Although technical advances enable normal epicardial coronary artery blood flow to be restored in most patients suffering myocardial infarction, restoration of blood flow is not always followed by improved myocardial perfusion. Recently, therefore, interest in the assessment of myocardial perfusion has grown, and a number of different assessment methods are available. The aim of this article was to provide an evaluation of the additional information that can be obtained from the widely used technique of conventional coronary angiography. We present a review of the data on epicardial coronary artery blood flow (both semiquantitative and quantitative) and on microvascular blood flow that can be obtained using coronary angiography and discuss their prognostic significance.

Key words: Coronary angiography. Coronary blood flow. Myocardial perfusion.

INTRODUCTION

The main aim in treating acute myocardial infarction (AMI) is to restore patency in the epicardial coronary artery. The theory of the “open artery” is based on two fundamental factors: time (as soon as possible) and size (as much flow as possible). Whatever the reperfusion method used, as demonstrated in many studies,1-6 the final aim is that the angiographic parameter, epicardial blood flow, is normal. Given that the latest developments make it possible to restore “normal” epicardial flow in more than 90% of the patients and that, given this is achieved, a significant number of patients still have unresolved ST segment and their myocardial perfusion is not restored under myocardial contrast echocardiography (MCE), interest has shifted from the epicardial arteries towards myocardial perfusion. There are several methods to assess the state of coronary microcirculation and myocardial perfusion, from the simplest—analyzing a previously resolved ST-segment elevation in the electrocardiogram (ECG),7-19 to the more complex—positron emission tomography (PET).20-22 The aim of this article is to review the findings obtained with coronary angiography18,23-29 to assess the quality of both epicardial and microvascular reperfusion.

RELEVANCE AND LIMITATIONS OF ASSESSING EPICARDIAL FLOW

Open Epicardial Artery: TIMI Flow Grading

The evaluation of blood flow in the epicardial coronary artery was formalized 20 years ago by the TIMI research group (Thrombolysis In Myocardial Infarction) with the so-called TIMI flow grades.1 Table 1 shows the characteristics of each grade.

Many studies have demonstrated the correlation between this parameter and later events such as:

Coronariografía: más allá de la anatomía coronaria

Aunque los avances tecnológicos permiten restaurar el flujo coronario normal en la arteria epicárdica en la mayoría de los pacientes con infarto de miocardio, no en todos los casos se traduce en la mejora de la perfusión miocárdica; por ello, el interés clínico en la evaluación de ésta ha crecido recientemente. Son varios los métodos que permiten valorar este parámetro, pero el objetivo de esta revisión es analizar la información adicional que ofrece una técnica ampliamente usada, la simple coronariografía. Se revisan los datos de flujo epicárdico (tanto de forma semicuantitativa como cuantitativa) y microvascular que se pueden obtener con la coronariografía y su implicación pronóstica.

Palabras clave: Angiografía coronaria. Flujo coronario. Perfusión miocárdica.
reinfarction, mortality, free wall rupture, development of ventricular aneurysm or the appearance of arrhythmias. This correlation with prognosis, which was initially described for thrombolytic treatment in acute myocardial infarction (AMI), has also been extended to percutaneous coronary intervention therapy (PCI). This relationship has been shown to be so strong that TIMI 3 flow is normally used as a parameter to evaluate the efficacy of different treatments instead of the relevant clinical events.

This classification allows us to establish the superiority of TIMI 3 flow over other parameters, even over TIMI grade 2: 2 meta-analyses report that early mortality was significantly lower among patients with TIMI 3 flow at 90 min after fibrinolysis than in the group with TIMI 2 flow (3.7% vs 6.6%; odds ratio [OR] =0.55; 95% confidence interval [CI], 0.4-0.76) or than in group with TIMI 0 or TIMI 1 flows (9.2%; OR=0.38; 95% CI, 0.29-0.5). With the development of repatency therapy using PCI, the use of these predictors has continued to prove their validity, although some studies point out that the difference in mortality between TIMI 2 and 3 grades might not be so marked nowadays with the use of invasive therapies that combine fibrinolytic drugs and PCI.

On the other hand, technical developments in the intervention field (e.g. stenting, thrombectomy devices, distal protection systems) have not been associated universally with an improvement in TIMI flow. Nevertheless, this grading system has some limitations:

1. The most relevant limitation is its subjectivity, which leads to important discrepancies, even when...
the analyzes assessment is performed by core laboratories with wide experience.\textsuperscript{62,63}

2. The filling time of the left anterior descending coronary artery (LAD) is higher than in other arteries, because this is normally the longest artery. Given that the filling of this artery can be simultaneously compared with the filling of the circumflex artery, the tendency to assign a TIMI grade 2 flow is much greater than with the right coronary artery (RCA).\textsuperscript{64}

3. The TIMI group itself has modified (without much acceptance) the grading system to distinguish up to 3 different subgroups in TIMI 2\textsuperscript{65} (Table 1). These changes include factors such as washout speed that will be later discussed.

4. Finally, we cannot discard the presence of factors that could significantly modify grading, such as the pressure and phase within the cardiac cycle at which the contrast injection is administered, the heart rate and blood pressure of the patient, the use of vasodilators, etc. The impact of these factors is discussed in the next section.

Open Epicardial Artery: Quantification. Corrected TIMI Frame Count

In the light of the potential limitations of the TIMI flow grading system, new evaluation systems have been developed that more deeply characterize flow and improve the reproducibility of results: the corrected TIMI frame count (cTFC) system developed by Gibson et al\textsuperscript{64} is the most widely validated. Basically, it quantifies the TIMI flow grade by measuring the time it takes the contrast agent to fill the entire length of the epicardial artery. In order to standardize the criteria, several distal bifurcations were defined to serve as “final landmarks”: the “whale’s tail” at the apex of the LAD, the longest total distance along which dye travels in the circumflex system and yet passes through the culprit lesion, and the first branch of the posterolateral artery in the right coronary artery (Figure 1). The difference in the number of frames between the last one and the first (where the contrast agent fills at least 70% of the arterial ostium and starts to move in an anterograde direction) constitutes the TIMI frame count.

Some of the methodological aspects of this system are outlined as follows:

1. As described,\textsuperscript{64} the length of the LAD is 1.7 times greater than the circumflex and the right coronary arteries. Thus, a correction factor was introduced in the TFC system when analyzing the LAD: the corrected TIMI frame count (cTFC) is the result of the absolute difference divided by the correction factor, 1.7.

2. All the values initially published as “frame counts” referred to the video format standard in the United States, NTSC: 30 frames per second. In order
TABLE 2. Values of the Corrected TIMI Frame Count (by Number of Frames)

<table>
<thead>
<tr>
<th>Recording Speed</th>
<th>Normal Values (Healthy Volunteers)</th>
<th>TIMI 3 Flow (After Infarction)</th>
<th>TIMI 4 Flow (After Infarction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 frames/s</td>
<td>&lt;21</td>
<td>&lt;40</td>
<td>&lt;14</td>
</tr>
<tr>
<td>25 frames/s</td>
<td>&lt;18</td>
<td>&lt;33</td>
<td>&lt;12</td>
</tr>
<tr>
<td>12.5 frames/s</td>
<td>&lt;9</td>
<td>&lt;17</td>
<td>&lt;6</td>
</tr>
<tr>
<td>Seconds</td>
<td>0.7</td>
<td>1.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

2. This is an easy method that does not require special equipment and can be performed immediately after capturing angiographic images.

3. The cut-off points shown in Table 2 allow us to classify unclear epicardial flows.

Nevertheless, the method presents certain limitations as it has been found that some factors can significantly change the values calculated:

1. Heart rate. An increase of 20 heart beats/min shortens the count by 5 frames. 90
2. Using nitrates increases the count by 6 frames. 90
3. Injecting during the protodiastolic period reduces the count by 3-6 frames. 90
4. When the LAD is the culprit artery of the infarction: in such cases the count is higher than in the other arteries by 8 frames, even after correcting for length and adjusting for other variables. 92

It has not been demonstrated whether the calculation is affected by patient-dependent factors (e.g., age, sex, body size, blood pressure, or cardiovascular risk factors52) or by procedure-dependent factors (injection pressure31 or type of contrast agent31).

Taking this method as a basis, another assessment system has been developed, not only for the epicardial blood flow, but also for microcirculation flow—the assessment of the coronary blood flow reserve by analyzing the relationship of cTFC at baseline and cTFC after the administration of adenosine. This parameter has been correlated with Doppler guidewire analysis74,86 although other studies have not confirmed this.77

**ASSESSMENT OF MYOCARDIAL PERFUSION AND MICROCIRCULATION**

**Open Microvasculature: Assessment.**

**Myocardial Blush**

Since the classic descriptions of reperfusion injury and no reflow events were presented,2 the attempts to assess the state of myocardial perfusion after an infarction have increased. The resolution of the ST-segment18-20 is the simplest and most reproducible analysis. Another method widely used is the MCE18,20 which, apart from being a non-invasive method, can be quantified. In both cases, the results have been correlated with the appearance of subsequent events.71,72,74,98

With the increasing implementation of PCI as the treatment of choice for AMI, the availability of an early angiography is quite frequent and this has permitted the development of the myocardial blu...
Thus, the 2
Treatment of Suboptimal Myocardial Reperfusion
52,57,115-120,136,140
60
123,124
109,110
or the angiography are analyzed. Their
On the other hand, a correlation has been
114
overload inhibitor) Pending EVOLVE Study
MCE,

125,126
113
127
18
55,56,128-132

Myocardial perfusion grade [TMPG]). This was
entry and clearance of the contrast medium (TIMI
unaffected contralateral or ipsilateral territories. The
other is a dynamic analysis system that assesses the
intensity of regional contrast as well as the speed of
other is a dynamic analysis system that assesses the
intensity of myocardial contrast as well as the speed of

TABLE 3. Treatment of Suboptimal Myocardial Reperfusion

<table>
<thead>
<tr>
<th>Drug/Method</th>
<th>Result</th>
<th>Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vinpamil</td>
<td>Positive</td>
<td>Small studies[99,114]</td>
</tr>
<tr>
<td>Nicorandil</td>
<td>Positive</td>
<td>Small studies[111,112]</td>
</tr>
<tr>
<td>Cariprodine (Na+K+ pump inhibitor)</td>
<td>Negative</td>
<td>GUARDIAN Study[115]</td>
</tr>
<tr>
<td>Intracoronary adenosine</td>
<td>Positive</td>
<td>AMISTAD II Study[116]</td>
</tr>
<tr>
<td>Abciximab (glycoprotein IIb/IIIa inhibitors)</td>
<td>Positive</td>
<td>Several studies[117,118,119,120]</td>
</tr>
<tr>
<td>Pexelizumab (complement inhibitor)</td>
<td>Pending</td>
<td>APEX AMI Study[121]</td>
</tr>
<tr>
<td>Hu3F9a (antibody anti-CD18)</td>
<td>Negative</td>
<td>HALT-MI Study[122]</td>
</tr>
<tr>
<td>Catatol (IgG overload inhibitor)</td>
<td>Pending</td>
<td>EVOLVE Study[123,124]</td>
</tr>
<tr>
<td>Hypothermia</td>
<td>Non-conclusive</td>
<td>Preliminary studies[125,126]</td>
</tr>
<tr>
<td>Aqueous hyperoxygenation</td>
<td>Non-conclusive</td>
<td>Preliminary studies[127]</td>
</tr>
<tr>
<td>Thrombectomy devices</td>
<td>Positive</td>
<td>Small studies[128,129,130]</td>
</tr>
<tr>
<td>Distal protection devices</td>
<td>Negative</td>
<td>EMERALD Study[131]</td>
</tr>
</tbody>
</table>

concept: the penetration of iodized contrast medium
into the capillaries yields a “ground-glass”
angiographic image in the irrigated myocardial
territory. Two different systems to assess myocardial
blush have been suggested. The first one is a
videodensitometric system proposed by van’t Hof et
al[25] which analyzes the intensity of regional contrast
(myocardial blush grade [MBG]) compared to the
unaffected contralateral or ipsilateral territories. The
other is a dynamic analysis system that assesses the
intensity of myocardial contrast as well as the speed of
entry and clearance of the contrast medium (TIMI
myocardial perfusion grade [TMPG]). This was
developed by Gibson et al.[24] Table 1 shows the four
grades within each classification. Normal perfusion is
identically graded in both systems: grade 3. Worse
myocardial perfusion is shown by grades 0 in both
systems; and major reperfusion injury (hemorrhagic
transformation or persistent extravasation) are
included in TMPG 1 and MBG 0, respectively. Cases of
MBG 1 and 2 cannot really be extrapolated to the
TMPG system, and so a subclassification has been
proposed for these cases: the TMPG 0.5.23 Thus, the 2
systems are not as different as they might initially
appear. Figure 2 shows some examples of myocardial
perfusion analysis.

Although the existence of these 2 systems may
bring into question the validity of the method, the faci
is that TMPG22,24 and MBG25,59,105 correlate with
mortality (Figure 3), even when only TIMI grade 3
flow patients are included. The influence of these
parameters has also been shown in the percentage of
myocardium salvaged in respect to the risk area105 and
the mortality in patients in shock105 or on the
relationship between mortality and the evolution time
of AMI.109,110 On the other hand, a correlation has been
found between these systems and other parameters
independently related with prognosis after infarction,
such as the analysis of coronary flow reserve with
Doppler guidewire,107,108 MCE,16,45,56 analysis of
infarction size by single photon emission computed
tomography (SPECT)17 or resolution of ST-segment
elevation.13,28,30,108

The assessment of myocardial blush has its own
limitations:

1. The qualitative character of this parameter makes
it inherently subjective. Thus, intra- and inter-observer
consistency is limited, as described by one of the
groups with the greatest experience.23 In most studies,
the analysis of MBG or TMPG is performed in central
laboratories, and thus, the consistency with the
assessments carried out by other observers might not
be suitable.

2. Many of the studies carried out tend to group
patients with MBG 2 and 3 or TMPG 2 and 3 into
a single group with suitable perfusion. Given that
it has been demonstrated that the prognosis of patients
with TIMI 2 and TIMI 3 flow is not equivalent,
this simplification of the system is most probably
wrong.

3. Nevertheless, the fundamental limitation is not
methodological, but refers to the unsolved challenge
to treating suboptimal myocardial perfusion after
coronary repatency. Table 3 sums up evidence
published in this domain.

The correlation between the analysis of ST-segment
resolution and myocardial blush is controversial
because, although both have been related to clinical
events, they do not always seem to match in every
patient. What could be interpreted as a limitation tends
to be assessed as another “anomalous” event, which
are not uncommon in cardiology: the “electrical
recovery” shown in the ECG is not always associated
with integrity of the microvascular endothelium and
recovery of perfusion, and vice versa. In fact, the 2
methods are complementary when the size of the
infarction,14 or the angiography are analyzed. Their
complementarity is also shown by the fact that the
There is ample literature available on the correlation between MCE and angiography, although a perfect correlation is not always found, even though both methods, at least theoretically, analyze myocardial perfusion. Bearing in mind that this is a dynamic event (some days after the infarction, many patients that initially did not show suitable myocardial blush may show a much better grade\(^{135}\)), the discrepancies may be due to the behavior of the different contrast agent used—echographic contrast agents (microbubbles) always remain in the intravascular space, whereas radiological contrast media (and paramagnetic contrast used in magnetic resonance) often present extravascular passage, subsequently returning to the bloodstream. Thus, some authors\(^{137}\) argue that angiography or magnetic resonance do not actually assess myocardial perfusion, but rather capillary patency, the state of the endothelium, and the edema and interstitial hemorrhage i.e. reperfusion injury.

Figure 2. Examples of myocardial perfusion analysis. A: persistent stain of the septum (delimited by the arrows); grade 1 myocardial perfusion (TMPG), grade 0 myocardial blush (MBG) in LAD. B: persistent myocardial stain in the diaphragm territory; TMPG 1, MBG 5 grades in RCA. C: persistent capillary stain (small vessels are visualized) in RCA. D: lower intensity stain than in left coronary artery in the diaphragmatic territory (black arrow, TMPG 2 and MBG 2 grades) and barely present in posteroanterior (white arrow, TMPG 0.5 and MBG 1 grades). E: normal myocardial stain (TMPG grade 3 and MBG grade 3) of left coronary artery: A donut-like image in LAO cranial projection. F: normal myocardial stain (TMPG 3 and MBG 3 grades) of RCA; example of digital subtraction (DSA).
Open Microvasculature: Quantification. Future Development

Myocardial perfusion assessed by angiography is analyzed by using several quantitative methods:

1. Methods based on digital subtraction angiography (DSA),\(^{85,138,139}\) widely used in vascular radiology, but little used in coronary angiography, may facilitate the quantification of the opacified area (in theory, this is “equivalent” to areas quantified in MCE), blush intensity (“MBG quantification”)\(^{107,140}\) or the speed at which the blush appears or disappears (“TMPG quantification”).\(^{138}\) For DSA to be more applicable, several studies are working on the development of techniques, such as moving mask, to attempt to neutralize the movements inherent to the heart.

2. A quantification system, based on cTFC has been suggested. This quantifies the number of frames between the entrance of the contrast agent into the myocardium and the peak blush intensity: the TIMI myocardial frame count. This count is significantly greater in patients with AMI with ST-segment elevation than in patients with NSTEACS.\(^{141}\)

3. Our group has developed a quantification system known as the Coronary Clearance Frame Count (CCFC) with good correlation with TMPG\(^{142}\) grades.

![Figure 3. Mortality after AMI and myocardial blush grades. A: mortality rate in relation to the myocardial blush grade at 1 month (Gibson et al\(^{24}\)), in the longer term (follow-up 1.8±1.7 years [van’t Hof et al\(^{25}\)] and after 1 year [Stone et al\(^{29}\)]. B: mortality in relation to the myocardial blush grade in the patients with TIMI 3 flow in the culprit artery at 1 month (Gibson et al\(^{24}\)) and after 1 year (Stone et al\(^{29}\)). TMPG: TIMI myocardial perfusion grade; MBG: myocardial blush grade.]
contrast disappears from the arterial ostium and when it begins to disappear from the distal bifurcation described in the cTFC system. Although its potential clinical relevance has not been established yet, it shows correlation with myocardial perfusion TMPG grade 2 or 3, creating a cut-off point (45 images) that makes it possible to differentiate the better perfusion grades.

cTFC Analysis and Myocardial Blush: Practical Considerations

Both the quantitative analysis of epicardial blood flow (cTFC) and microvasculature flow can be carried out online with current digital equipment, or offline with software for image review. Nevertheless, if the imaging conditions are not optimal, the interpretation and later analysis may be biased. Thus, some standard recommendations are made:

1. Imaging field: 23 cm. Not magnifying the image enables recording the whole length of the artery without the need for panning. This is particularly important for the correct analysis of myocardial blush, especially when DSA is used. The quality of current DSA images (fixed mask) is also highly dependent on maintaining apnea during the recording.

2. Imaging speed: ideally, 25 frames/s. Nevertheless, cTFC can be calculated at any recording speed, and subsequently it can be expressed in seconds or adjusted to the recommended speed.

3. Recording time: up to the appearance of contrast in the venous phase. This is very relevant for the TMPG analysis system. In this case, it is also particularly important to leave at least 30 s between one injection and the following one, and not to record immediately after contrast tests (it may incorrectly assign TMPG 1 values).

4. Selective projections:
   a) Analysis of cTFC: Recording images in PA or RAO projection (0°-30°) is recommended with caudal angulation (20°-30°) for the left coronary artery and in LAO projection (45°-60°) for the right coronary artery.
   b) Blush analysis: the recommended projections differ from the previous ones, especially in the left coronary artery, where perfusion territories may be seen as overlapping. Thus, LAO projection (45°-60°) is recommended with cranial angulation (20°-30°), which makes it possible to see a donut-like image, or a left lateral projection (90°) in the case of the left coronary artery; for the right coronary artery, an LAO projection is recommended (45°-60°) with or without cranial angulation or RAO (30°).

From a practical point of view, in our center we systematically analyze myocardial perfusion data from angiographies (according to both the TMPG and the MBG system) in all cases of angioplasty within the context of AMI and in other cases of intervention with no reflow events or slow final blood flow, reserving cTFC and CCFC for cases with high values of the TMPG, to classify epicardial blood flow or perfusion. In all these cases, the information obtained is always complemented by electrocardiographic analysis of ST-segment resolution.

CONCLUSIONS

Coronary angiography offers relevant but simple and easy to interpret information, not only on the state of the epicardial coronary circulation (TIMI flow in the epicardial artery and its quantification, TIMI frame count), but also on the state of microvascular circulation (myocardial blush grades: TIMI myocardial perfusion and myocardial blush grades). These data allow us to reliably assess the patient’s prognosis. The development of a quantitative variant of these techniques could improve their predictive power.

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