Effect of Emitted Power on Waveform Intensity in Transcranial Doppler

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This study assesses the problem of transcranial Doppler recording failure and seeks to determine the extent to which this can be ameliorated by increased emitted power. We hypothesized that waveform intensity is directly related to the rate and quality of successful recording and may be compared quantitatively among groups of patients. Among a large group of patients recorded at 800 mW/cm² emitted power, intensity was strongest in white men, weakest in black women, and intermediate in black men and white women. It declined with age in women of either race, but not in men of either race. Analysis of the effect of emitted power on intensity predicted that significant numbers of waveforms recorded at 800 mW/cm² could not be recorded at the current clinical standards of 100 mW/cm², the difference being most pronounced in elderly black women. Temporal bone window thickness measured in a series of adult cadaver skulls was least in white men, greatest in black women, and intermediate in black men and white women. The findings of this study support the hypothesis that temporal bone window thickness is an important determinant of recording difficulty and suggest that increased emitted power can significantly increase successful recording, particularly in black and elderly patients. Increased power alone, however, cannot completely solve the recording problem within safe limits. (Stroke 1990;21:1573-1578)

A major limitation of the use of transcranial Doppler (TCD) in elderly stroke patients is the frequency of failure to obtain a recording. Several centers, using the standard transducer power of 100 mW/cm², have reported greater difficulty in elderly than young patients, in women than men, and in black people than white. However, these reports provide little quantitative information that might serve to set goals for improved instrument design. This study was undertaken to assess the problem of TCD recording failure in different age, sex, and racial groups and to determine to what degree this failure can be ameliorated by increased emitted power. We measured the intensity of the recorded waveform in a large group of patients to compare age, sex, and racial subgroups among them. We hypothesized that the ease and accuracy of an examination was related to waveform intensity, which would serve as a quantitative criterion for comparison.

Doubling of emitted power results in a waveform intensity increase of 3 dB, but it was not known by how much this would improve the rate of successful recording. We addressed this question in a separate, smaller group of patients in whom only low-intensity waveforms could be recorded. In these difficult patients, we made recordings over a range of emitted power to determine the power and intensity levels below which recording was not possible. We therefore could determine the effect of emitted power on the rate and quality of success.

In transcranial recording, most of the applied ultrasound energy is lost by absorption and scatter in the temporal bone. Measurements of bone window thickness comprise the basis for understanding clinical recording problems. We therefore made such measurements in cadavers to serve as background for the measurements in patients and to permit a limited test of the hypothesis that bone window thickness is related to waveform intensity.

Subjects and Methods

We studied two groups of patients seen in our TCD laboratory between May 1, 1988 and September 1, 1989. We also made temporal bone window measurements in a group of cadavers.

The clinical studies were made with a Medasonics Transpect (Medsonics, Freemont, Calif.) with a hand-held transducer in the range-gated pulsed-wave mode at 2 MHz. The instrument was modified to yield 800 mW/cm² emitted power, meaning an in situ intensity of 800 mW/cm² spatial peak temporal average. This is compared with 95 mW/cm² in the stan-
standard Transpect, based on calibration by hydrophone in a deaerated water bath. Pulse duration was 12 \mu\text{sec}, and pulse repetition frequency was 10.4 kHz for the depth range of 25–62 mm. The sample volume was 12 mm in length and approximately 5 mm in diameter; these dimensions did not vary significantly between depths of 40 and 60 mm.

The recording consisted of the velocity waveform at a specific depth between 55 and 45 mm from the temporal scalp surface. Systolic velocity (SV) and diastolic velocity (DV) in centimeters per second, averaged over 5–10 cardiac cycles comprising about 5 seconds of recording time, were measured directly on the cathode ray tube display with a cursor controlled on the instrument panel. The mean velocity (MV) was computed by the instrument using a fast Fourier transform analysis, and this was compared with the arithmetic calculation \( MV = DV + (SV - DV) / 3.9 \).

The Transpect instrument had two gain controls that could be adjusted independently to optimize contrast between background noise and velocity waveform. These were called “noise level” and “dynamic range.” The noise level was a threshold below which weaker signals would not be displayed. Lowering the noise level made more low-intensity signal visible, but also included more background noise. Dynamic range specified the highest intensity above noise level to be displayed on the cathode ray tube screen, that is, the loudest component of the waveform, represented by the brightest contrast. Lesser intensities were displayed automatically with less bright contrast. The instrument contained a tuning program that automatically selected the noise level and dynamic range settings, which gave the optimal waveform display. With this program in effect, the sum of noise level and dynamic range was the intensity in decibels of the loudest component of the waveform spectrum. Spurious values resulted when random noise that was displayed on the cathode ray tube, usually due to mechanical disturbance of the transducer, was louder than the loudest component of the waveform. Displays containing such disturbances were excluded.

In the first patient group, measurements were made over a range of ages. Forty-two black females, 28 black males, 126 white females, and 150 white males were studied. About half of these examinations were conducted by the author and the remainder by technologists whose window finding skills were comparable to the author’s. These were consecutive patients in whom at least one middle cerebral artery (MCA) could be recorded from a depth between 55 and 45 mm from the temporal scalp, excluding only those patients in group 2 (below). One or more segments of one or both MCAs were insonated at 800 mW/cm\(^2\) emitted power. Each MCA segment, at 5-mm intervals from 55 to 45 mm depth, was counted as an independent observation. The reason for the depth selection was to confine the observations to the main MCA trunk. Deeper than 55 mm, recording is likely from carotid siphon, whereas superficial to 45 mm recording is likely from MCA branches. Failures were not counted because an exact record was not kept initially of patients in whom insonation was tried unsuccessfully. In the latter half of the study, records of failures were kept, so the approximate failure rate for subsamples of each group could be estimated.

In the second patient group, measurements were made over a range of emitted power. The author examined 15 patients, including six black women aged 66–76, one black man aged 33, three white women aged 43–65, and five white men aged 45–80. The criterion for selection was that the technologist was having difficulty because of suspected poor temporal window. No more than three arterial segments from any one patient were included, and no more than two from one side, in which case there was a significant difference in angle of insonation between them. Twenty-seven separate segments were studied between a depth of 55 and 45 mm from the temporal scalp surface. Each segment was treated as an independent observation. Because of the differences in angle of insonation, it was presumed that different amounts of bone were traversed by the recorded signals at each segment.

A satisfactory velocity waveform was obtained initially for each segment at 800 mW/cm\(^2\) emitted power. Then, without moving the transducer, power was successively reduced. Additional waveforms of the same segment were recorded at 600, 400, 200, 80, and 40 mW/cm\(^2\) or until no waveform could be distinguished from background noise. The reflected intensity of each waveform was noted. When the waveform could no longer be distinguished from background noise, its intensity was assumed to be zero.

Cadaver temporal bone window measurements were made on 31 cadavers, all those that were available in the University of Alabama Gross Anatomy Laboratory in July 1987. These included 13 white men, 11 white women, two black men, and five black women. All were adult, but their ages at death were unknown. The minimum thickness of the squamous portion of the temporal bone in the region of the usual clinical temporal windows, above the zygomatic arch anterior to the external ear canal, was measured with calipers having a measurement error of ±0.1 mm. Several measurements were made in each temporal bone, the thinnest measurement for each side being recorded. Thus, each cadaver provided two window measurements.

**Results**

The average waveform intensity at 800 mW/cm\(^2\) emitted power in white males of patient group 1 was approximately 29 dB at all ages above 30 and was slightly higher below 30. In black males, the average was approximately 27 dB at all ages above 30. Too few patients younger than 30 were studied to establish a reliable mean. In white women, the average waveform intensity declined from 33 dB below age 30 to 28 dB above age 50. In black women there was a stronger age
effect, as the average declined from 32 dB below age 30 to 24 dB above age 50 (Figure 1). In a small subsample comprising 95 segments among 19 black women older than 70, the mean was only 18.7 dB.

A two-factor analysis of variance was used to investigate effects of race and sex on intensity among groups. Fisher's protected least significance difference test was used to compare pairs of means. Pearson's coefficient was calculated for the correlation between age and intensity for each race and sex group. All the means were significantly different from each other among the 51–99-year-old groups, with white male > white female > black male > black female (Table 1). The differences were less strong among the 31–50-year-old groups, those between white and black males not being significant.

In patients aged 51–99, failure to record any MCA waveforms occurred among two of 76 white males (3%), six of 53 white females (11%), one of 24 black males (4%), and eight of 19 black females (42%) (Figure 2). Sample sizes were too small for the low failure rates among younger patients to reveal meaningful differences. According to Fisher's exact test,

**Figure 1.** Distribution according to age of waveform intensities (decibels) recorded at 800 mW/cm². Upper panel: White male; lower panel: black female. All intensities below 22.5 dB would not be detected at 100 mW/cm². Data for white female and black male (not shown) were intermediate (see Table 1).

**Figure 2.** Success rates of recording middle cerebral artery waveforms in patients aged 51–99. Open bars represent actual attempts at 800 mW/cm²; hatched bars represent calculated success rate at 100 mW/cm² assuming 10.5 dB intensity reduction from 800 mW/cm² recording. Black female (BF) significantly lower than others (p<0.01). WM, white male; WF, white female; BM, black male.

**Table 1. Waveform Intensity Mean and Number of Arterial Segments Insonated for Patient Subgroups by Age**

<table>
<thead>
<tr>
<th>Patient subgroup</th>
<th>0–30</th>
<th>31–50</th>
<th>51–99</th>
<th>Pearson R</th>
</tr>
</thead>
<tbody>
<tr>
<td>White male Mean (SD)</td>
<td>34.4 (5.4)</td>
<td>29.1 (7.3)</td>
<td>29.5 (6.5)</td>
<td>-0.087 (p=0.009)</td>
</tr>
<tr>
<td>White male n</td>
<td>39</td>
<td>164</td>
<td>697</td>
<td></td>
</tr>
<tr>
<td>White female Mean (SD)</td>
<td>32.6 (5.2)</td>
<td>31.3 (6.6)</td>
<td>27.7 (6.3)</td>
<td>-0.386 (p=0.0001)</td>
</tr>
<tr>
<td>White female n</td>
<td>158</td>
<td>211</td>
<td>387</td>
<td></td>
</tr>
<tr>
<td>Black male Mean (SD)</td>
<td>...</td>
<td>27.9 (6.6)</td>
<td>26.9 (5.6)</td>
<td>NS</td>
</tr>
<tr>
<td>Black male n</td>
<td>...</td>
<td>79</td>
<td>176</td>
<td></td>
</tr>
<tr>
<td>Black female Mean (SD)</td>
<td>32.1 (5.5)</td>
<td>23.5 (6.8)</td>
<td>23.9 (6.4)</td>
<td>-0.411 (p=0.0001)</td>
</tr>
<tr>
<td>Black female n</td>
<td>51</td>
<td>48</td>
<td>191</td>
<td></td>
</tr>
</tbody>
</table>

0–30: no significant differences; 31–50: black female significantly lower than others (p<0.001), black male lower than white female (p<0.01) but not different from white male, white female lower than white male (p<0.01); 51–99: all differences strongly significant (p<0.0001). Pearson R: coefficient of correlation between intensity and age (significance of difference between R and zero also shown).
black females were significantly different from each of the other groups ($p<0.01$), but the differences among the others were not.

Failure to record a waveform in patient group 2 became more frequent as emitted power was reduced from 800 mW/cm$^2$. This occurred in one of the 27 studied MCA segments at 400 mW/cm$^2$, in two more at 200 mW/cm$^2$, in seven more at 80 mW/cm$^2$, and in two more or a total of 12 of the 27 at 40 mW/cm$^2$. Success rates thus were 100% at 800 mW/cm$^2$ (according to the selection criterion) and at 600 mW/cm$^2$, 96% at 400 mW/cm$^2$, 88% at 200 mW/cm$^2$, 62% at 80 mW/cm$^2$, and 55% at 40 mW/cm$^2$ (Figure 3). In Figure 3, the mean waveform intensity in decibels as a function of log of emitted power declined linearly from 26.5 dB at 800 mW/cm$^2$ to 10 dB at 40 mW/cm$^2$. Thus, doubling the emitted power increased the reflected signal intensity by approximately 3.5 dB and increased the yield of successful recordings by approximately 10%. Because this regression was obtained by counting failures to discern a waveform as an intensity of 0 dB, this is a slight overestimate. The actual threshold for recognition of a waveform was approximately 12 dB.

Waveforms were degraded below 22 dB. The computed mean velocity became grossly inaccurate compared with the calculated value or was not displayed at all. Below 18 dB, even with manual editing of the waveform, the measured peak velocity was often decreased to approximately 80% of that measured above 22 dB. This was because the highest frequency components of the waveform usually were not the loudest and hence could not be distinguished from background noise.

The thinnest windows in cadaver temporal bones were in white males, intermediate in white females and black males, and thickest in black females (Table 2). Windows in black males and white females were not significantly different, whereas they were significantly thicker than in white males ($p<0.03$) and thinner than in black females ($p<0.003$). Comparisons among groups used a one-way analysis of variance. Individual comparisons of pairs of means used Fisher's protected least significance difference test.

The average thickness for each cadaver group, plotted against the average waveform intensity for the patients aged 51–99 in patient group 1, revealed a nearly linear relationship (Figure 4).

**Discussion**

The experimentally determined power and intensity relationship so closely corresponding to that predicted from basic physical principle validates the measuring system used and justifies the concept of quantitative comparison of intensity among groups as an index predictive of rate and quality of successful examination. Thus, at 800 mW/cm$^2$ the waveform intensity was approximately 10.5 dB greater than would be obtained at the current clinical standard of 100 mW/cm$^2$. For waveform intensities greater than about 35 dB, this difference would not be clinically significant because the waveform of approximately 25

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**Table 2. Temporal Bone Window Thicknesses in Cadavers**

<table>
<thead>
<tr>
<th>Patient subgroup</th>
<th>Mean</th>
<th>SD</th>
<th>Range</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>White male</td>
<td>1.83</td>
<td>0.46</td>
<td>1.0–2.9</td>
<td>13</td>
</tr>
<tr>
<td>White female</td>
<td>2.24</td>
<td>0.56</td>
<td>1.0–3.0</td>
<td>11</td>
</tr>
<tr>
<td>Black male</td>
<td>2.35</td>
<td>0.38</td>
<td>2.0–2.9</td>
<td>2</td>
</tr>
<tr>
<td>Black female</td>
<td>3.52</td>
<td>0.93</td>
<td>2.3–5.4</td>
<td>5</td>
</tr>
</tbody>
</table>

Difference between white female and black male not significant; both greater than white male ($p<0.03$) and less than black female ($p<0.003$).
dB to be obtained at 100 mW/cm² still would be detectable and not degraded at 100 mW/cm².

A waveform with intensity as low as 23 dB at 800 mW/cm² would be barely detectable at 100 mW/cm², having an intensity of only 12.5 dB, virtually at the threshold of detection. Such a waveform likely would be degraded with underestimation of velocity, a frequent problem below approximately 22 dB. Window-finding was easy in patients with intensity greater than 30 dB but became increasingly difficult below approximately 25 dB.

The practical significance of increased power can be estimated by subtracting 10.5 dB from the intensity of each waveform recorded at 800 mW/cm². Assuming all those waveforms with resulting intensity less than 12 dB at 100 mW/cm² to be undetectable, in the 51–99 age groups this would exclude 13% of the waveforms in white men, 18% in white women, 23% in black men, and 50% in black women. The effects would be minor in young patients. This is illustrated in Figure 2, in which the estimated effect of the hypothetical power reduction is added to the failure rate actually noted at 800 mW/cm², and in Figure 1, in which the effect on the actually recorded waveforms of the reduction of emitted power would be as if the detection threshold at 800 mW/cm² were raised to 22.5 dB. An additional effect of the lowered power would be a greater difficulty in window-finding near the detection threshold; thus, the failure rate in practice would be higher than that predicted simply by subtracting intensity or raising detection threshold at a known window.

Because ultrasound absorption and scatter by bone are much greater than by any other tissue, measurements of temporal bone window thickness form the anatomical basis for understanding practical clinical recording problems. The relationship shown in Figure 4 is of course artificial because it compares measurements in living patients and cadavers and assumes that the cadaver sex and race subgroups represent the same subgroups as among the clinical patients. Nevertheless, acknowledging these limitations, the relationship lends support to the hypothesis that temporal bone window thickness is a major determinant of waveform intensity and hence of recording difficulty. Naturally, it would be desirable to make window measurements in the same patients as those in which the waveform intensities were recorded. In a pilot study using computed tomographic scanning, this proved not practical. Although bone thickness clearly was demonstrated, the effects of volume averaging and random computed tomographic slicing excluded location of the thinnest portions of the squamous temporal bone.

In the thickest cadaver temporal bones, the inner table was often roughened or scalloped. The thinnest point often was a narrow cylindrical depression with domed vault. Often, the base diameter of the window at the surface of the inner table was less than 0.5 cm. In such cases of narrow window diameter, there would be a “collimating” effect on the ultrasound beam passing through thick bone. This might severely restrict the angles that could be used, so that some vessels could not be insonated. Inner table scalloping demands persistence in the search for a window in difficult patients.

In our experience with 800 mW/cm², patients being examined have never complained of discomfort and the author has not noted discomfort when examining himself. There was no warming of the transducer during either hand-held examination or up to 3 hours of monitoring during surgery. In some cases, it has been possible to avoid arteriography because of normal TCD findings that would not have been possible at 100 mW/cm². Similarly, in several cases of carotid endarterectomy, the decision to place a shunt was facilitated by availability of the TCD because of increased power.

Extrapolation of the observed yield and power relation of approximately 10% per doubling suggests that substantially solving the recording problem in elderly black women by simply increasing applied power would require at least three further doublings (×8) from the presently used 800 mW/cm², to about 6,400 mW/cm². The constraint on applied power is the possibility of tissue damage. The threshold to production of histological lesions is more than 100 W for 1 second, about 10 W for 10 seconds, and more than 1.5 W for 1,000 seconds.10–12 Guidelines for the avoidance of any biological effect are more stringent. There is a consensus that 100 mW/cm² is safe up to 24 hours. Within the range of 1–500 seconds, the product (time × intensity) less than 50 Joules is thought to be safe, even in the fetus.13,14

It is symptomatic of the early state of TCD development that the Food and Drug Administration lumps the procedure with fetal applications without acknowledging that in transcranial examination, approximately 90% of applied power is lost in 1–2 mm of skull, whereas hair and skin account for relatively little power loss.15–18 This should set the safety limit in adults to 1,000 mW/cm², although this would not be safe in children or patients who had undergone craniotomy. Considerably more power might be safe for patients with poorer windows, but 6,400 mW/cm² might not be safe for routine practice unless there were a reliable way to determine temporal bone thickness before examination. Even so, scalp burns might result from such power.

A possible approach to determination of bone thickness in vivo would be to incorporate A-mode instrumentation to enable detection of standing echoes at the inner and outer table of the skull. This difference, with the velocity of sound in bone, would yield a quantitative index of thickness.

The Transpect used in this study had a “window finder” that displayed qualitatively the intensity of signal strength (independently of waveform) returning from the depth of 70 mm. Although this intensity should give an indication of signal loss by the bone, from which thickness might be inferred, it was not helpful in the present study nor have we found it
useful in clinical examinations. The reason for this may be the “collimating” effect of narrow windows. Thus, even when there was sufficient energy penetration, the narrow window may have excluded the needed angle for successful insonation.

A practical approach to improved recording might be the application of signal averaging, as used in clinical neurophysiology for detecting cerebral cortical evoked potentials. The principle is that repetition of events that occur at a consistent time with a consistent amplitude sums the events, whereas the summation of random noise above and below baseline approaches zero. This enhances the signal-to-noise ratio as the square root of the number of repetitions. Thus, in a patient with a regular cardiac rhythm, the sweep could be triggered by the R wave of the electrocardiogram. As few as four or eight cardiac cycles might be required to make a waveform distinct that, without averaging, might be audible, but not visible. With the presently used instrument, the threshold for distinguishing a waveform from background noise was approximately 12 dB. If that threshold could be lowered to 3 dB with averaging, this would have the effect of three doublings of power, the estimated need for the most difficult patients in current clinical practice.

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References


KEY WORDS • temporal bone • ultrasonics • transcranial Doppler
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