The Acoustic Reflex at a 1000 Hz Probe Frequency: Phasor and Vector Analysis

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ABSTRACT
Phasor plots of reflex growth functions have been inconclusive concerning the effect of the reflex for mass dominated ears. The present study aimed to establish whether vector plots clarified the effects of the reflex for phasors not showing a clear circular shape. Measured admittance data (ipsilateral reflexes across a wide intensity range) was represented as both phasor diagrams and converted to impedance quantities, represented as vectors. The results analysed for 34 ears showed few unclassifiable phasor diagrams. In addition, all growth functions showed increased stiffness on vector analysis. Resistance changes appeared to be variable. The results suggest that vector diagrams may be a useful way of representing data that is not clearly represented via phasor diagrams. The current study, however, does not clarify the pattern for mass dominated ears.

OPSOMMING
Fasor-uitstippeling van refleksiewe groeifunksies was tot nog toe onafdoende ten opsigte van die refleks se uitwerking by massa-gedomineerde ore. Die onderhawige studie het as mikpunt gehad om vas te stel of vektor-uitstippeling die uitwerking van die refleks opgeklaar het ten aansien van fasore wat nie 'n duidelik sirkulêre vorm vertoon het nie. Gemete toegangsdata (ipsi-laterale reflekse oor 'n wye intensiteits-spektrum) is weergegee sowel as fasor-diagramme as omgesit in skynweerstand-syfers, aangebied in vektore-vorm. Die uitslae ten aansien van 34 ore wat ontleed is, het weining onklassifiseerbare fasor-diagramme opgelewer. Bowendien, alle groeifunksies het verhoogde styfheid vertoon by vektor-ontleding. Weerstandsveranderinge was skynbaar wisselend. Die resultate wys in die rigting dat vektor-diagramme moontlik 'n nuttige manier mag wees om data weer te gee wat nie duidelik deur fasor-diagramme weergegee word nie. Die huidige studie klaar egter nie die patroon vir massa-gedomineerde ore op nie.

KEY WORDS: immittance, reflex measures, high probe frequency, phasors, vectors

INTRODUCTION

The middle ear acts as a transducer of sound from the external environment to the cochlea (Berlin & Cullen, 1980). The effects of the acoustic reflex on the transmission of sound through the middle ear can be observed indirectly through immittance measures (Wiley & Block, 1985). This technique has been used extensively in the literature to describe the effects of the reflex on transmission properties of the middle ear at low probe frequencies (226 and 678 Hz). However, the effects of the reflex recorded at higher probe frequencies using immittance measures, have not been fully investigated in the literature. This is of particular interest given that baseline transmission properties differ across the frequency range in human ears (Berlin & Cullen, 1980).

There are several ways of representing the quantities of the relationship between admittance and impedance components (Van Camp & Creten, 1976). Rectangular notation represents the magnitudes of both components of admittance (susceptance (B) and conductance (G)) or impedance (reactance (X) and resistance (R)) as co-ordinates (B;G) or (X;R). Polar notation represents the components of admittance or impedance as having both magnitude and phase angle (degree) (magnitude ; <0). Dynamic aspects of middle ear function, such as reflex growth functions, may be represented as phasor diagrams, using rectangular notation (joining up the coordinates). This method has been used by Lutman (1984) and Reynolds and Morton (1995) to investigate the effect of the acoustic reflex. Vector diagrams, as used by Bennett and Weatherby (1979) show the dynamic aspects of the reflex by selecting points along the dynamic process and representing aspects of the reflex in both polar and rectangular notation. Immittance recordings of the acoustic reflex are usually made in admittance rather than impedance components, because there is a linear relationship between the admittance components at the probe tip and the plane of the tympanic membrane (Margolis, 1981). However, impedance quantities are usually used to explain immittance patterns (Van Camp & Creten, 1976). It is possible to correct measurements made at the probe tip to the level of the tympanic membrane, and to convert these components from admittance to impedance, using the formulae shown in Table 1.

Researchers agree that the major effect of the reflex at low probe frequencies (220 and 660 Hz) is an increase in stiffness or negative reactance (Feldman & Williams, 1976;

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Bennett & Weatherby, 1979, Lutman, McKenzie & Swan, 1984; Reynolds and Morton, 1994). This is made clear in phasor diagrams, which show circular, anticlockwise movement. This same effect is shown as an increase in negative phase angle on vector diagrams.

TABLE 1: Formulae to convert admittance (Y) components to components to impedance (Z) components (Margolis, 1981).

$jX = -jB/(B^2 + G^2)$	$R = G/(B^2 + G^2)$
X = Reactance B = Susceptance	R = Resistance G = Conductance

Reynolds and Morton (1995) examined whether phasor plots at 1000 Hz, where normal ears may not be stiffness dominated, followed the circular, anti-clockwise phasor diagram, indicating the constant resistance, stiffness change model proposed by Lutman (1984). While the majority of their phasor diagrams matched Lutman's (1984) model, some of their plots were difficult to interpret, particularly those derived from ears that were mass dominated at the probe frequency used (1000 Hz).

The reasons for some phasor plots deviating from the standard model proposed by Lutman (1984) could have been due to procedural variables, such as the nonsimultaneous recording of susceptance and conductance, or could be due to the effect of the reflex on systems where transmission properties are at or above resonance. Previous researchers have found variable effects of the reflex on resistance. This variability influences the overall effect at higher probe frequencies due to smaller reactance effects which cannot so easily mask the resistance changes that are occurring, as happens for low probe frequencies (Sprague, Wiley & Block, 1981; Bennett & Weatherby, 1979; and Feldman & Williams, 1976). It is possible that phasor diagrams are unclassifiable when significant resistance changes occur, and as they interact with reactance changes, cause irregularities in the shape of the phasor. If this were the case, then phasor diagrams may not be the clearest means to show the effect of the reflex, for high probe frequencies or mass dominated ears, but the true effect of the reflex may be clarified through representing the effect of the reflex through plotting the resistance and reactance changes as vectors.

This study aimed to explore whether unclassifiable phasor representations of admittance measures could be explained by means of vector representations of impedance values derived from the same reflex measures. Of further interest was whether mass dominated systems were always responsible for unclassifiable phasor plots as suggested by Reynolds and Morton (1995) and the present study therefore also investigated the relationship between baseline transmission and the phasor plots obtained. Clarification as to whether deviations from the constant resistance, stiffness change model were related to the means of representation was therefore the focus of the study.

METHODOLOGY

SUBJECTS

Thirty four normal hearing young adults served as subjects. Data was collected from one ear per subject to prevent duplication of results due to the very small inter-aural differences reported in subjects by Hall (1979) and Creten, Van der Heyning and Van Camp (1985). Subjects were required to be within 18 and 30 years of age, and to have no known history of ear pathology. Normal hearing was determined as pure tone air and bone conduction thresholds within normal limits (-10 and 25 dB HL), as defined by Goodman (1965, cited by Yantis, 1985). Air and bone conduction thresholds were required to be within 10 dB of each other to exclude any middle ear pathology not known to the subject. In addition, normal middle ear functioning was required, and this was established on the basis of tympanometry and acoustic reflex measurements. Subjects were required to have a single peaked admittance tympanogram at 226 Hz probe frequency, and ipsilateral acoustic reflex thresholds within normal limits (70 - 100 dB HL), as defined by Northern, Gabbard and Kinder (1985), for 500, 1000 and 2000 Hz stimulus frequencies, measured at a 226 Hz probe frequency.

APPARATUS

Hearing thresholds for all subjects were established using either a GSI 10 Clinical Audiometer, with TDH-50P headphones and B71 bone vibrator, or a Beltone 2000 Audiometer, with TDH-50P headphones and B71 bone vibrator. Both audiometers are calibrated in hearing level and meet the ANSI S.26-1981 standard for clinical audiometers.

Immittance measurements were carried out using a GSI-33 (Version 2) Middle Ear Analyser, which meets the ANSI S.3.39-1987 standard for acoustic-immittance instruments. The instrument was calibrated for the specific altitude of the test environment (98 m above sea level). Calibration checks, following the manufacturer's instructions, were carried out on each day of the data collection.

All hearing threshold measurements were carried out in acoustically treated audiometric suites (IAC 109), meeting the SABS 0182 (1982) code of practice.

PROCEDURE

Baseline information for each subject was established first in order to relate phasor and vector classifications to transmission at 1000 Hz. Baseline transmission at 1000 Hz for both susceptance (B) and conductance (G), recorded simultaneously, was established for each ear according to the Vanhuyse, Creten and Van Camp (1975) classification. Tympanometric values were recorded at pressure values of -350 daPa, and tympanometric peak, in order to correct the values to the plane of the tympanic membrane (Shanks, Wilson and Cambron, 1993). A positive-to-negative (+200 daPa to -400 daPa) pressure sweep procedure was used. Pressure was varied at a rate of 50 daPa per second (Grason-Stadler, 1987). Shanks and Lilly (1981) and Margolis, Van Camp, Wilson, and Creten (1985) found that positive to negative pressure sweeps result in less complex tympanometric patterns than negative to positive pressure sweeps.

Acoustic reflexes were recorded at stimulus frequencies of 500 Hz and 1000 Hz at a 1000 Hz probe frequency, for susceptance, followed by conductance, as these measures could not be displayed simultaneously. The intensity range used was 66-106 dB HL. A 4 dB increment size was used. This increment size has been used in other studies (for example, Reynolds and Morton, 1995). The

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millimho change (magnitude of the reflex growth) at each intensity level was recorded as well as the direction of the reflex growth (i.e., whether it was positive or negative). The stimulus duration was kept constant at 1.5 seconds, as time related aspects were not being investigated in this study.

Susceptance recording always preceded conductance recordings, and measurements at 500 Hz preceded measurements at 1000 Hz. Each subject's testing was completed within one day.

DATA ORGANISATION AND DATA ANALYSIS:

Data was corrected to the plane of the tympanic membrane by subtracting the susceptance and conductance values at -350 daPa from those values at tympanometric peak, as suggested by Shanks et al. (1993). Observed reflex values (x) were added to the corrected baseline values (Bc;Gc) for each intensity level: (Bc + x; Gc + x).

Phasor representation:

Corrected susceptance and conductance values were represented in the form of phasor diagrams for each reflex growth function recorded. In such diagrams, conductance values are represented on the X-axis and susceptance values on the Y-axis. A phasor trajectory was obtained by joining up the coordinates at each point and the shape of the trajectory was then classified. The axes used for each graph were standard for all graphs, but the scaling for each graph was different. This was done in order to maximize the visual representation of each phasor plot. The resulting phasors were classified as either:

1. Fitting with the Lutman (1984) model of an anti-clockwise circular movement, indicating constant resistance, and an increase in stiffness. These were termed classifiable.
2. Phasor plots not fitting the Lutman (1984) model. These were termed unclassifiable.

TABLE 2: Summary of baseline transmission characteristics of subjects in this study. (n=34).

	Number of Subjects	Van Huyse Classification
Stiffness dominated ears	4	1B1G
Ears at resonance	20	3B1G
Mass dominated ears	10	3B3G

TABLE 3: Results of the phasor analysis of growth functions obtained for 500 and 1000 Hz stimuli (n = 68).

	Classified Phasors	Unclassified Phasors
Stifness dominated ears	6	2
Ears at resonance	34	6
Mass dominated ears	18	2

Frequency counts of the number of phasor plots classified as above were recorded in table form.

Vector diagrams:

All corrected susceptance and conductance values were converted to reactance and resistance values by means of the formulae presented in Table 1 (Margolis, 1981). These corrected and converted reactance and resistance values were plotted on vector diagrams, which allowed for examination of the impedance data. Vectors were classified as showing an increase in stiffness (+S), a decrease in stiffness (-S), or no change in stiffness (oS), and an increase in resistance (+R), a decrease in resistance (-R), no change in resistance (oR) or variable resistance (vR) at threshold and suprathreshold levels.

From this, the effects of the reflex on reactance (increase or decrease in stiffness) and changes in resistance could be extracted and presented in table form.

RESULTS AND DISCUSSION

The distribution of ears used in the study across types of baseline characteristics is shown in Table 2. As expected, the majority of ears were at resonance at this frequency, with only a small number of ears being stiffness dominated. The ten mass dominated ears at the 1000 Hz probe frequency were of particular interest, given the focus of the study.

As normal ears are expected to be close to resonance at 1000 Hz (Colletti, 1977), it would be necessary to use a higher probe frequency to measure the reflex for many mass dominated ears, and the ten were considered to be a sufficient number to clarify the research question.

Table 3 shows, that similarly to Reynolds and Morton (1995), the majority of phasor plots obtained were matched to the constant resistance, stiffness change model explained by Lutman (1984). An example of this is provided in Figure 1.

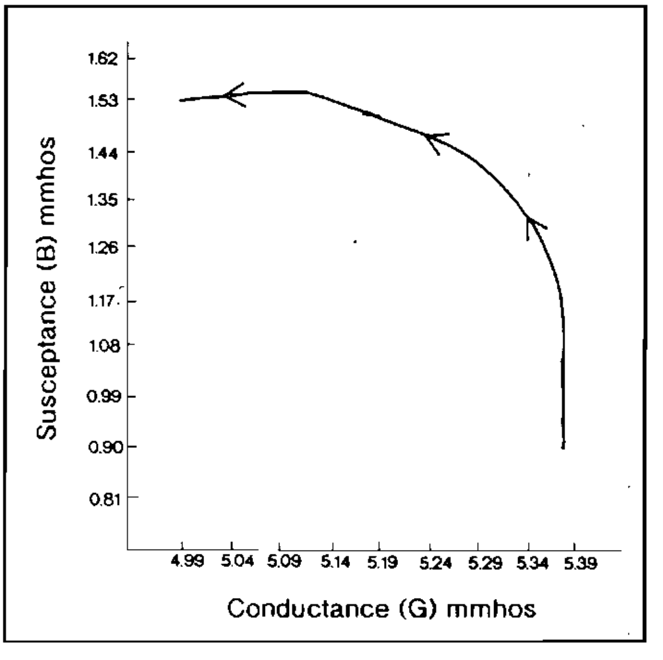

FIGURE 1: Example of classifiable phasors demonstrating anticlockwise, circular movement form baseline to suprathreshold levels.

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However, an unexpected result was the distribution of unclassifiable phasors across ears, regardless of baseline transmission properties. Unlike Reynolds and Morton (1995), who found that those phasors that deviated from the model were from mass dominated ears, the results of the present study indicated that unclassifiable phasors were obtained from stiffness dominated ears, ears at resonance, and mass dominated ears. Both the present study and the Reynolds and Morton (1995) study did not differentiate between degrees of mass domination within subjects. It is possible that the ears in the present study behaved similarly to ears at resonance or stiffness domination with the added stiffness effect of the reflex, which, as shown below, was demonstrated for the reflex patterns obtained. Given that normal ears are expected to be close to resonance at 1000 Hz, it may be necessary to use a higher probe frequency to demonstrate the effect of the reflex for mass dominated ears, although problems will be encountered in the measurement of such small immittance changes in mass dominated ears (Lutman, 1995).

Of particular interest in the results of this study, is the nature of the deviation from the model. Clearly, as shown in the examples in Figure 2, the deviations from the constant resistance, stiffness change model are not marked in the present study, and all showed overall patterns that could be broadly described as circular, anticlockwise movement, at least for some portion of the phasor plot. These results are shown in Table 4, where a brief description of the phasors obtained is provided. It is evident from this table that the patterns which were not strictly showing anticlockwise movement with the activation of the reflex typically showed clockwise movement close to threshold, and then at suprathreshold levels the typical pattern of anticlockwise movement was seen. Examples of this are provided in Figure 2A. One contributing factor to this pattern may relate to the determination of reflex threshold, as it is possible that the threshold values obtained were not the actual thresholds of the subjects, and that true threshold was reached at higher intensity levels, where the pattern was consistent with the model.

The criteria used to determine threshold on the GSI 33, derived from Bennett and Weatherby (1979), may not be absolute threshold values. Lutman (1984) argues that there is some question regarding the accurateness of the criterion values given by Grason-Stadler (1987). It is therefore possible that absolute thresholds were not obtained at the level at which they were recorded. This would mean that only two phasors did not actually match the model (see Table 4). These two demonstrated deviations from the model at suprathreshold intensity levels. An example is shown in Figure 2B. It is well documented that the reflex reaches saturation (Wilson and McBride, 1978), and it may be that the complex interaction of immittance components, coupled with saturation of the reflex contributed to the patterns obtained.

In analyzing the results of the study using vector analysis, an attempt was made to clarify the effect of the reflex, particularly for phasors which were not classifiable. In spite of the few unclassifiable phasors obtained, the vector analysis did provide some useful information, shown in Tables 5, 6 and 7, particularly as regards the unresolved

TABLE 4: Description and frequency count of unclassifiable phasors (N=10)

Classifiable at threshold, & unclassifiable at suprathreshold levels	2
Unclassifiable at threshold, & classifiable at suprathreshold levels	8

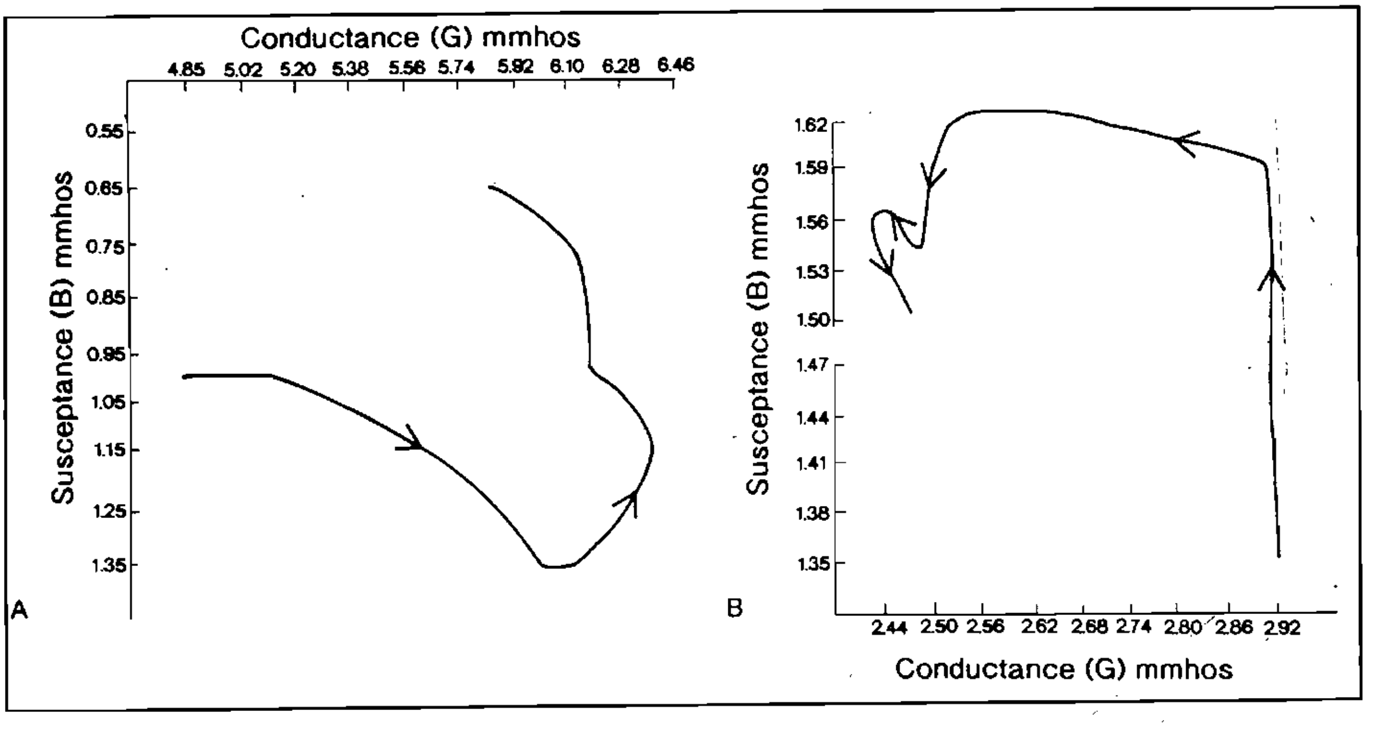

FIGURE 2: Examples of unclassifiable phasors.
a) Represents clockwise movement at threshold, followed by anticlockwise circular movement.
b) Represents anticlockwise movement at threshold, followed by deviations from the model at suprathreshold levels.

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question of the effect of the reflex on resistance.

Consistent with all previous studies , for example Lutman et al. (1984) and Reynolds and Morton (1995), is that the effect of the reflex on reactance is an increase in stiffness. During the course of some of the reflex growth functions obtained in the present study , there was some deviation from this pattern at threshold, but as mentioned above, this may have related to the definition of threshold. Interestingly, two growth functions, both obtained from mass dominated ears showed decreased stiffness at suprathreshold levels, as shown in Table 5. However, these growth functions were classifiable within the model, as this pattern did not emerge for the unclassifiable phasors, as shown in the detailed analysis in Table 7. Thus, there did not appear to be any relationship between the reactance change and the classifiability of phasors.

A variety of effects on resistance were observed, consistent with previous findings (for example Sprague et al., 1981). As shown in Table 6, the most common effects were decreased resistance at threshold, with most demonstrating increased resistance at higher intensity levels. Several of these typical patterns were also obtained from unclassifiable phasors (see Table 7), thus indicating that there was no clear relationship between the resistance pattern and the classifiability of phasors.

CONCLUSIONS

While the reactance and resistance changes from classifiable and unclassifiable phasors across ears with differing baseline properties were not differentiated in the results of this study, some interesting observations relating to phasor and vector analysis of reflex growth functions were nonetheless evident. As the complex interaction of reactance and resistance change was demonstrated in unclassifiable phasors, isolating the effects of the reflex on impedance quantities does allow for the identification of increased stiffness, in spite of fairly obscure phasor patterns, possibly making this a useful tool for clinical interpretation of obscure reflex patterns. However, identifying expected patterns for mass dominated ears appears to require either a more sophisticated form of recording reflex phenomena, or more sophisticated form of analysis. Factors contributing to the lack of clarity of the effect may relate to the nonsimultaneous recording of the reflex, but probably the most overriding factor is the use of a probe frequency where normal ears are typically at resonance. Thus in order to clarify the effect of the reflex for mass dominated ears, a higher probe frequency should be incorporated for studies of normal ears, but this is not currently possible using commercially available equipment, due to the increasing complexity of immittance recordings as ears deviate from simple stiff systems. One further

TABLE 5: Vector Analysis: Effect of the reflex on stiffness reactance.

+S = increase in stiffness
-S = decrease in stiffness
oS = no change in stiffness
; = shows the difference between baseline, threshold and suprathreshold levels.

	Stiffness Dominated Ears	Ears at Resonance	Mass Dominated Ears
+S	8	24	7
-S;+S	0	10	11
oS;+S	0	6	0
+S;-S	0	0	2

TABLE 6: Vector Analysis: Effect of the reflex on resistance.

+R = increase in resistance
-R = decrease in resistance
oR = no change in resistance
vR = variable resistance changes
; = shows the difference between baseline, threshold and suprathreshold levels.

	Stiffness dominated ears	Ears at resonance	Mass dominated ears
oR;+R	3	2	0
-R;+R	2	21	11
+R	0	0	4
oR;-R	0	2	0
-R	2	7	2
vR	0	4	1
oR	1	0	0
-R;oR	0	4	2

TABLE 7: Detailed vectorial description of the ten unclassifiable phasors.

+S = increase in stiffness
-S = decrease in stiffness
oS = no change in stiffness
+R = increase in resistance
-R = decrease in resistance
oR = no change in resistance
vR = variable resistance changes
; = shows the difference between baseline, threshold and suprathreshold levels.

Stiffness dominated ears	Ears at resonance	Mass dominated ears
+S, oR;+R	oS;+S, -R;+R	-S;+S -R;+R
+S, -R;+R	+S, -R	-S;+S -R;+R
oS;+S, vR	+S, -R;oR	
	-S;+S, -R	
	+S, -R;+R	

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possibility may be to investigate the pattern of reflex growth functions in pathological ears, or in ears selected because of their marked mass domination at the probe frequency, rather than in terms of simply a normal phenomenon, as was the case in the present investigation.

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