A whisper from the past: does plethysmography still have a role in the contemporary evaluation of peripheral arterial intervention?

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Abstract:

Introduction: Air plethysmography (APG), or pulse volume recording (PVR), is a quantitative, non-invasive method for assessing arterial hemodynamics by measuring limb volume changes from pulsatile blood flow. Although its venous applications are well established, its arterial role, especially in revascularization assessment, has not been clearly defined. This narrative review examined the physiological basis, technical implementation, and clinical utility of APG in evaluating open and endovascular arterial interventions.

Methods: A narrative literature review of PubMed, Scopus and Web of Science electronic databases (1960-2025) identified studies describing APG use in intra-operative assessment, post-operative surveillance, or functional evaluation of peripheral revascularization. Only verified peer-reviewed studies were included.

Results: In open bypass surgery, intra-operative APG provides immediate feedback on graft function and anastomotic integrity, with improved waveform amplitude predicting durable patency. Serial post-operative measurements detect early hemodynamic decline, before clinical or Duplex evidence of failure. After endovascular therapy, APG offers a functional measure of perfusion improvement, particularly valuable when imaging is limited by calcification. APG also quantifies post-operative reactive hyperaemia and transient limb oedema, reflecting physiologic reperfusion responses.

Conclusion: APG remains a useful, yet underutilized method for assessing arterial revascularization. By providing reproducible, calcification-independent, and physiologically meaningful data, it complements Duplex ultrasonography and may re-emerge as a key modality in post-operative hemodynamic surveillance of peripheral arterial intervention.

Key-words: air plethysmography, pulse volume recording, hemodynamics, peripheral arterial intervention, surveillance

INTRODUCTION

Peripheral arterial disease (PAD) is a common manifestation of systemic atherosclerosis, characterized by progressive narrowing and occlusion of peripheral arteries, leading to chronic tissue ischemia, claudication, and in advanced stages, critical limb-threatening ischemia.[1] The management of PAD has evolved substantially over the past decades, moving from exclusively open surgical bypass to a multidisciplinary approach, encompassing endovascular, open, and hybrid revascularization techniques.[1] These interventions aim to restore perfusion, relieve symptoms, and prevent limb loss, and their success is determined by durable patency and sustained hemodynamic improvement.[1,2]

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doi: 10.59037/w5xvpj52

ISSN 2732-7175 / 2025 Hellenic Society of Vascular and Endovascular Surgery Published by Rotonda Publications

Non-invasive hemodynamic assessment constitutes the cornerstone in the diagnosis and post-operative surveillance of PAD.[1,3] Accurate evaluation of arterial flow dynamics is essential for quantifying ischemic severity, determining the adequacy of revascularization, and detecting early graft or stent failure.[1,2] Conventional techniques such as the ankle-brachial index (ABI) and continuous-wave Doppler waveform analysis remain fundamental tools, but their sensitivity is limited in cases of arterial wall calcification, multilevel disease, or post-interventional settings.[3,4] These limitations have prompted the adoption of complementary modalities, capable of providing a more direct, physiologic representation of regional perfusion.[3]

Air plethysmography (APG), also referred to as pulse volume recording (PVR), offers a quantitative, non-invasive method for assessing arterial hemodynamics, through the measurement of limb volume changes induced by pulsatile blood flow.[5] The technique records pressure variations within an air-filled cuff that encircles the limb segment, generating characteristic waveforms that reflect arterial compliance, peripheral resistance, and inflow dynamics.[5,6] Since its introduction in the 1970s, APG has been employed both intra-operatively, where it can verify restoration of distal pulsatility after revascularization, and post-operatively, as a reproducible tool for non-invasive monitoring of perfusion recovery.[7,8] Although its clinical use is dominated by its venous applications, the growing emphasis on objective functional assessment have reawakened interest in its role for evaluating outcomes following open and endovascular arterial interventions.[9]

The aim of this narrative review was to provide a comprehensive and critical appraisal of the role of APG in the evaluation of peripheral arterial interventions. Specifically, it sought to elucidate the physiological principles of APG, its technical applications in both open and endovascular arterial reconstruction, and its value in assessing procedural success and long-term hemodynamic outcomes. By summarizing evidence from historical and contemporary studies, this review aimed to define the diagnostic accuracy, and prognostic implications of APG-derived parameters, such as waveform amplitude, in relation to graft and stent patency, re-intervention rates, and post-operative limb edema, therefore, highlighting its contemporary role within the context of modern vascular imaging and hemodynamic arterial assessment.

METHODS

A comprehensive narrative review of the literature was conducted on the use APG in the evaluation of peripheral arterial interventions. An extensive, electronic search strategy was applied to PubMed, Scopus, and Web of Science databases, focusing on studies published between 1960 and 2025. The search strategy used various combinations of the following keywords: “air plethysmography”, “pulse volume recording”, “peripheral arterial disease”, “bypass surgery”, “angioplasty”, “endovascular”, “hemodynamic monitoring”, and “limb perfusion”. The last search was run on 14 October 2025. Only articles published in English and indexed in peer-reviewed journals were included. Eligible studies were those reporting original clinical data, intra-operative or post-operative plethysmographic assessments, or methodological advancements relevant to arterial hemodynamics. Publications restricted solely to venous plethysmography were excluded. Additional references were identified through manual screening of bibliographies from relevant articles, with cross-referencing to original reports whenever possible. Data were synthesized narratively to highlight physiologic principles, intra- and post-operative applications, and comparative outcomes across open and endovascular interventions. No formal quantitative meta-analysis was performed, given the heterogeneity of methodologies, outcome measures, and study designs.

Principles and technical aspects of APG

APG quantifies changes in limb segmental volume by detecting pressure variations within air-filled cuffs positioned circumferentially around the extremity.[5] These cuffs are connected to sensitive transducers, that record minute fluctuations in air pressure, corresponding to volumetric changes, typically in the range of 75-400cm^3, induced by arterial pulsations during the cardiac cycle.[5] The resulting waveform, commonly referred to as PVR, reflects the dynamic relationship between arterial inflow, vascular compliance, and peripheral resistance.[6]

Characteristic waveform morphology provides qualitative and quantitative information on the severity of arterial obstruction.[6,9,10] A triphasic contour represents normal arterial compliance and unobstructed flow, while a biphasic configuration indicates reduced elasticity or moderate proximal stenosis.[6,9,10] A monophasic or flattened waveform denotes severe inflow limitation or distal perfusion deficit, often associated with critical limb ischemia.[6,9,10] In clinical practice, segmental measurements are typically performed at standardized levels - thigh, calf, ankle, and foot - to delineate the anatomical level of disease, and to monitor post-operative hemodynamic improvement.[7,10]

Because APG assesses pulsatile volume change rather than static pressure, it remains unaffected by arterial wall calcification and non-compressibility, that can compromise the accuracy of ABI measurements.[7,11] This renders the method particularly valuable in patients with diabetes mellitus, chronic kidney disease, or medial arterial calcinosis, where conventional ABI is often unreliable.[12] Beyond its diagnostic capacity, the reproducibility and quantitative nature of APG make it a useful adjunct in both intra-operative and post-operative monitoring of lower limb revascularization.[6,10]

Historical role in open arterial surgery

The earliest clinical applications of APG were closely associated with open arterial surgery, where the method served as a real-time hemodynamic monitoring tool.[8] Intra-operative plethysmographic recordings provided immediate, objective assessment of graft patency and distal perfusion following arterial reconstruction, long before the widespread availability of Duplex ultrasonography.[13,14]

Griffin et al[13] conducted one of the seminal studies on intra-operative segmental plethysmography, analyzing 156 vascular operations, that included femoropopliteal and femorodistal bypasses, as well as endarterectomies. Restoration of a normal pulsatile waveform immediately after graft or endarterectomy closure predicted durable post-operative patency in 94% of limbs, while the absence of pulsatility correlated strongly with technical failure requiring immediate revision. These early data underscored the value of waveform morphology as a sensitive indicator of flow restoration and anastomotic adequacy.[13]

Baird et al[14] subsequently expanded on these findings in a series of 83 limbs undergoing femoropopliteal or femorodistal bypass procedures. Mean pulse amplitude increased from 4.5mm prior to revascularization to 18mm post-reconstruction, quantitatively confirming improved perfusion. Importantly, intra-operative waveform deterioration identified with an accuracy of 86% graft or distal anastomotic defects in 11% of cases, all of which were corrected before wound closure, thus preventing early graft failure. When APG is used in addition to traditional angiography, the diagnostic accuracy improved to 95%.[9] These results established intra-operative APG as an effective adjunct to Doppler ultrasonography, particularly in distal reconstructions, where even subtle technical errors could jeopardize long-term graft success.[14]

In the post-operative setting, segmental plethysmography was adopted as a non-invasive tool for early detection of graft dysfunction.[15] Studies from the 1970s and 1980s demonstrated that an increase in waveform amplitude greater than 25% at the calf or thigh level following bypass correlated with successful revascularization and improved ankle systolic pressures.[16,17] Conversely, progressive amplitude reduction or delayed systolic upstroke during follow-up was found to precede graft stenosis, often weeks before clinical symptoms emerged, or before it got angiographically confirmed.[18,19] These observations highlighted the prognostic value of plethysmographic waveforms as early indicators of hemodynamic compromise, and provided the foundation for integrating APG into long-term graft surveillance protocols.[7,10]

Modern application in endovascular interventions

The rapid expansion of endovascular therapy, including percutaneous transluminal angioplasty, stent implantation, and atherectomy, has created a growing need for accurate, reproducible, and non-invasive methods to evaluate procedural efficacy and long-term hemodynamic improvement.[20,21] Although Duplex ultrasonography remains the reference standard for post-intervention assessment, APG offers distinct physiological insights.[21] Unlike Doppler imaging, which provides localized velocity measurements at discrete arterial sites, APG reflects the cumulative hemodynamic effect of revascularization on distal perfusion and overall limb compliance.[21] This global perfusion assessment could complement imaging-based modalities by quantifying the functional improvement in limb blood flow.[10] However, the literature around the use of APG/PVR for assessment and surveillance of endovascular intervention is scarce.

In a prospective evaluation of 120 limbs treated with infra-inguinal angioplasty, McPharlin et al[23] demonstrated that pulse volume waveforms improved following technically successful interventions, whereas limbs with suboptimal angiographic results showed minimal or no change in amplitude. However, these findings were not significant, and the authors noted that absolute waveform amplitude alone was less predictive of long-term patency than Doppler-derived peak systolic velocity ratios. Moreover, in the context of stent surveillance, preservation or further enhancement of waveform amplitude and contour stability has been correlated with sustained luminal patency, whereas waveform flattening or amplitude attenuation frequently precede Duplex-detected in-stent restenosis.[24,25] However, the broader integration of APG into routine endovascular surveillance has been limited by the absence of standardized criteria for waveform interpretation, and the lack of comprehensive normative datasets. This emphasizies the complementary, rather than substitutive, role of APG in the endovascular era.[23]

Comparative patency outcomes: open vs endovascular

When comparing the use of APG across open and endovascular revascularization strategies, several hemodynamic and clinical outcome domains warrant consideration, including patency, re-intervention rates, and post-operative limb volume dynamics.[10] In open arterial reconstructions, intra-operative APG has consistently demonstrated a strong predictive relationship with early graft patency.[13,14] Restoration of a normal or near-normal waveform at the time of graft completion correlates with durable hemodynamic success, while persistent waveform attenuation frequently indicates technical error or residual inflow obstruction.[13,14] In contrast, although endovascular interventions show a similar directional correlation, the strength of this association is often attenuated due to confounding factors, such as distal microvascular resistance, recoil, or uncorrected outflow disease.[23] Some studies have suggested that an increase in PVR amplitude exceeding 30%, immediately after the procedure, predicts superior primary patency at 12 months.[26,27] However, these findings remain preliminary and require validation in larger prospective cohorts.

Post-operative limb hyperemia and oedema

Post-operative limb edema represents another important but often underappreciated domain in which APG provides unique insights.[28] Following arterial revascularization, the limb undergoes dynamic hemodynamic and microvascular adjustments.[29] Restoration of arterial inflow induces reactive hyperaemia, characterized by transiently increased perfusion driven by ischemic vasodilation, accumulation of vasodilatory metabolites, and increased capillary permeability.[30] APG, through real-time quantification of limb volume changes, provides a sensitive, non-invasive measure of this hyperaemic response.[10] Early post-operative recordings typically show marked increases in pulse amplitude and baseline limb volume, reflecting both restored inflow and microvascular reactivity.[31,32] Serial APG measurements after open bypass demonstrate limb volume increases of 5-8% during the first postoperative week, with gradual normalization as venous drainage adapts.[31,32] This transient swelling generally corresponds to successful revascularization, whereas persistent or progressive edema, particularly if accompanied by reduced waveform amplitude, may indicate venous outflow obstruction or reperfusion injury.[13-15]

Endovascular interventions are typically associated with smaller and shorter-duration postoperative volume increase, likely due to reduced tissue dissection, preservation of lymphatic pathways, and lower inflammatory response.[33] By concurrently monitoring arterial pulse amplitude, waveform contour, and total limb volume, APG could provide comprehensive insight into both macrovascular inflow restoration and microvascular reperfusion dynamics.[10] Unfortunately, there are no studies focusing on hemodynamic assessment of post-operative leg edema with APG, following endovascular peripheral intervention.

Beyond serving as a sensitive marker of arterial patency, APG offers valuable information on postoperative tissue physiology, enabling differentiation between expected hyperaemic responses, benign edema, and pathologic perfusion abnormalities.[34] By integrating both perfusion and volume metrics, plethysmography provides a more comprehensive evaluation of procedural efficacy and limb recovery.[34] Following successful revascularization, reactive hyperaemia produces a transient rise in pulse amplitude and a brisk systolic upstroke, reflecting restored inflow and vasodilatory response.[11,14,25] In contrast, benign postoperative edema manifests as a sustained increase in baseline limb volume with preserved waveform contour, representing transient capillary leakage and lymphatic adaptation rather than arterial compromise.[11,14,25] Conversely, pathologic perfusion abnormalities, such as graft stenosis or in-stent restenosis, are characterized by persistent amplitude reduction, delayed upstroke, and waveform flattening, often preceding clinical or Duplex-detected deterioration.[11,14,25] Future studies integrating APG-derived volume metrics with biochemical or imaging markers of microcirculatory function may further elucidate the complex interactions between revascularization and tissue recovery.

Integration of APG in modern clinical practice

In contemporary vascular practice, APG serves as a valuable adjunctive rather than primary diagnostic modality for the evaluation of peripheral arterial interventions.[7,10,23] During open bypass surgery, intra-operative APG provides immediate, objective confirmation of technical success by documenting the restoration of pulsatile flow and quantifiable hemodynamic improvement across reconstructed segments.[13-19] This real-time feedback allows intra-operative correction of residual defects, complementing duplex and intraoperative flow assessments.[13,14] In endovascular procedures, APG functions as a global physiological assessment tool, offering whole-limb perfusion insight when duplex ultrasonography is inconclusive or technically limited by heavy arterial calcification, deep vessel location, or acoustic shadowing.[20-25]

Incorporating standardized APG protocols into structured post-intervention surveillance pathways could enhance early recognition of hemodynamic deterioration preceding overt graft or stent failure.[6,10,11,21] Several studies have already been mentioned demonstrating that waveform amplitude decline and loss of triphasic flow often precede symptomatic restenosis or ABI reduction, emphasizing the role of APG as an early warning signal for re-intervention.[13-16] Such proactive monitoring has the potential to improve long-term patency and limb salvage outcomes.[13-16] As the demand grows for objective, reproducible, and cost-effective follow-up modalities, particularly in elderly, diabetic, and multimorbid PAD populations, APG may regain a central position within multimodal hemodynamic assessment frameworks, complementing Duplex ultrasonography, ABI, and imaging-based surveillance after both open and endovascular arterial reconstruction.

Future perspectives

Recent technological advances have transformed traditional APG into sophisticated, digital hemodynamic monitoring systems, capable of multi-segmental data acquisition and automated waveform analysis.[35] Modern devices employ high-resolution pressure transducers and digital signal processing to improve sensitivity, reduce operator dependency, and enable precise temporal and amplitude quantification of arterial waveforms.[35] Segmental and multi-level recordings now allow a more detailed hemodynamic assessment of arterial inflow and outflow dynamics, complementing Duplex ultrasonography.[35] Emerging research explores the fusion of APG with near-infrared spectroscopy and photoplethysmography to provide simultaneous macro- and microcirculatory assessment.[36] In parallel, machine-learning algorithms trained on plethysmographic waveform datasets have demonstrated the potential to identify restenosis and hemodynamic deterioration with high diagnostic accuracy.[37] Although these systems remain in the developmental phase, their philosophy suggests a transition from descriptive waveform interpretation to data-driven, precision hemodynamic monitoring, amplified by machine-learning-enhanced analysis, thus positioning APG as a valuable adjunct in the future of vascular diagnostics.[37]

Limitations

The primary limitation of this review lies in the heterogeneity of available data. Published studies on APG in arterial reconstruction span more than five decades, encompassing diverse devices, calibration methods, and waveform analysis techniques, which limit direct comparison and pooled interpretation. Many early studies predate modern imaging and lack standardized outcome reporting or objective validation against reference modalities, such as Duplex ultrasonography or angiography. In addition, small sample sizes and retrospective designs predominate in the existing literature, with few prospective investigations assessing APG as a predictive surveillance tool. The absence of standardized diagnostic thresholds and normative datasets further constrains the generalizability of findings. Finally, current evidence remains preliminary and requires validation in contemporary patient cohorts with standardized post-intervention follow-up protocols.

CONCLUSION

APG remains a robust, non-invasive physiological tool capable of providing quantitative insights into arterial inflow, waveform morphology, and limb perfusion dynamics after revascularization. It offers valuable complementary data to conventional imaging modalities, facilitating intra-operative verification of technical success, early detection of hemodynamic deterioration, and functional assessment of tissue reperfusion. Its ability to simultaneously capture macrovascular and microvascular adjustments, such as reactive hyperemia and transient post-operative edema, underscores its physiological relevance beyond simple patency assessment. Despite historical underutilization, renewed technological advances, position APG/PVR for a potential resurgence in modern vascular practice. Standardization of acquisition protocols and validation of predictive metrics will be key to defining its future role within multimodal surveillance strategies after peripheral arterial intervention.

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