radial pulse wave, is easier to measure than the radial augmentation index. The aim of this study was to analyze the possibility of using systolic wave width as a complementary tool for the assessment of systolic wave reflection which is directly related to the degree of endothelial dysfunction and to aortic augmentation. We performed a population study on 120 healthy men between 17 and 65 years old with normal blood pressure. Records of the radial wave pulse were obtained, based on the movement of the arterial walls, by a capacitive sensor in contact with the surface of the wrist over the radial artery. Each record was processed and its amplitude was normalized; the augmentation index and systolic wave width at half its maximum height were calculated. We found that systolic wave width was different among subjects with the same augmentation index, showing different values of the amplitude of the reflected wave. Both parameters increased with age (r correlation value 0.9). The systolic wave width is an alternative index of ageing. It might assess the arterial system when it is difficult to measure augmentation index or when comparisons between individuals result ambiguous.

Rev Argent Cardiol 2008;76:272-277.

**Key words >** Arterial pulse - Radial artery - Physiology

**Abbreviations >**

| | | | |
|---|---|---|---|
| **SWW** | Systolic wave width | **SW** | Systolic pressure wave |
| **RAIx** | Radial augmentation index | **SR** | Systolic reflection |
| **DW** | Diastolic wave | **PS** | Propagation speed |
| **PW** | Arterial pulse wave | | |

## BACKGROUND

Analysis of the arterial pulse wave (PW) from the record of the radial pulse reveals the existence of a reflection of the systolic pressure wave (SW) in the end arteries. (1) This systolic reflection (SR) occurs during the down slope of the SW from the radial pressure record. Figure 1 shows the typical records of a young subject, an adult and an elder. Systolic pressure and diastolic pressure are represented in the graph as amplitudes of 100% and 0%, respectively. Basically, in young subjects the SW is narrow and the diastolic wave (DW) is wide. As years go by, the SW expands and the amplitude of the DW decreases. The amplitude of the SR is low in young people and is located at the bottom of the SW. As age increases, the SR arrives earlier at the recording site as a consequence of a rise in the propagation speed (PS) of the pressure wave and in the arterial vasoconstrictor tone; thus the amplitude of the SR increases. In the elder, the amplitude of the SR is great and it appears next to the vertex of a wide SW. (2) The effects of hypertension are similar to natural ageing, though they appear in younger persons. (3)

The magnitude and the location of the SR reflect the extent of aortic augmentation which is harmful to the left ventricle and the aortic wall. Aortic augmentation starts in the ascending aorta and is frequent in adults and in the elder with a high propagation speed of the PW that anticipates the arrival of the SR. When SR coincides with the plateau of the aortic SW, the aortic pressure rises. The myocardium is overstrained in order to maintain the systolic volume, and arterial walls are subjected to a greater tension, producing the breakage of elastin fibers in the arterial wall, with the subsequent reduction in aortic

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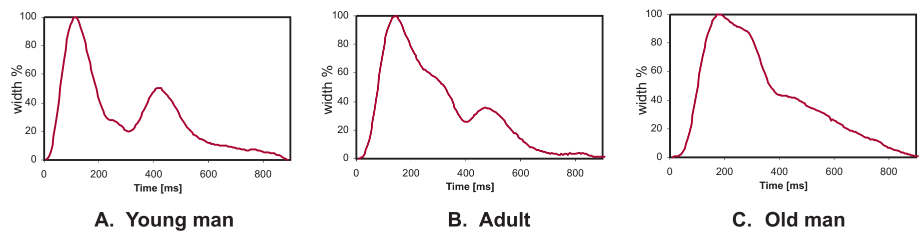


**Fig. 1.** Pulse wave records from healthy men of different ages. Note the changes produced with ageing: systolic wave widens, diastolic wave decreases and, between both of them, systolic reflection arrives earlier and has higher amplitude.

distensibility and development of ventricular hypertrophy. (4)

The magnitude of the SR depends on the vasoconstrictor tone in the end arteries where reflections are produced. The endothelium acts as an organ responsible of controlling the vasoconstrictor tone. Physical stimuli, such as parietal stress or friction stress produced by the velocity of blood flow, and chemical stimuli as hormones and vasoactive substances, act on the endothelium. In response to these stimuli, the endothelium releases vasodilator substances as nitric oxide or vasoconstrictor agents as endothelin which act on the smooth muscle of vessels modifying the arterial diameter in order to keep parietal stress and blood flow velocity constant. It also controls the production of prothrombotic, antithrombotic and fibrinolytic substances. The endothelium promotes the proliferation and migration of smooth muscle cells, white cells adhesion, and triggers immunological and inflammatory processes in the arterial wall. (5) Ageing produces a gradual deterioration of endothelial function; however, hypertension and atherosclerosis are responsible for the premature loss of endothelium function. (6-8) Endothelial dysfunction is an independent predictor of coronary events as it also compromises the coronary arteries. (9)

The presence of an increased SR in young people suggests endothelial dysfunction, a process which precedes most cardiovascular diseases. (5) In order to assess this phenomenon, Hayward et al. used the radial augmentation index (RAIx), defined as the amplitude of the SR obtained in the pulse wave record normalized between 0% and 100%. (7) The RAIx is an index of arterial ageing related to arterial distensibility that is used in the assessment of cardiovascular drugs and as an early marker of cardiovascular risk. (10, 11)

The Health Department of the National University of Mar del Plata has implemented a cardiovascular risk detection program which includes the assessment of the radial pulse wave based on the record of the movement of the wall of the radial artery; the records achieved with this technique are very similar to those obtained with tonometry. (12) Radial augmentation index was used as an assessment parameter; the pattern obtained differed according to the age of healthy subjects and of subjects with hypertension in order to perform a statistical comparison between each new case with the average value according to age. (13) Some ambiguous situations arose when similar values of RAIx were detected among individuals; however, their SRs were evidently different. Other subjects presented a uniform exponential fall on the SW, suggesting decreased amplitude of the SR; thus, the estimation of RAIx turned out to be difficult. In this way, the assessment of endothelial dysfunction on the basis of RAIx might lead to uncertainty, not only to determine the normal pattern but also to evaluate each individual case.

The aim of the present study is to analyze the possibility of using the systolic wave width (SWW), a parameter obtained from the record of radial pulse wave which is easier to measure than the radial augmentation index, and is a complementary tool for the assessment of systolic wave reflection, directly related to the degree of endothelial dysfunction and to aortic augmentation.

## MATERIAL AND METHODS

We conducted a population-based study on 120 healthy normotensive male subjects aged 17-65. The population included had no previous history of cardiovascular disease or cardiovascular related conditions. A protocol of bioethics was followed. Subjects with hypertension, diabetes mellitus and hyperlipidemia were excluded. Table 1 shows the clinical characteristics of the population. Twenty subjects were current smokers of an average of 14 cigarettes a day. After 20 minutes at rest, records were obtained between 3 pm and 7 pm while the volunteers remained seated; room temperature fluctuated between 15 ºC and 25 ºC. Subjects were advised not to smoke and not to drink any infusion within 3 hours prior to the study. Records of the radial wave pulse were obtained, based on the movement of the arterial walls, with a capacitive sensor of our own design placed in contact with the surface of the wrist over the radial artery. The sensor consists of a 1 $cm^2$ isolated metal plate that creates an electrical capacitor when placed over the skin. Variations in the volume of the underlying artery, subsequent to blood pressure wave, produce a movement in the plate of about ten microns according to the electrical capacity on the whole. A transducer converts the variations of capacity in variations of tension, which are digitalized at a rate of 200 samples/second. Data acquisition is done on a Standard 800 MHz Pentium III PC through the printer port connection, dis-

**Table 1.** Population characteristics (values are presented in means and in 95% confidence intervals)

| Decade | No cases | Weight (kg) | Systolic pressure (mm Hg) | Diastolic pressure (mm Hg) (kg/m$^2$) | Body mass index | Heart rate (bpm) |
|---|---|---|---|---|---|---|
| 2ª | 16 | 65.1 ± 8.6 | 127.5 ± 5.9 | 75.9 ± 3.8 | 22.1 ± 0.9 | 76.0 ± 4.5 |
| 3ª | 21 | 80.8 ± 5.4 | 116.5 ± 14.7 | 77.3 ± 7.6 | 25.4 ± 1.4 | 72.3 ± 3.8 |
| 4ª | 30 | 79.3 ± 3.4 | 119.4 ± 9.2 | 81.8 ± 3.7 | 25.9 ± 1.0 | 73.5 ± 4.6 |
| 5ª | 25 | 75.0 ± 3.8 | 126.8 ± 15.4 | 82.4 ± 3.5 | 25.0 ± 1.0 | 69.4 ± 3.2 |
| 6ª | 23 | 85.7 ± 6.7 | 130.2 ± 2.6 | 84.5 ± 1.7 | 27.4 ± 2.0 | 71.4 ± 4.4 |
| 7ª | 5 | 79.5 ± 4.4 | 134.2 ± 3.4 | 84.2 ± 4.5 | 25.7 ± 2.1 | 69.8 ± 7.0 |

played on screen and saved for subsequent processing (Figure 2).

The arterial distension in normotensive subjects is approximately proportional to the pressure inside the vessel; in this way the records obtained were similar to the tonometric pressure. Fifty cardiac cycles were recorded in each case. Breathing movements produce changes in intrathoracic pressure and modulate arterial pulse wave; this effect might be seen in prolonged records. (14) Eight cardiac cycles close to maximum inspiratory movement were averaged in order to consider this effect and to eliminate artifacts produced in the arm muscles.

Radial augmentation index was calculated on each averaged record, normalized in amplitude (0% to 100%). The estimation was based on the shoulder of the SR (see Figure 5 later). (2) The exact point is determined with software that analyzes the variation of slope in the area of maximum amplitude of the SR. Systolic wave width at half its maximum height was calculated. This relative value was chosen as Nichols et al. stated that aortic augmentation at the level of the ascending aorta becomes evident with values of RAIx greater than 50%, and systolic pressure increases due to SR. (2)

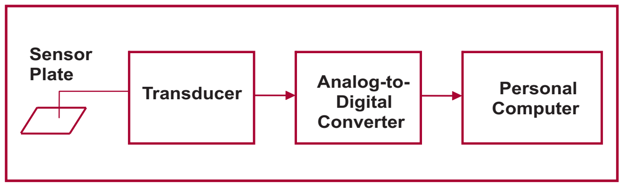


**Fig. 2.** Diagram of the record system. A sensor plate is placed in contact with the surface of the wrist over the radial artery creating an electrical capacitor. The movement of the plate produces variations of capacity which are converted into variations of tension by means of a transducer. The signals are digitalized by an analog-to-digital converter and introduced into a conventional PC, where they are displayed, processed and saved.

## RESULTS

Figure 3 A shows changes in RAIx according to age between the second and the seventeenth decades of life. These results are similar to those reported by other researches using conventional tonometry. (2, 10) The evolution of SWW with age is seen in Figure 3 B. Figure 4 displays a graph of the RAIx in function of the SWW for the same group. Indeed, subjects with similar values of RAIx had very different SWW, with variations between 100 and 150 msec for a same value of RAIx. The left side of the diagram corresponds to subjects with reduced SR and to young people, while the right side of the graph represents elder subjects or increased SR. The correlation between RAIx and SWW resulted to be $r^2 = 0.81$, indicating that there is an indirect relationship between both variables.

In Figure 5 two records of WP serve as example. The SR displayed in a graph at the bottom of each record was obtained in a mathematical way. In Figure 5 B, the record shows a slight convexity in the down slope of the SW, indicating low amplitude of the SR. In absence of SR, the down slope of the SW tends to adopt an exponential shape (concave). Both records show a RAIx of 64% in spite of different amplitudes of SR. A SR of increased amplitude reflects a greater SWW calculated at half its maximum height. Figure 5 A and 5 B show SWW records of 176 msec and 166 msec, respectively.

In subjects without SR for unknown reasons, measuring RAIx presented a problem. Figure 5 C belongs to a young man; the down slope of SW resembles an exponential function, indicating the total absence of SR. It is not possible to calculate RAIx in cases similar to the aforementioned.

## DISCUSSION

We have found that SWW increases with age in a similar way to RAIx, suggesting that it might be considered an index of arterial ageing.

The similarity between both graphs in Figures 3 A and B might indicate the presence of a direct relationship between both variables. If that were the case, it would make no sense to consider SWW as RAIx is a widely used parameter and it has already been demonstrated that its increase is related with greater incidence of cardiovascular events. (10) Nevertheless, the graph in Figure 4 rules out this possibility, as it shows that subjects with the same RAIx might have

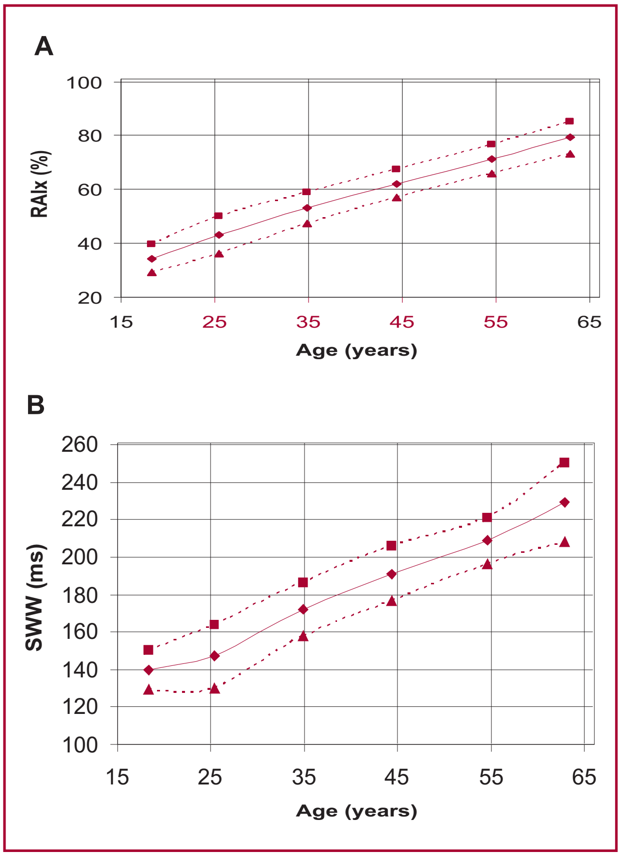


**Fig. 3.** Graphs of RAIx and SWW versus age. **A.** Development of radial augmentation index with age for a group of 120 healthy subjects between 17 and 65 years of age. **B.** Development of systolic wave width for the same group measured at half its maximum height. Dotted lines: 95% confidence interval.

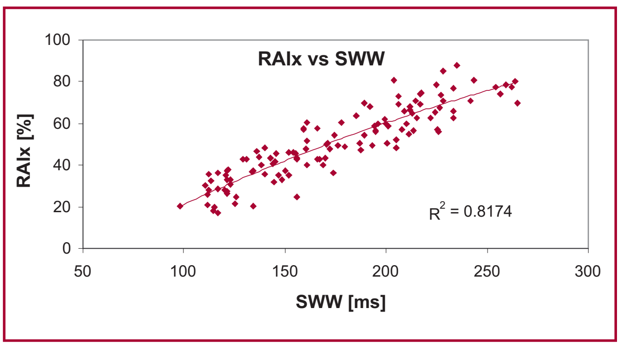


**Fig. 4.** Graph of systolic wave width versus radial augmentation index. For each value of RAIx there are individuals with different values of SWW which indicate different amplitudes of systolic reflection. Young people were generally located in the left inferior area and the elder in the right superior area.

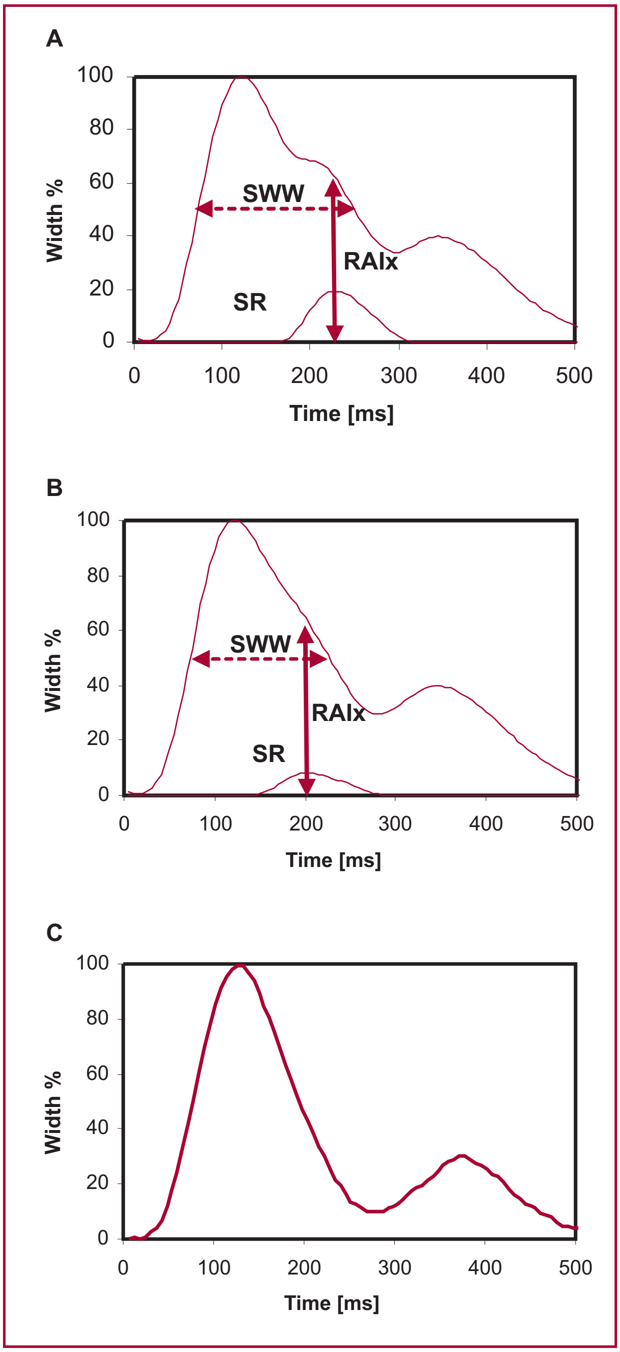


**Fig. 5. A and B.** Records from adults with the same values of RAIx and different SR amplitudes. The inferior area of both records shows the SR on a graph. The vertical line corresponds to its maximum value. The value of the PW in that instant is the RAIx and corresponds to the SR maximum. The subject with the greatest SR has the widest PW. **C.** Record with absence of systolic reflection. In this case, RAIx is undetermined. The low value of SWW reveals the absence of reflection.

different values of SWW, and this is the general situation and not an exception.

Figure 5 A and B gives an example of what has been previously mentioned and explains this finding. Systolic reflection does not start in an only place; it is the resultant of a sum of reflections originated in different areas, such as the aortoiliac bifurcation, renal arteries, etc. (15, 16) Radial augmentation index depends on the amplitude and timing the SR and on ventricular ejection.

The amplitude of the SR depends on the vasoconstrictor tone of end arteries and arterioles. The infusion of nitroglycerin reduces almost immediately the amplitude of the SR without changing the PS in the aorta. (17) In young subjects, nitric oxide endothelium-dependent vasodilatation is intact and keeps the smooth muscle tone of the arteries in a low level. This function is gradually lost with ageing and the amplitude of the SR increases.

However, timing of SR arrival to the site where it is recorded depends on changes on the PS of the pulse wave in the aortic area and in end arteries and arterioles where SR occurs, and on the distance to the nearest site of reflection. When the SR arrives prematurely in the radial area without changing its amplitude, it occupies an upper position in the down slope of the PW, and the RAIx increases. Systolic reflection may arrive early as a consequence of a greater PS or short stature. According to Moens equation, SP depends on arterial wall elasticity. As a consequence of ageing, elastin layers break, and collagen fibers and calcium deposits increase, leading to arterial stiffness. (2, 19) Thus, PS increases and the SR arrives prematurely in the aortic root or in the record area, increasing the augmentation index.

Radial augmentation index from the subject in Figure 5 B is higher because the SR arrives slightly earlier than the reflection represented in Figure 5 A. In this way, paradoxically the subject whose SR has a higher amplitude presents the same RAIx than the other. The situation is different if the SWW is considered. In Figure 5 A, the higher amplitude of the SR increases the bottom of its SW resulting in a larger SWW. This implies that the individual from Figure 5 A is exposed to the hemodynamic effects of an increased SR: greater afterload and aortic wall stress with unfavorable long-term outcomes.

As both indices respond to different properties of the circulatory system, they might be used together, expanding the clinical use of the RAIx. The graph in Figure 4 shows that coordinates located in the lower areas and to the left correspond to subjects with SR of lower amplitudes, with better endothelial function and with an arterial system with improved hemodynamic characteristics. (20)

Systolic wave width might be used as an alternative index of arterial ageing not completely correlated with RAIx. In subjects without SR (Figure 6) it is difficult and sometimes impossible to estimate RAIx; in these cases, measurement of SWW might serve to assess the arterial system.

Individuals with the same RAIx might have different values of SWW, indicating that they present SRs of different values. In subjects with the same value of RAIx, the amplitude of the SR will be greater in those with increased SWW. This statement is supported by Nichols et al. who claim that the individual differences of arterial stiffness with the use of RAIx should be interpreted cautiously, as it depends not only on PS but also on other factors. (2)

To conclude, this paper presents SWW, a new parameter easy to measure that gives complementary information to RAIx and which can be obtained when it is difficult to measure augmentation index.

## RESUMEN

### Índice para la evaluación de las reflexiones mediante análisis de la onda de pulso radial

En el presente trabajo se analiza la posibilidad de utilizar un parámetro obtenido del registro de la onda de pulso radial, el ancho de la onda sistólica, que es más sencillo de medir aún que el índice de aumentación radial y que complementaría a este último en la evaluación de la amplitud de la reflexión sistólica, directamente relacionada con el grado de disfunción endotelial y el fenómeno de aumentación aórtica. Se efectuó un estudio poblacional sobre 120 varones normotensos sanos con edades entre 17 y 65 años. Se obtuvo en ellos el registro de la onda de pulso radial en base al registro del movimiento de las paredes de la arteria mediante un sensor capacitivo aplicado sobre la zona de palpación del pulso. Cada registro se procesó y normalizó en amplitud y se calculó el índice de aumentación radial y el ancho de la onda sistólica al 50% de su altura máxima. Se halló que individuos con el mismo índice de aumentación poseían distintos valores de ancho de onda sistólica, lo cual evidencia distintos valores de amplitud de la onda reflejada. Ambos parámetros aumentaron con la edad y su correlación r resultó de 0,9. Se propone la utilización del ancho de la onda sistólica como un índice de envejecimiento alternativo, que permitiría evaluar el sistema arterial cuando la medición del índice de aumentación resultara dificultosa o la comparación entre individuos fuera ambigua.

**Palabras clave >** Pulso arterial - Arteria radial - Fisiología

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