A Review of Transit-time Flow Measurement for Assessing Graft Patency

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ABSTRACT

Anastomotic quality is a critical issue in minimally invasive coronary artery bypass surgery, particularly "off-pump". It is important to detect a "poor" anastomosis during the procedure so future re-operation can be avoided. Methods such as intraoperative angiography, thermal angiography, probing of the anastomosis, and graft flow measurement have been used intraoperatively to help identify anastomotic errors. With the evolution of stabilizers, graft patency rates for off-pump cases have improved, but many believe they are still not as high as those of the conventional procedure. For off-pump surgery to be accepted and practiced universally, patency rates must be equivalent to those of "on-pump" cases. Transit-time flow measurement has become an increasingly popular non-invasive method for assessing anastomotic quality. However, it is difficult to establish whether an anastomosis is patent based on mean graft flow alone. Spectral analysis of graft flow waveforms reveal characteristic patterns that identify intermediate ranges of stenosis between fully patent and totally occluded. Together, these two components of graft flow have been used in the construction of a neural network to help identify "faulty" anastomoses. Transit-time flow measurement is a noninvasive tool that can be beneficial in identifying fully patent or nearly occluded grafts, and may also help in distinguishing intermediate stenoses.

INTRODUCTION

Anastomotic quality is a critical issue in minimally invasive coronary artery bypass grafting (mini-CABG) surgery, particularly during "off-pump" procedures. CABG cases performed without the aid of cardiopulmonary bypass (CPB) are commonly believed to be more technically demanding than the conventional procedure. It is very important to detect the construction of a "poor" anastomosis during the primary surgery so future re-operation can be avoided. Therefore, several methods of intraoperative assessment of anastomotic quality have been developed to help verify graft patency prior to closure of the patient. One method that has recently gained more attention is the use of graft flow for assessment of anastomotic quality. However, the efficacy of this method has not been well established. The purpose of this review is to help clarify the evaluation of graft flow using transit-time flow measurement for verification of graft patency.

CABG without CPB has been practiced for more than a decade [Benetti 1985, Pfister 1992, Buffolo 1996], although it currently lacks universal acceptance because of concerns over anastomotic quality [Gundry 1992]. Modern approaches emphasize the expanded use of the mammary artery [Loop 1986, Galbut 1993, Cameron 1996], smaller incisions, decreased hospital stay, and lower cost [King 1997]. Less invasive CABG has been shown to result in an improved neurological outcome when compared with the conventional procedure [BhaskerRao 1998]. However, greater concern still prevails over the quality of the anastomosis in this procedure, preventing its universal acceptance.

Off-pump CABG (OPCAB) has become less technically demanding with the development of thoracoscopic IMA harvesting and the use of stabilizers [Subramanian 1997]. However, in the pre-stabilizer era, graft patency after OPCAB sometimes resulted in an unacceptable failure rate [Pagni 1997]. Although stabilizers have greatly improved the quality of off-pump CABG and clinical outcome of patients [Subramanian 1997], it is still necessary to find a way to ensure that the surgeon has produced an anastomosis that will maintain long-term patency.

Anastomosis Assessment Techniques

The key to long-term patency is the identification and correction of imperfect anastomoses during the original surgery. However, a proven reliable intraoperative method for anastomotic quality assessment does not exist. Tradi-

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tionally, surgeons rely on probing of the anastomosis, absence of hemodynamic compromise, and/or the absence of abnormalities in ECG as methods for determining the adequacy of their anastomoses. These methods are not totally reliable and may only detect severely obstructed anastomoses.

Angiography is considered the "gold standard" for the assessment of anastomotic quality. However, angiography is not readily available in most operating rooms and it is invasive, costly, and time consuming. Thermal coronary angiography (TCA) (or infrared thermography) is a noninvasive method that requires no interference with the surgical procedure [Shabbo 1982, Mohr 1989, Lawson 1993, Falk 1995]. TCA is similar to angiography in that it gives visual representation of grafts and the attached coronaries. However, due to anatomical reasons, certain coronary arteries cannot be viewed and thermal imaging can be compromised by excessive epicardial fat [Falk 1995].

A variety of flow and velocity measurement techniques have been used for several years to detect graft patency. Theory and perioperative measurements have suggested that adequate blood flow and velocity through the graft are required for long-term patency [Walker 1972, Folts 1975, Geha 1975]. However, electromagnetic flow measurements are often difficult to obtain, and are sensitive to drift and zero adjustment [Wolpath 1998]. Doppler flow measurement is affected by insonation angle and indicates only velocity [Wolpath 1998]. More recently, transit-time flow measurement has been used as a measurement tool for graft flow [Wolpath 1998]. This technique provides a mean flow as well as continuous waveform analysis yielding improved accuracy in the detection of failed grafts [Lundell 1993, Canver 1994].

Assessment of Anastomotic Quality with Flow Probes

Surgeons commonly associate low graft flow with anastomotic error. However, mean flow values do not correlate with clinical outcome or long-term patency [Louagie 1994, Canver 1997]. We have shown that mean graft flow did not change significantly until graft stenosis was greater than 75% [Jaber 1998b]. It may also be possible to have a patent anastomosis with a low mean graft flow. Conversely, high mean graft flow is felt to confirm a patent anastomosis, but again, it may also be possible to have high graft flow with a stenotic anastomosis. Therefore, interpretation of anastomotic quality as a function of mean graft flow may be difficult. This may help explain why investigators have been unable to correlate mean graft flow with clinical outcome.

Visual assessment of flow waveforms has also been shown to be unreliable and may lead to the acceptance of faulty anastomoses [Jaber 1998a]. In a survey conducted by our group [Jaber 1998a], international experts in the field of cardiothoracic surgery were unable to use visual assessment of flow morphology and/or mean flows to detect certain levels of anastomotic error (see Figure 1 ◎). Most surgeons could identify either fully patent or nearly occluded grafts. However, there was a high failure rate in the ability to detect severe degrees of anastomotic stenosis. The ability to detect severely stenotic grafts would be extremely valuable, because these grafts could then be immediately revised. Therefore, some method of assessment needs to be developed to help detect intermediate degrees of stenosis less than total occlusion.

Due to the peculiar physiology of the coronary circulation, flow through bypass grafts occurs primarily during diastole with a short systolic peak. Absence of diastolic flow is indicative of an occluded graft. In a graft that is not totally obstructed but still has some degree of stenosis, the flow may be predominantly diastolic, but exhibit taller systolic peaks.

An Animal Model for Evaluation of Graft Flow

An animal model was developed by our group to evaluate graft flow using time domain analyses of the waveform [Jaber 1998b] (see Figure 2 ◎). In twenty-seven dogs, 46 IMA grafts to the LAD were constructed. In this study, we were able to create reproducible stenoses in the mammary to LAD anastomosis and analyze the changes in graft flow tracings and graft flow parameters (see Figure 3 ◎).

Due to the dynamic character of the variables that affect graft flow (blood pressure, heart rate, coronary resistance, and graft diameter), the initial optimal mean flow could not be defined. Differences in flow tracing morphology were virtually indistinguishable from fully patent to moderately stenotic anastomoses. Moreover, grafts with up to 75% stenosis still had predominantly diastolic flow, and only grafts with greater than 75% stenosis exhibited significantly reduced diastolic flow. A possible explanation is that the autoregulation of the coronary circulation may mask potentially "poor" grafts by acutely increasing flow through the stenotic anastomosis. In addition, mildly stenotic grafts may improve with time. Calafiore et al. reported that lesser degrees of stenosis may remodel and show full patency on delayed angiography [Calafiore 1998].

Since it has been shown that the surgeon can only visually detect a nearly occluded graft through transit-time flow measurement [Jaber 1998a, Jaber 1998b], the use of spectral analysis may help distinguish some of the intermediate degrees of anastomotic stenosis (see Figure 4 ◎). Using magnitude and phase components of the flow waveforms, we were able to compare different harmonics and establish similarities or differences [Koenig 1999]. Spectral analysis resulted in the detection of significant differences between patent and mild-to-moderate stenosis, moderately severe stenosis, and severe stenosis.

With the use of graft flow physiological parameters and the application of spectral analysis to the graph flow data, a neural network was built and tested to help improve anastomotic error detection [Cerrito 1999] (see Figure 5 ◎). A neural network finds a mathematical process to predict an output when given inputs. It accumulates knowledge of the pattern of the interconnectivity of the inputs. Weights are then assigned to the inputs based on accumulated knowledge of the neural network. As the knowledge increases, the assigned weights change and become more defined. The neural network can then be validated using a testing set.

Our neural network was trained to estimate high or low patency at a cut-off value of 50%. This value was used to represent an "acceptable" anastomosis of less than 50% stenosis, or an anastomosis that "should be redone" with a stenosis greater than 50%. The neural network was shown to be very accurate in the estimation of anastomotic quality. However, this study involved hemodynamic data from canine models and needs to be applied in a human study for any future clinical applications. Although the results of the canine study were encouraging, there are other important variables that were excluded such as the presence of coronary artery obstructive lesions. The future for clinical application of neural network analysis will require a database of graft flow measurements correlated to varying degrees of anastomotic stenosis, validated by angiography. In turn, these data would be used in the development of a device that assesses a graft flow waveform in real-time and quickly alerts the surgeon to the graft's patency or lack thereof.

An issue that may cause limitations or problems with flow measurement is competitive flow. Competitive flow to a grafted coronary artery causes reduced or retrograde graft flow, which may have a significant effect on both mean graft flow and flow waveform morphology [Suma 1991, Juleff 1992, Lust 1994]. In the aforementioned studies reported by our group, the graft flows were recorded with the proximal LAD snared to avoid the effects of competitive flow on graft flow physiology. However, if used intraoperatively without snaring of the proximal coronary artery, competitive flow may alter the ability of the surgeon to assess the quality of the anastomosis. In fact, unreported studies by our group have shown that competitive flow may give misleading information regarding graft patency. In instances where graft flow was measured in a fully patent graft undergoing competitive flow, a taller systolic peak appeared while diastolic flow seemed diminished. In addition, when graft flow was measured in a severely stenotic graft undergoing competitive flow, diastolic flow appeared more prominent giving the surgeon a false perception of a "good" quality anastomosis (see Figure 6). Therefore, surgeons may wish to use extra caution when assessing graft patency when the native vessel is not totally occluded.

An additional important variable that needs to be addressed is the effect of distal coronary artery disease on graft flow. Often in CABG procedures, the coronary artery that is grafted may contain lesions distal to the anastomotic site. This may alter the physiology of coronary flow and have an effect on graft flow as well.

Presently, late graft patency after OPCABG is an important issue that contains many unknowns [Mack 1998]. With the evolution of less invasive and off-pump coronary bypass, flow asssessment is a crucial verification step that assures surgeons of a high quality anastomosis before completion of the procedure. As technological improvements occur (such as stabilizers, robotics, anastomotic suturing devices), the need for confirmation may gradually lessen. In the meantime, transit-time flow measurement with spectral and neural network analysis may provide the best noninvasive means of assuring against technical error in graft construction.

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