proved by the concomitant use of real-time frequency analysis.

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PREVIOUS REPORTS on the clinical application of the ocular pneumoplethysmograph (OPG-Gee) have emphasized the screening aspect of this instrument in the detection of hemodynamically significant carotid lesions.1,2 These reports were based on data obtained between 1973 and 1978, during which time the maximum vacuum capacity of the instrument was 300 mm Hg. Early in 1978 the instrument was modified to allow a maximum vacuum capacity of 500 mm Hg. The data derived with the latter instrument have substantially improved its accuracy as a screening device. However, an aspect of the instrument not previously emphasized is its ability to characterize the physiology of hemodynamically significant carotid lesions and the intracranial consequences of the various combinations of these lesions, as they are encountered clinically in the individual patient. This report describes this physiology in 667 patients, all of whom underwent arteriography.

Methods
Although a number of factors contribute to the hemodynamic significance of a carotid lesion, the principal element is the relationship between the cross-sectional area of the residual lumen at the level of the lesion and the cross-sectional area of the normal artery distal to the carotid bulb. Arteriography defines the lumen diameter at these two levels, but if the same diameters are noted in two planes at right angles to each other, cross-sectional areas can be calculated. Experimental work has defined a 75% cross-sectional area stenosis as flow-reducing or critical.3 Figure 1 is a diagrammatic representation of these two stenoses as seen in the typical location in the internal carotid artery. Although only one plane is demonstrated in each instance, cross-sections of both define the stenoses as circumferential.

The standard procedure for the OPG study is as follows. With the patient in the sitting position, both brachial blood pressures are determined by arm cuff and auscultation. This is a very important step, as any substantial difference in these measurements is indicative of considerable arterial stenosis on the side of the lower pressure. With the patient in the supine position, the OPG test is done as previously described.4 Immediately upon completion of the test, with the patient remaining in the supine position, the brachial blood pressure is again measured in the standard fashion. This determination is made in the arm with the higher pressure noted in the sitting position. The bilateral ophthalmic systolic pressures (OSP) as determined by the OPG are then plotted against the brachial systolic pressure (BSP) measured immediately after the OPG test. The BSP is plotted on the x-axis (abscissa) of a graph, and the OSP is plotted on the y-axis (ordinate). The resulting point is termed a (BSP,OSP) coordinate. The derivation of the criteria are:

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Carotid Physiology with Ocular Pneumoplethysmography

WILLIAM GEE, M.D.

SUMMARY The ocular pneumoplethysmograph (OPG-Gee) defines both the qualitative and quantitative physiology of the carotid arterial hemisystems and associated hemodynamically significant lesions. This report defines this physiology in 667 patients, all of whom underwent arteriography.
A. For a unilateral hemodynamically significant carotid lesion (stenosis or occlusion).
1. Both OSP’s are above the lower limit of normal, as characterized by the formula OSP = 39 + 0.43 BSP, and the OSP on the side of the lesion is at least 5 mm Hg lower than the contralateral OSP, or
2. The OSP on the side of the hemodynamically patent carotid artery is above the lower limit of normal, and the OSP on the side of the hemodynamically significant carotid lesion is on or below the lower limit of normal, no matter what the degree of separation of the respective OSP’s.

B. For bilateral hemodynamically significant carotid lesions (stenoses and/or occlusions).
1. Both OSP’s respective to a patient are on or below the lower limit of normal.
2. These OSP’s may be equal, or they may be unequal to a varying degree.
C. For no hemodynamically significant carotid lesions.
1. Both OSP’s respective to a patient are above the lower limit of normal.
2. The OSP’s are usually equal, but may be unequal by as much as 4 mm Hg.

In order to simplify the correlation of the anatomic data derived from the arteriographic interpretations with the physiologic data derived from the OPG studies, each carotid artery respective to a patient was designated, on the basis of its arteriographic appearance, in one of three ways: 1. (O) – occlusion. 2. (S) – 75% or greater, cross-sectional area stenosis. 3. (N) – neither of these lesions. The six possible categories totaled 767 patients, which exceeds the base number of patients studied (667), because 176 of the base number of patients underwent 192 carotid endarterectomies, and many of these patients moved from one category to another, as result of operation. Each category of patients will be described physiologically, on the basis of the (BSP,OSP) coordinates peculiar to each.

Results

Category 1 (N-N)
These 330 patients had no carotid lesions of hemodynamic significance. In all of these patients the two ophthalmic systolic pressures respective to each patient were equal. Therefore, both of the (BSP,OSP) coordinates respective to each patient are identical, and they are represented by one dot in the graph in figure 2. The mean value of the OSP for any given value of the BSP can be calculated by the formula OSP = 55 + 0.43 BSP. The middle oblique line in figure 2 is the graphic representation of this formula. The standard error of estimates (s_y.x) for this regression line is 8 mm Hg. The upper and lower oblique lines on the graph represent the regression line, ± 2 s_y.x. Hence, the lower line is represented by the formula OSP = 39 ± 0.43 BSP. It is around this line that the criteria for abnormality of the OPG were constructed. Hereafter, this line will be termed the line of demarcation. If this line of demarcation is specified as the lower limit of normal, the eight (BSP,OSP) coordinates in figure 2 which are on or below this line are abnormal, by definition. Therefore, the OPG studies in these eight patients must be considered bilaterally (16) false-positive.

Category 2 (S-N)
Each of these 208 patients had a unilateral carotid stenosis of hemodynamic significance (75% or greater, cross-sectional area), with hemodynamic patency on the opposite side. The composite (BSP,OSP) coordinates, on the side of the stenosed arteries, are in...
figure 3. The oblique line on the graph is the mean of the OSP for any given BSP, and it is represented by the formula OSP = 58 + 0.32 BSP. In each S-N patient the OSP on the side of the stenosis was at least 5 mm Hg less than on the contralateral side. In 50% of the patients the difference in the OSP's respective to each ranged between 5–9 mm Hg, 10–14 mm Hg in 26%, and greater than 14 mm Hg in the 24% remaining. Thus, the ability to precisely measure the very small pressure differences is essential to the accuracy of determining unilateral carotid stenoses of hemodynamic significance. The OSP to BSP relationship on the side of the patent arteries (N) is OSP = 62 + 0.37 BSP, which closely approximates that for the data of the patients in Category 1.

Category 3 (O-N)

Each of the 111 patients in this group had a unilateral carotid occlusion, with the opposite carotid system hemodynamically patent. The composite (BSP,OSP) coordinates, on the side of the occlusions, are in figure 4. The oblique line on the graph is the mean of the OSP for any given BSP, and it is represented by the formula OSP = 46 + 0.34 BSP. In each O-N patient, the OSP on the side of the occlusion was at least 5 mm Hg less than on the contralateral side. However, in contrast to the S-N patients in Category 2, the difference in the ophthalmic systolic pressures respective to each was 5–9 mm Hg in only 18%, 10–14 mm Hg in 25%, and greater than 14 mm Hg in 57% remaining. The OSP to BSP relationship on the side of the patent arteries (N) is OSP = 52 + 0.43 BSP, which closely approximates that for the data of the patients in Category 1.

Category 4 (S-S)

The 53 patients in this group had bilateral carotid stenoses of hemodynamic significance. The 106 (BSP,OSP) coordinates respective to the patients are in figure 5. The 16 horizontally paired circles represent the equal ophthalmic systolic pressures respective to each of these patients. The ophthalmic systolic pressures respective to each of the remaining patients were unequal, and each data pair is represented by two open circles connected by a vertical line. The oblique solid line on the graph is the mean of the OSP for any given BSP, and it is represented by the formula OSP = 39 + 0.38 BSP. The interrupted oblique line on the graph is the line of demarcation of the N-N patients in Category 1. Above the line of demarcation are five pair of data in which the respective ophthalmic systolic pressures are equal (four patients) or unequal by less than 5 mm Hg (one patient). By the criteria previously described, these five OPG studies are not abnormal, and they are, by definition, false-negative. On a per artery basis,
these five patients constitute ten false-negative OPG results. In addition, in six patients, one OSP respective to each was above the line of demarcation, and each of these is a false-negative finding. Finally, in one patient in whom OSP’s differed by more than 5 mm Hg, but both of which were above the line of demarcation, the higher OSP must be termed false-negative, for a total of 17 false-negative results in the 106 arteries characterized.

**Category 5 (O-S)**

Each of these 43 patients had a unilateral carotid occlusion and a contralateral carotid stenosis of hemodynamic significance. The 86 (BSP,OSP) coordinates respective to these patients are in figure 6. If the ophthalmic systolic pressures respective to a patient are equal (nine patients), they are represented by horizontally paired circles, with one of the circles open to denote the stenosed artery and with one of the circles solid to denote the occluded artery. If the ophthalmic systolic pressures respective to a patient are unequal (34 patients), the two coordinates are connected by a vertical line. Again the open and solid circles denote, respectively, the stenosed and occluded arteries. In nine of these 34 patients the ophthalmic systolic pressure on the side of the carotid occlusion exceeded the ophthalmic systolic pressure on the side of the carotid stenosis. Thus, in 18 of the 43 patients (42%), the ophthalmic systolic pressure being delivered by collateral routes, on the side of carotid occlusion, equaled or exceeded that being delivered to the eye via a stenosed carotid vessel. The oblique interrupted line on the graph represents the line of demarcation of the N-N patients in Category 1. The oblique solid line is the mean of the OSP for any given BSP in these 43 patients, and it is represented by the formula OSP = 50 + 0.29 BSP. Although all 43 patients in this group had abnormal OPG studies, there were six false-negative
strokes, on a per artery basis. In three patients the OSP's respective to each were above the line of demarcation but separated by more than 5 mm Hg. The higher OSP respective to each patient constituted a false-negative finding. In three other patients one OSP respective to each was above the line of demarcation, and each is a false-negative result.

Category 6 (O-O)
The 22 patients in this group have bilateral carotid occlusions, as documented by angiography. The data from each patient is represented by paired solid circles, as seen in figure 7. In the five patients in whom the respective ophthalmic systolic pressures are equal, the (BSP, OSP) coordinates are represented by horizontally coupled solid circles. Each of the remaining 17 patients had unequal ophthalmic systolic pressures. The data pair for each of these patients is arranged in a vertical plane, and the solid circles are connected by a vertical line. The oblique interrupted line on the graph represents the line of demarcation as derived from the data of the patients in Category 1 (Figure 2).

Data Conclusions
The data apply in two ways, the screening capacity of the instrument and the documentation of the quantitative physiology of the carotid arterial hemisystems. Under the circumstances of screening, two qualifications are necessary. On a per patient basis, the OPG study and the arteriogram are either positive or negative. For the OPG test and the arteriogram to be positive, they must demonstrate the presence of at least one OPG studies, one patient had one OSP above the line of demarcation. On a per artery basis, this is a false-negative result.

Summary of Categories
In 48/118 patients (41%) in Categories 4, 5 and 6, the difference in the two ophthalmic systolic pressures respective to each was less than 5 mm Hg. Without comparison with the appropriate brachial systolic pressures, all of these studies would have been interpreted as normal. The importance of this criterion for the interpretation of OPG-Gee studies is emphasized. Figure 8 is a graphic demonstration of the OSP to BSP relationships in the six categories. Four distinct groups are noted: 1. N-N. 2. N-S (side of stenosis). 3. S-S, S-O, N-O (side of occlusion). 4. O-O. The two extremes (N-N, O-O) and the remaining alignments are as expected, when the various arteriographic configurations are considered.
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FIGURE 7. Arteriography documented bilateral carotid occlusions in these 22 patients. All (BSP, OSP) coordinates are represented by solid circles. The data pairs which horizontally abut represent five patients in whom the ophthalmic systolic pressures respective to each were equal. The remaining 17 data pairs are connected by vertical lines, denoting unequal ophthalmic systolic pressures in each patient. The horizontal solid line on the graph is the mean of the OSP for any given BSP. The interrupted oblique line is the line of demarcation as derived from the data of the patients in Category 1 (Figure 2).

hemodynamically significant carotid lesion. In comparison with the arteriographic findings, the patient OPG study was false-negative in five and false-positive in eight, for an overall accuracy of 98%.

In an evaluation of the instrument for the documentation of the quantitative physiology of the carotid arterial hemisystems, the same two qualifications previously stated are applicable, but on a per artery, rather than a per patient basis. In comparison with the arteriographic findings, the artery OPG study was false-negative in 24 and false-positive in 16, for an overall accuracy of 97%. These conclusions are summarized in the table.

The data from an additional 47 patients were not included in this study. Arteriograms in these patients demonstrated little or no atherosclerosis of one carotid artery, and an atherosclerotic carotid stenosis bordering on pressure-significance in the other carotid artery. In 25 of these 47 patients the OPG indicated that the carotid stenosis was of pressure-significance, but the majority of the reviewers of the arteriograms felt that the respective stenoses were approaching, but not yet pressure-significant. If these patients had been included in the study, they would appear in Category 1. In 22 of the 47 patients the arteriographic configurations were the same as in the group of 25 patients, but the majority of the arteriographic reviewers felt that the single stenosis respective to each patient had reached pressure-significance. The OPG tests in these 22 patients were indicative of no carotid stenosis of pressure-significance. If these patients had been included in the study, they would appear in Category 2.

Although the arteriogram is universally accepted as the "gold standard", difference of opinion does exist in the determination of the degree of a carotid stenosis in some percentage of cases. If it were concluded that the OPG tests were wrong in all 47 patients, and if these data were included in the study, it would result in an additional 25 false-positive OPG tests in Category 1 and 22 false-negative OPG tests in Category 2. Recalculation of these data would result in a per patient sensitivity, specificity and accuracy of 94%, 91% and 93%, respectively, and a per artery sensitivity, specificity and accuracy of 92%, 96% and 95% respectively. The per patient accuracy of 93% is in very close agreement with the results of three independent studies, which were 93%, 93.5% and 92.5%, respectively.5-7

Comments

Prior to March 1978 the maximum vacuum capacity of the ocular pneumoplethysmograph was 300 mm Hg, which did not permit measurement of ophthalmic systolic pressures above 110 mm Hg. The initial criteria for interpretation were published in a 1977 report.1 As data accumulated, these initial criteria were modified in a 1979 report.2 In February 1978 the instrument was modified to permit a maximum vacuum of 500 mm Hg, which allows the measurement of ophthalmic systolic pressures up to 145 mm Hg. A preliminary report
establishing the initial criteria for interpretation with the modified instrument was published in 1980.8 The present study represents an accumulation of data from March 1978 through March 1981, and the criteria for interpretation are slightly different.

It is important to distinguish the criteria contained in this report from criteria recently published regarding immediate postoperative OPG tests.9 The latter criteria are applicable only to immediate postoperative tests, and they should not be confused with those in this report. In fact, it was the application of the standard criteria in this report to immediate postoperative tests which generated a large number of "false-positive" tests, as confirmed by postoperative arteriography. These observations prompted the development of the special criteria applicable only to immediate postoperative (recovery room) tests.

Comparison of preoperative and postoperative OPG-Gee data will demonstrate the restoration of normal physiology as a result of endarterectomy of hemodynamically significant carotid stenoses. However, operation and anesthesia can profoundly affect the intrinsic fluid dynamics of the eye, as well as the cardiovascular system. Although immediate postoperative (recovery room) and short-term postoperative (3–5 days) studies have proved to be quite valuable for detection of early postoperative occlusion,9 they can be quite misleading regarding the physiology of the carotid arterial system in the steady state. Postoperative studies for comparison with preoperative studies should be and were obtained no less than 4–6 weeks after operation. Our routine is to obtain serial postoperative studies at six month intervals after operation. A group of 68 patients who underwent carotid endarterectomies of hemodynamically significant carotid stenoses, in whom the opposite carotid arteries were functionally patent (without hemodynamically significant stenosis or total occlusion) were converted from Category 2 (S-N) to Category 1 (N-N). The preoperative data are represented by the mean of the OSP for any given BSP, and the formula of this mean is \( OSP = 50 + 0.36 \times BSP \). This very closely approximates that described for all of the patients in Category 2 (fig. 3). The mean of the postoperative OSP for any given BSP is represented by the formula \( OSP = 61 + 0.39 \times BSP \). This very closely approximates that described for all of the patients in Category 1 (fig. 2). The average improvement as a result of operation is 15.5 mm Hg, which is very close to the average difference of 13.5

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**TABLE Sensitivity, Specificity, and Overall Accuracy of the OPG-Gee, on a Per Patient Basis and on a Per Artery Basis**

| Arteriogram | Posi...
mm Hg between all of the patients in Category 1 as compared to Category 2.

The 118 patients in the last three categories, all of whom have bilateral carotid lesions of hemodynamic significance, demonstrate quantitatively the consequence of the combined lesions respective to each. Two previous reports document the quantitative physiologic changes resulting from carotid endarterectomies in such patients.8, 10

Over the past three decades there has been a shift in the emphasis on the etiology of central nervous system symptoms as a result of carotid atherosclerosis. Originally, these symptoms were related to blood flow impairment. An emphasis on embolus-related disease followed. A recent report suggests that the incidence of recurrent transient ischemic attacks and strokes is low in patients in whom the OPG test is negative, whereas the incidence of both is significantly increased in patients in whom the OPG test is positive.11

The quantitative element of ocular pneumoplethysmography reflects the intracranial consequences of hemodynamically significant carotid lesions. The consequence of unilateral hemodynamically significant carotid stenoses is not profound, but the physiologic alteration as a result of carotid endarterectomy in these patients can be precisely documented. Unilateral occlusion, rather than stenosis, results in a more profound change. In the 111 patients in Category 3, all of whom had a unilateral carotid occlusion with a functionally patent contralateral vessel, 35/111 (32%) had ophthalmic systolic pressures, on the side of occlusion, which were completely within normal limits, as defined by the data from the patients in Category 1. At the other extreme were 15/111 patients (14%) whose ophthalmic systolic pressures, via collateral routes, on the side of occlusion, were so low that a fall in brachial systolic pressure, spontaneous or therapeutic, would lower the respective ophthalmic systolic pressure on the side of occlusion to a precarious level of 60 mm Hg. When the entire group is considered, it is obvious that there is a wide variability in the adequacy of intrinsic collateral routes. Operative construction of a collateral route might be totally unnecessary in 35 of these patients, and 15 patients might benefit from such a procedure. A recent report lends support to this concept.12

The purposes of this paper are twofold. The first is the definition of criteria for interpretation of the ocular pneumoplethysmograph, when the instrument is used as a screening device, for the detection of hemodynamically significant carotid lesions. The second is the description of the physiologic consequences of the presence of unilateral or bilateral carotid lesions of hemodynamic consequence. Omission of history, physical examination and clinical course in these patients has permitted an orderly concise presentation of these data.

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