Paraplegic pressure sore frequency versus circulation measurements

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Abstract—Paraplegic subjects (N=34) were examined to determine the association of pressure sore history with respect to ankle pressure ratio and buttocks cutaneous plethysmographic harmonic persistence. No relationship was found between pressure sore history and ankle pressure ratio. No significant difference in ankle pressure ratios exists for those who have a pressure sore history as compared to those who have not experienced a pressure sore in 5 years. Those subjects with a diminished buttocks circulation harmonic persistence are more likely to have experienced one or more pressure sores than those subjects with normal circulation characteristics. A Poisson distribution analysis of multiple pressure sore occurrence suggests that repeated pressure sores are unlikely to arise as the result of chance.

Key words: *ankle pressure ratio, blood circulation, paraplegia, photoplethysmographic analysis, pressure sores.*

INTRODUCTION

While many possible etiological factors have been associated with pressure sore incidence, local circulation failure has received special emphasis. In this view, external force acts to cut off local blood circulation in addition to those tissue fluids supplying nutrients. As given by Brand (3), "The death of the cells is a biological death from deprivation, rather than a mechanical death from disruption."

In the case of paraplegic patients, such deprivation may be conjectured to arise from a combination of limited

mobility (implying unchanging body loads over long time periods), the maintenance of improper seating stresses (13), and a general lessening of systolic pressure associated with paralysis (15). In support of this hypothesis, photoplethysmographic (PPG) measurements of paraplegic cutaneous circulation within the buttocks area while seated upon a hard surface indicate median flow rates to be approximately one-third that of normal subjects (2).

However, reduced circulation, while consistent with the possibility of pressure sore onset, is of itself a seriously incomplete indication of potential trauma. Noting that many hours of stasis may be required to establish necrosis (11,4), a mere lessening of local blood flow circulation, even a major reduction, may have no deleterious effect.

In this work, we examine the relationship of pressure sore occurrence to ankle pressure ratio and buttocks cutaneous circulation in a more rigorous fashion. Known incidents of trauma, as given by a direct count of pressure sores experienced by each paraplegic subject over a prior 5-year period, are compared with ankle pressure ratios and local PPG wave shape readings taken at the interface between buttocks and a hard seat. Wave shape is quantified through harmonic analysis, in which the number of significant harmonics comprising the PPG wave form, rather than the pulse amplitude, is employed as a measure of pulsatile flow intensity.

Harmonic analysis of pulsatile flow intensity has the advantage of independence from considerations of gain or signal amplitude. The procedure is one of transforming pulsatile wave forms into a corresponding series of simple harmonic terms: a process in which a representative wave form, established by averaging successive signals, is

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disassembled into its constituent pulses—a series of wave trains. Evaluation is effected by noting the persistence and relative strength of higher harmonics, as compared to the fundamental. Application of this process to mercury strain gauge measurements employed to detect arterial deficiency has been given by Strandness (16) and Bennett and Fischer (1).

Pulse volume harmonic analysis does not reflect the absolute value of pulsatility or that of flow volume. Instead, the number and magnitude of higher harmonics are responsive to the rate of onset of pulsatile flow, a factor termed “acceleration” (14). In other words, the presence of higher harmonics implies nothing about the total quantity of blood being transported per pulse. Only the vigor of onset of the flow pulse is reflected in the presence of higher harmonics. The absence of higher harmonics, and the resulting sluggishness of blood pulse onset, has been associated with aspects of peripheral arterial deficiency by Strandness (16), Winsor *et al.* (19), Lee and Trainor (14), and Kempczinski and Yao (12).

The insensitivity of harmonic analysis to basic signal strength has a practical advantage other than the obvious one of freedom of concern over electronic gain settings and drift. The application of external mechanical load, forcing a reduction of local tissue blood flow, does not alter the resulting harmonic analysis results. Thus, where considerable external loading necessarily exists, as in sitting, harmonic analysis permits a comparison of pulse onset characteristics independently of that decrease in flow owing to transverse tissue loadings; a comparison is permitted between individuals experiencing pulsatile flows of greatly differing magnitudes due to either different loads or states of health.

This work examines the hypothesis that an association exists between those paraplegic subjects contracting pressure sores and ankle pressure ratio measurements or possibly buttocks skin flow circulation measurements, as determined by harmonic persistence of PPG output. In the interest of simplicity, the hypothesis ignores the numerous secondary factors implicated in trauma such as nutrition, hygienic habits, etc.

METHODS AND PROCEDURES

Thirty-four paraplegic subjects appearing at the Castle Point VA Medical Center were recruited without concern for other ailments, aside from those presenting current pressure sores or other immediate trauma. In the case of border line or incomplete quadriplegics, a practical

threshold was employed: those capable of unaided transfer between wheelchairs were accepted as paraplegic subjects.

The medical records of each subject were examined to determine the frequency and location of pressure sores contracted over a prior 5-year period. Each listed sore was of sufficient intensity to require medical attention. No attempt was made to gauge the severity of trauma or to correlate the various therapeutic procedures employed. Each subject was initially examined at brachial and ankle locales with conventional segmental Doppler plethysmography (Bi-directional Doppler, Model 1010A, Parks Electronics Lab, Beaverton, OR). Segmental blood pressure measurement employed a standard clinical procedure (12), in which local blood flow systolic pressure is established by noting the magnitude of cuff counter-pressure just sufficient to permit flow to enter a previously-occluded limb. Such data were normalized by dividing the measured values of ankle blood pressure by brachial blood pressure. The resulting ratio (ankle pressure ratio) has been long associated with degrees of peripheral arterial disease (5,12,14,16).

Upon transferring to an instrumented hard wheelchair seat (2) containing devices sensing pressure, shear, and PPG pulse in the region of the ischial tuberosities, readings were obtained in sitting. Through use of wheelchair arm rest push-ups, the subject was directed to shift his body position slightly to four different locations arranged to offer an increment of roughly one cm of buttocks translation for each positional change. A complete set of force and blood flow data was gathered at each buttocks location within a total elapsed time of 4 minutes for all sites.

Immediate inspection of the data assured the existence of some minimal loading on all four sensors (two pressure, one shear, one PPG). In certain cases, however, subjects off-loaded body weight from monitored portions of the seat to remote portions of the buttocks, resulting in no data. Data inspection also indicated the existence of some minimal arterial flow as shown by pulsatility in the PPG trace. In some instances, it proved possible to load the monitored area of the seat so heavily as to produce arterial occlusion. Lacking any pulsatile flow, harmonic analysis is impossible. A slight shifting of the subject's position invariably eliminated this difficulty. Finally, the data assured the existence of adequate replication of harmonic analysis output.

Of the four sets of data, the first was discarded as possibly influenced by the novelty of the test situation. No further examination of initial-run data was attempted. Of the remaining three runs, at least two were required to offer the same harmonic analysis result. Usually all three were

similar. However, in certain rare cases uncontrollable body motions acted to preclude replication. In this event (four paraplegic subjects), the data were dropped from consideration. Normal subject data did not suffer this difficulty. We have not investigated further the reasons for variability of output. Normal or control subjects (N=23) were drawn from hospital staff workers and those patients presenting symptoms unrelated to either paralysis or circulation disorders.

The transformation of real time PPG data through Fast Fourier Transform techniques was accomplished by a dedicated computer (Smartscope Model 700, T.G. Branden Corp, Portland, OR). This method provided a flat response to within 0.5 percent from DC to 5 Hz and an unstated accuracy within the 5 to 10 Hz band of monitored frequency. In practice, no employment of frequency data beyond 6.5 Hz proved necessary. Spectra chosen for averaging consisted of those ten cycles most recently stored prior to ceasing input. All earlier spectra were automatically dumped. Thus, the total time period examined consisted of ten consecutive heartbeats, equal to an order of magnitude of 8 seconds. Hard copy printouts of each harmonic analysis were obtained from a conventional digital plotter (Hewlett Packard Model 7225B).

The electronic means by which spectral analysis is performed is beyond the scope of this work; the classic monograph by Tukey and Blackman (18) remains a sound introduction to technique. For our purposes, it is sufficient to accept spectrum analyzers as devices presenting the relative intensity of pulse components as a function of frequency. If we imagine a wave form consisting of two perfect sine waves of associated frequencies (fundamental plus second harmonic) to pass through such a device, the output (**Figure 1A**) consists of two single spikes, each of a certain magnitude at a noted frequency. If perfect wide-band Gaussian noise is processed (**Figure 1B**), the output consists of a horizontal line indicating equal intensity at all frequencies. If the noted input signals are combined (**Figure 1C**), the output display features the appropriate analysis of sine wave constituents emerging from a background of noise. If the input wave form is not a perfect composite sine wave, but is reasonably periodic and accompanied with a background of noise, the analysis appears as in **Figure 1D**. An integration of the harmonics, with due allowance for the intensity of each harmonic, will equate with the original wave form.

The means of harmonic evaluation employed in this work consists of gauging harmonic strength relative to the local existent noise level. The actual gauge is of the "yes or no" type: either the harmonic spike stands above the

local noise level and is judged "present," or it does not, and is judged "absent." The fundamental, second, and third harmonics of PPG wave forms were rated in this fashion. These particular harmonics were chosen for evaluation as invariably representing, when taken together, the basic wave form contour.

Actual harmonic analysis raw data, traced from hard copy printouts, is given as **Figure 2**. These represent the PPG wave form analysis results of that soft tissue located near the ischial tuberosity when seated. The axes portray frequency in Hertz (horizontal) versus relative magnitude in decibels (vertical). The intensity magnitude range (10 dB) represents a voltage ratio of 3.16 to 1, or a power ratio of 10 to 1. In practice, signal intensity results have been employed solely in a qualitative sense. No attempt has been made to assess the quantitative significance of signal intensity. The fundamental frequency was determined from the separately recorded PPG trace (i.e., the pulse rate at the time of recording). Higher harmonics were taken as simple multiples of the fundamental frequency. In this fashion, the proper harmonic peaks were located for a normal subject (**Figure 2** top) or for a paraplegic subject (**Figure 2** bottom).

Evaluation consisted of noting the highest harmonic perceptible above background noise. This was accomplished by joining (transparent straightedge) those background peaks straddling a point of interest. If the imaginary line so created fell below the intensity level of the point of interest, the harmonic was judged "present;" if it did not, the harmonic was judged "absent." In the case of the normal subject trace, all three harmonics were judged present. In the case of the paraplegic subject, while the fundamental stands well above background noise, the higher harmonics demonstrate a marked attenuation. The second and third harmonics are exceeded by background noise intensity, as shown by higher adjacent peaks. Hence, this trace was evaluated to be "fundamental only." (All evaluation was performed solely by that author possessing an engineering background.)

RESULTS

The pressure sore history of the paraplegic subject group (N=34) is given in **Tables 1** and **2**. During the preceding 5-year period, half the subjects had experienced no pressure sores (listed as P-Neg) and half had developed one or more pressure sores (listed as P-Pos). The frequency of pressure sore occurrence is also given (i.e., the number of subjects contracting 0, 1, 2, or 3 pressure sores over

Figure 1.

Hypothetical spectrum analysis outputs. Anticipated results, given: (A) an input of a composite wave form consisting of two perfect sine waves, one at twice the frequency of the other; (B) an input of perfect Gaussian noise; (C) an input consisting of (A) plus (B); and, (D) an input consisting of an imperfect composite sine wave containing two wave trains, one of which is twice the frequency of the other. The constituent pulses are reasonably periodic and are witnessed against a background of perfect noise.

Figure 2.

Data evaluation, PPG harmonic analysis. *Top:* Raw results, normal subject. *Bottom:* Raw results, paraplegic subject. At issue is the strength of harmonic peaks (fundamental, second, and third) relative to background intensity. Note that in the top trace, all three peaks stand above the background; in the lower trace only the fundamental stands above the background.

Table 1.

Frequency of paraplegic subject pressure sores (N=34).

Pressure sores per subject	Subjects P-Neg	Subjects P-Pos	Pressure sores
0	17	—	0
1	—	11	11
2	—	2	4
3	—	4	12
Total	17	17	27

P-Neg subjects have experienced no pressure sores over the prior 5-year period.
P-Pos subjects have experienced one or more pressure sores over the 5-year period.

the monitored time span). The total number of pressure sores, 27, experienced by the entire paraplegic subject group is examined in terms of physical location in **Table 2**. Note that the buttocks location accounted for more than half the pressure sore trauma experienced by the test group.

In comparing ankle pressure ratios for the two subgroups (P-Neg and P-Pos), the lower value of a left versus right side of the body comparison was chosen without concern for pressure sore locale. The P-Neg group averaged 0.95 with a median value of 0.94. The corresponding P-Pos group values are 0.90 and 0.96. Value spread within each group is considerable; the lowest P-Neg result (0.56) and the lowest P-Pos value (0.48) each suggest peripheral arterial deficiency. The respective standard deviations are 0.18 and 0.19.

The similarity of ankle pressure ratio results for the two subgroups suggests that pressure sore history is not reflected in ankle pressure ratio measurements. Examination of all ankle pressure ratio data (**Figure 5**) confirms the lack of ankle pressure ratio sensitivity to trauma.

As noted above, PPG harmonic analysis has been performed without concern for the precise magnitude of local sitting loads, beyond assurance of an existing pressure value between "no contact" and "occlusive pressure"

Table 2.

Location and number of paraplegic subject pressure sores (N=34).

Location	Pressure sores
Buttocks	15
Lower leg	7
Hip, thigh	3
Back, sacral	2
Total pressure sores	27

limits. To examine the validity of data gathered in this fashion, tests were conducted employing the finger pads of normal subjects. Typical results are given in **Figures 3 and 4**. The variable in this case is the amount of pressure developed at the finger pad of a given subject, altering from light contact pressure (**Figure 3**) to near occlusion (**Figure 4**). The basic PPG signal output is given at the left side of each figure and the harmonic analysis at the right. Note that the PPG signal is sensitive to the application of pressure, but the harmonic analyses are not; by the standard of measurement employed in this work (the relative strength of higher harmonics to background noise), there is no difference between the low pressure and high pressure harmonic analysis results. Extending this test to eight normal subjects produced identical results without exception.

Buttocks PPG harmonic results are given in **Figure 6**. The bar graphs indicate the percentage of subjects, within each population, displaying listed harmonics, ranging from the fundamental plus second and third harmonics (left), to the fundamental plus second harmonic only (center), to the fundamental alone (right).

All normal subjects display at least a fundamental plus second harmonic (100 percent); the majority (61 percent) manifest a fundamental plus second and third harmonics. The P-Neg group yields a somewhat smaller frequency of those presenting all three harmonics (55 percent), a lesser number of those with a fundamental and second harmonic only (33 percent), and some subjects (12 percent) with a fundamental only.

P-Pos subjects are least likely to manifest all three harmonics (27 percent). The majority of such subjects display only a fundamental and second harmonic (53 percent), and about 20 percent yield a fundamental alone.

Combining percentile harmonic values within each specified group results in the compilation of **Figure 7**. As the population shifts from normal to P-Neg to P-Pos, the percentile of subjects displaying all three harmonics decreases accordingly. A median subject value (50 percentile point) falls within those displaying all three harmonics for normal subjects (left) and for P-Neg subjects (center). However, the P-Pos median value includes only the fundamental plus second harmonic (i.e., the median P-Pos subject displays no third harmonic).

The essential observation of this work is the decline in the display of higher harmonics as one moves from normal to P-Neg to P-Pos. The absence of higher harmonics is not of itself an invariant indicator of trauma, nor is the converse always true. Indeed, many P-Pos subjects yield a normal display. However, a trend exists in which a larger number of normal subjects manifest higher harmonic

Figure 3.

Left: Photoplethysmographic raw data gathered from a normal finger pad under light pressure. *Right:* Corresponding harmonic analysis of raw data.

Figure 4.

Left: PPG raw data, one minute later. Subject is now pressing hard on finger pad, almost to the point of occlusion. Amplitude of signal greatly decreased. *Right:* Harmonic analysis is only slightly altered; first three harmonics remain clearly evident above background level.

Figure 5.

Ankle pressure data of all paraplegic subjects. *Left:* Those without a pressure sore history in the prior 5 years, labeled P-Neg. *Right:* Those with a pressure sore history, labeled P-Pos.

circulation characteristics than do paraplegic subjects, and a larger number of paraplegic subjects without recent pressure sore trauma exhibit a superior display as compared to those with a history of pressure sores.

DISCUSSION

This work examines the possibility that those paraplegics with a history of one or more pressure sores differ in their peripheral circulation characteristics from those who do not contract pressure sores. It is of interest to consider a contrary but not quite opposite proposition: development of multiple pressure sores is a random event.

Figure 6.

(A) Distribution of subjects displaying all three harmonics. (B) Distribution of subjects displaying fundamental and second harmonic only. (C) Distribution of subjects displaying fundamental only.

To test for randomness of repeated trauma, the Poisson distribution of multiple pressure sores has been calculated employing the average chance of initial occurrence (17 out of 34) as given in **Table 1**. The results offer little support to the concept of random trauma; in the extreme case of those experiencing three or more pressure sores, the actual subject count is 5.7 times as large as the number expected

to arise from chance. In other words, repeated trauma is not a chance event. It follows that those paraplegic subjects contracting multiple pressure sores are different in some fashion from those who contract only one pressure sore. Nothing in the Poisson distribution calculation permits any comment on the larger issue: the manner in which those contracting pressure sores differ from those who

do not.

To examine the peripheral circulation aspects of this issue, we have grouped together all those with a history of pressure sores (P-Pos) without concern for frequency of trauma. When compared to those without a pressure sore history over a 5-year period (P-Neg), by the standard of ankle pressure ratio, the two subgroups are so alike in mean and median values as to suggest ankle pressure ratio insensitivity to pressure sore trauma. By the standard of PPG harmonic decrement at the buttocks, the two subgroups differ in that more P-Pos subjects demonstrate a decreased blood flow intensity, as compared to P-Neg subjects. Normal subjects are found most likely to yield a full complement of blood flow harmonics.

In short, more paraplegics with a diminished buttocks cutaneous circulation experience pressure sore trauma than those with a normal buttocks cutaneous circulation. Such a result is not intuitively surprising. It supports the well-known view that pressure sores result from a dearth of local nutrients, or possibly reflect the circulation's inability to carry away an overabundance of metabolites.

Yet, peripheral circulation tests based upon conventional ankle pressure ratio tests yielded no clear result. We are led to consider the manner in which PPG measurements differ from those of ankle pressure testing.

Segmental pressure tests measure the "total head" or locally available hydraulic pressure developed through the arterial system to a point of interest. Composed of both

Figure 7.

Harmonic distribution as a function of subject type. Note that the median subject in both Normal and P-Neg groups displays all three harmonics, while the median P-Pos subject lacks a third harmonic.

static and kinetic energy terms delivered through major and minor vessels, the result amounts to an integrated, lumped sum of pressure escalation and attenuation along all flow paths leading to the site under test—in this work, the ankle. Noting that more than half of all recorded pressure sores developed at the buttocks (**Table 2**), it is our conjecture that ankle pressure measurements are too remote from the site of likely trauma to serve as a useful indicator.

In contrast, PPG measurements respond only to local skin flow at the site examined. Those vessels examined are a function of the light frequency employed. Infrared light senses small arteries, whereas green light responds to arteriolar flow (8). For the green filtered sensor (back scattering) used in this work, only cutaneous arterioles are perceived.

PPG pulse amplitude correlates well with pulse volume magnitude. Pulse volume comparisons between mercury strain gauge and PPG sensors in normal humans (17) were found to offer a correlation coefficient of 0.94. Similar experiments (sensors mounted on adjacent fingers) by Dorlas and Nijboer (7) in 107 patients during anesthesia indicated that “the changes in amplitude of both plethysmograms proved to be identical in 98 percent of the total...”

Thus, PPG amplitude may be said to offer quantitative insight into pulse volume. However, our study employs PPG wave form characteristics, rather than amplitude, as a measuring rod. As given in **Figures 3** and **4**, PPG wave form harmonic analysis is not influenced by transverse pressure applied to tissue, short of occlusive pressure. It follows that a response to pulse volume is unlikely.

PPG amplitude as a quantitative measure of blood flow remains uncertain. The early work of PPG inventor Hertzman (9) intimated qualitative merit to exist; that is, “amplitude of the volume pulse is a criterion of the blood supply of the skin.” Subsequent workers have sought a quantitative correlation between PPG amplitude and blood flow, as given by such measures as cc/min or cc/100 ml tissue/min. Modern results include those of Davis (6) who submitted quantitative linear correlations between flow and signal strength as seen in dogs ($r \geq 0.93$). The work of Trafford and Lafferty (17), employing human finger pulp, also demonstrated a linear relationship between PPG output and quantitative blood flow ($r \geq 0.87$). However, negative findings do exist, such as that of Hocherman and Palti (10). Further, those researchers suggesting PPG as a quantitative tool also warn of undesirable sensitivity to side factors such as the axial streaming of blood cells or the variation in hemoglobin content, or nonlinear response in the event of local nervous system excitation.

For these reasons, it is our premise that PPG amplitude

supplies no more than a useful qualitative indication of local blood flow. In choosing to monitor PPG wave form, we seek an aspect of flow other than mass rate. Plethysmographic wave form is known to be influenced by state of health. Specifically, higher harmonic components have been shown to diminish as a function of disease in peripheral arterial deficiency (16) and diabetes (19). While factors pertinent to higher harmonic persistence include wall distensibility and intraluminal pressure (5), investigators have focused on the “acceleration” or pulse onset aspect of pulsatile blood flow as a likely physical link between the absence of higher harmonics and the presence of disease. In this view, the rate of rise of pulse volume serves as an indicator of net local impulsive and flow resistance forces; a large rate of rise implies an energetic local arterial blood flow. The converse is also held true. It has been shown (1,16) that the higher harmonics, especially the second and third, are responsible for the rate of rise of pulse volume in normal and PVD subjects.

It is our conjecture that those paraplegic subjects evidencing an absence of higher harmonics experience a similar reduction in local arterial blood flow energetics. When vessel damping becomes pervasive and acts to diminish the pulsatility of flow, the higher harmonics vanish.

Our results indicate more paraplegics with diminished higher harmonic intensity experience pressure sores than do those with a normal complement of higher harmonics. A study of possible causal relationships between PPG harmonic intensity and pressure sore incidence would appear useful.

The use of harmonic analysis as an instrumental technique inevitably raises questions concerning the aptness and precision of application. For example, how much of the background noise represents a true physiological reaction as compared to circuit noise? What is the influence of sampling frequency, weighting, and filtering techniques? How does PPG light wave filtering and the consequent variation of tissue depth examined influence the outcome? Is the purely qualitative treatment of PPG harmonic amplitude, as given here, capable of extension to quantitative employment?

It is hoped that answers to these questions will be forthcoming as harmonic analysis usage becomes more widespread. At this time, we can say only that PPG harmonic analysis offers certain insights into the probability of pressure sore occurrence.

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