The direct anastomosis of a chest wall artery with a coronary artery was the beginning of modern coronary surgery. Coronary revascularization with the aid of a heart-lung machine (HLM) and cardioplegic heart stoppage has since become a standard intervention because of the stable, bloodless operative field that it affords. In Germany, about 54,000 coronary operations are performed every year, at a very high qualitative level comparable to the results reported from the USA, with a perioperative mortality below 3%. Despite progress in stent therapy for coronary lesions, operative coronary revascularization remains the procedure with the highest long-term survival rate for multiple-vessel disease (1).

Nonetheless, contact of the blood with surfaces made of foreign material is unavoidable when an HLM is used and induces a systemic inflammatory reaction. The ensuing organ dysfunction is a major contributor to the mortality and morbidity of coronary surgical procedures and represents a particular danger for elderly or diabetic patients and for those with cardiac or renal insufficiency or preexisting cerebral disease. The number of patients in these risk groups has risen steadily in recent years and will continue to rise.

In view of these facts, coronary revascularization procedures have been performed without the aid of an HLM since the 1980’s (“off-pump coronary artery bypass,” OPCAB). In the USA, 20–25% of all coronary revascularization procedures are now performed off pump. The procedure has not yet become as common in Germany, where about 10% of coronary bypass operations were performed off pump in 2005. The reasons for this are multiple: the implementation of off-pump coronary surgery depends on the personal commitment and specialization of the surgeon, as well as on the personnel available in the hospital and on a close collaboration between surgeons and anesthetists. Specific instruction in OPCAB has to be provided both to cardiac surgeons in training and to those already in practice. Special training courses satisfying the requirements for continuing medical education for surgical techniques give cardiac surgeons both the manual skills and the cognitive background knowledge they need to meet the challenge of OPCAB surgery (e1).
The purpose of this article is to describe the technical aspects of this procedure and to evaluate it critically. We will not discuss minimally invasive direct coronary artery bypass (MIDCAB) surgery here; this is a technique for the exclusive revascularization of the anterior wall vessels in the beating heart. The present analysis is based on large clinical case series, randomized studies, and meta-analyses published since 1995 and searchable through Medline/PubMed. The articles were found by searching on the terms OPCAB, mortality, patency, complications, renal insufficiency, stroke, elderly, and mid-term results.

**The surgical procedure**

Coronary surgery with the HLM is usually performed in standardized fashion: The heart is exposed by a median sternotomy, the patient is fully heparinized, and the HLM is connected (usually to the ascending aorta and the right atrium). Next, the ascending aorta is clamped, the heart is stopped with cardioplegia, and the coronary vessel is anastomosed to the bypass vessel under cardiac arrest. Veins were predominantly used in the early years of coronary surgery, but now the left internal thoracic artery (LITA, also called the left internal mammary artery – LIMA) is generally used for revascularization of the anterior wall. Use of the two internal thoracic arteries or other arterial vessels is now recommended, particularly in biologically younger patients, so that the degeneration that often occurs in venous bypass vessels over the long term can be avoided.

Once a decision is taken to perform coronary surgery on the beating heart, the operating room must be reorganized in a manner that affects not only the operating surgeons, but also the anesthesiologists and other anesthesia personnel.

**Anesthesia and hemodynamic control**

The patient’s hemodynamic state must be stabilized with volume control, positioning, and medications before any manipulation of the coronary vessels is performed. The relevant areas of the myocardium should be exposed only after hemodynamic stabilization has been achieved; this is particularly important when the lateral and posterior walls are to be exposed. If this principle is neglected, exposure of the coronary vessels can worsen the patient’s circulatory status to such a degree that pump failure ensues, and the rest of the operation must then be performed with the aid of a heart-lung machine.

In OPCAB, unlike on-pump surgery, the blood temperature and the patient’s core body temperature cannot be regulated by way of the heart-lung machine. The core body temperature should be kept above 36.5°C, because lower temperatures prolong the time required for artificial ventilation and also significantly increase blood loss. The patient is kept warm by positioning on a warming mat as well as with the application of inflatable warming trousers and the administration of warm intravenous fluids.
Exposure and stabilization of the target vessels

The target vessel is brought into the surgeon’s view, and the region where the anastomosis is to be performed is stabilized so that this will be possible, but without impairing the pumping function of the heart. The approach to the heart is through a median sternotomy, so that all coronary territories can be reached. The pericardium is opened, the left internal thoracic artery (sometimes the right one as well) is dissected free, and segments of the great saphenous vein are removed. Unfractionated heparin is given in the same dose that is used before connection of an HLM, and then the anastomosis is performed. Heparin is antagonized with protamine at the end of the operation. Revascularization usually begins with anastomosis of the internal thoracic artery to the anterior interventricular branch, which is relatively easy to expose by pulling on pericardial traction sutures.

Local stabilization is achieved with the aid of a stabilizer that either exerts pressure through a piston or else holds the area of the anastomosis in place with suction cups, while the rest of the heart continues to beat normally (figure 1). Opening of the coronary artery interrupts coronary perfusion and can therefore cause ischemia in the distal myocardium, to a degree depending on the availability of collateral blood supply. Brown et al. showed that a reduction of systolic contraction regularly occurs when coronary surgery is performed without a heart-lung machine and is reversible after coronary occlusion (20). The severity of myocardial ischemia depends on the extent of stenosis or occlusion of the affected coronary artery and on the collateral blood supply. Ischemia can be decreased by introducing a shunt tube into the coronary artery; at the same time, the shunt seals off the coronary vessel, so that the anastomosis can be performed relatively bloodlessly, and it prevents the inadvertent occlusion of the vessel with a suture (figure 2). Shunts can also damage the endothelium, however, and are therefore not used by some surgical teams.

Anastomoses on the coronary branches supplying the posterior wall of the heart must be performed after displacement of the beating heart. With this technique, called enucleation, the heart is moved in small steps into a more vertical position. Displacement of the heart can be facilitated with a suction apparatus attached to the cardiac apex (diagram). As long as the heart is moved in small steps, its posterolateral wall can be well exposed without any circulatory compromise, even if the heart is enlarged. The manner of performing the anastomosis has already been described.

Proximal anastomoses

Once the distal anastomoses between the vein and the coronary artery have been performed, the proximal anastomoses between the vein and the partly clamped ascending aorta are done next. If arteries alone are used, there is generally no need to perform a separate aortic anastomosis, as long as Y- or T-shaped arterio-arterial anastomoses are made between the arterial bypass vessels.

Discussion

High-risk patients with preexisting organ damage have more complications after on-pump procedures. Because high-risk patients have become more numerous, the concept of revascularization of the beating heart has been developed further in recent years. The technique, known as OPCAB, has been greatly facilitated by technical aids that stabilize the
area of the anastomosis and by the development of surgical techniques for the safe exposure of each target vessel. Nonetheless, the procedure has not yet become very popular in Germany. The main arguments raised against it have been a doubt as to the quality of the anastomoses, particularly in the posterior wall area, and the danger of incomplete revascularization. OPCAB surgery, a minimally invasive technique, must be shown to produce results that are as least as good as those of coronary surgery with a heart-lung machine, which is still regarded as the gold standard. Furthermore, subgroups of patients should be defined in whom the performance of surgery without a heart-lung machine decreases the operative risk. Relevant considerations include early mortality, the frequency of organ dysfunction, and the relative cost in comparison with the conventional method, as well as the middle- and long-range results.

Coronary surgery with the heart-lung machine has been established for decades and is now performed in largely standardized fashion; only in recent years has OPCAB surgery become standardized to a comparable extent. Because of steady technical improvement, the qualitative difference that once existed between these two methods (2) can no longer be demonstrated (3, 7). There are many publications comparing OPCAB with on-pump surgery, but not all of them are of an adequate scientific standard. The current scientific discussion centers on randomized studies and risk-adjusted observational studies.

The indication for OPCAB is particularly firm when the use of a heart-lung machine would be associated with an elevated perioperative risk, for example, in patients with
cerebrovascular insufficiency, chronic obstructive bronchitis, renal failure/dialysis dependence, or advanced biological age (box). In particular, patients with generalized arteriosclerosis stand to benefit from OPCAB, especially when arterial bypass vessels are used. The main rationale for using arterial bypass vessels in this patient group is not to achieve superior long-term patency rates but rather to avoid any unnecessary manipulation of the aorta, which might lead to thromboembolism, by creating arterio-arterial anastomoses between the bypass vessels.

The cardiac status of the patient and the morphology of the coronary arteries also influence the decision whether to operate on- or off-pump. If the patient is hemodynamically unstable before surgery, extracorporeal circulation must usually be rapidly instituted. On the other hand, unstable angina pectoris, particularly when it is due to anteroseptal ischemia, is a good indication for OPCAB, because this often crucial area of the myocardium can be immediately revascularized with the left internal thoracic artery. The technical possibilities for OPCAB surgery are limited if the coronary vessels take a deep intramyocardial or deep intrapericardial course, if the target vessels are heavily calcified over long segments, and if the lumen of the target coronary vessel is less than 1 mm wide.

Early mortality

In a retrospective evaluation of a cohort of more than 1 900 patients, the use of a heart-lung machine was found to be an independent prognostic factor for early mortality; patients operated on with the OPCAB technique had a survival advantage (e2, 4). Further studies confirmed this effect, which was stronger in elderly patients (over 75 years of age), reoperated patients, women, diabetics, and patients with diminished pump function (ejection fraction 30–50%) and arteriosclerosis of the aorta (5, 6, 7, 8, e3, e4). Cleveland et al. (9) analyzed the data of the Society of Thoracic Surgeons (STS) National Adult Cardiac Surgery Database, containing more than 115 000 conventional and 11 000 OPCAB procedures, with adjustment for risk, and reached a similar conclusion. In addition to these studies showing a significant survival advantage after OPCAB surgery as compared to surgery with a heart-lung machine, there are also many others involving smaller numbers of patients that show a statistically insignificant trend toward improved survival (e5, e6, e7) or no advantage at all (e8, 9, 10). Khan et al. reported a lower patency rate of bypass vessels in the OPCAB group at 3 months after surgery, but also confirmed the safety of the technique in the perioperative period (24).

A look at the meta-analyses that have been performed on this subject tends to reinforce the conclusions drawn in the individual studies: meta-analyses have shown either a reduction of mortality in all patients (12) or a reduction of the combined end-point of mortality, stroke, or myocardial infarction (13), a trend toward lower mortality (3), or no difference to the conventional technique (8). There are, however, other reports from the earlier years of OPCAB showing a higher perioperative mortality, particularly in diabetics (23).

As the mortality of the standard operation is low in any case, very large numbers of patients must be included in any analysis that is intended to reveal a difference in mortality that might be present. In the 1980's, for example, the Cleveland Clinic team was able to show the major prognostic significance of a LITA-RIVA (left internal thoracic artery to anterior interventricular branch) bypass by using registry data obtained from more than 10 000 patients. Earlier studies with smaller patient collectives had failed to detect any difference. The question whether revascularization of the beating heart negatively influences the quality of coronary anastomoses has been addressed in a number of studies. According to one meta-analysis, OPCAB patients may need reoperative revascularization procedures

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**BOX**

**Clinical factors favoring OPCAB**

- Compensated renal failure
- Dialysis dependence
- Chronic obstructive pulmonary disease
- Symptomatic peripheral arterial occlusive disease
- Advanced biological age
- Hemodynamic stability
more frequently (13), which would imply that, for the individual patient, the reduction of operative risk may need to be weighed against a potentially higher bypass occlusion rate.

The criticism is often expressed that OPCAB demands an unusual degree of technical skill from the operating surgeon and, therefore, can only yield good results in a small number of institutions. There is no doubt that this type of surgery requires a reorientation of surgical and anaesthesiological procedures with the aim of speeding up the "learning curve." It has been shown, however, that surgeons with smaller caseloads also rapidly become able to produce identical results, which clearly implies that the technique need not be restricted to a few, super-specialized surgeons (2, e5). A continuing problem in this context is the marked diminution of cardiac pumping function that can occur when an OPCAB procedure has to be rapidly converted to an on-pump procedure. Acute conversion is needed in 1–3% of all cases; it may be necessitated by the local interruption of the coronary artery during anastomosis or by intraoperative right or left heart failure when coronary perfusion drops below a critical value (14, 25).

The goal of conventional coronary surgery is total revascularization. With respect to revascularization, there is no longer any significant difference between OPCAB and the conventional technique in experienced hands (14), and even total arterial revascularization can be performed on the beating heart with excellent early postoperative patency rates (e5). In individual cases, however, it must still be asked whether the advantage to the patient from not using a heart-lung machine outweighs the total revascularization of all circulatory areas that can be achieved more easily by using it. In some cases, and depending on the precise coronary pathology that is present, a decision may be taken to revascularize only the vessels giving rise to symptoms, rather than to pursue the goal of total revascularization. A hybrid procedure can also be performed, with OPCAB to revascularize the dominant target area, followed by interventional revascularization of one or more further coronary vessels.

Stroke frequency and cerebral functional ability

One of the dreaded complications of coronary surgery is the appearance of cerebral functional deficits. Multiple teams have shown that the use of a heart-lung machine is an independent risk factor for stroke, particularly when the ascending aorta is atherosclerotic, and that not using an HLM reduces the perioperative risk of stroke in elderly patients (5, 9, 22, e7, e14, e15). The risk of stroke is reduced from circa 2% with the conventional technique to circa 0.4% with OPCAB (8, 21, 22). This is understandable because, in OPCAB, the aorta does not need to be manipulated to connect the HLM, nor does it need to be cross-clamped; when a venous bypass is performed, the aorta must only be side-clamped for the creation of the anastomosis. If the aorta is not clamped at all, as in total arterial revascularization, the rate of cerebral complications may be even lower.

On the other hand, studies of the cognitive function of elderly patients in the early postoperative phase (15) or of low-risk patients in the late postoperative phase (16) have shown no definite advantage for OPCAB compared to surgery with a heart-lung machine.

Renal failure

OPCAB surgery was expected to lower the rate of postoperative renal failure in patients with preoperatively elevated renal parameters (BUN, creatinine). The results of a number of individual studies seem to point in this direction, though no meta-analyses have been reported to date (3, 9, 12, 13, e9, e10, e11).

The matter of cost

When resources are scarce, the economic aspect gains in importance. Studies from England, the Netherlands, Canada, and the USA have shown that OPCAB is significantly less expensive than the on-pump alternative (17, 18, 22, e9, e12), particularly in elderly patients (3, 5, 14, 23, e13), because of a reduction of complications, shorter postoperative stays in the intensive care unit, less frequent need for transfusion, and lower overall personnel costs.

Middle-range results

The middle-range results (up to 5 years postoperatively) are comparable for OPCAB and on-pump bypass surgery with respect to quality of life, late mortality, or the occurrence of combined cardiac events (11, 12, 13, e11). A few publications have shown a possibly higher rate of reoperative revascularization procedures in the OPCAB group (12, 19, 24).
Conclusion

OPCAB surgery is a technically demanding method that has its rightful place in the cardiac surgical repertoire for individually tailored coronary surgery. It seems to be particularly beneficial to patients for whom surgery with a heart-lung machine and aortic cross-clamping might lead to excessive complications. It can be used with success if it is performed for the correct indications, with a newly reoriented anesthesiological concept, and with a properly applied, sequential surgical strategy. The goal is by no means to foist a novel surgical technique on every patient, just as it would be equally wrong to insist on the use of a heart-lung machine even for patients at elevated risk.

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Conflict of Interest Statement

The authors state that they have no conflict of interest as defined by the guidelines of the International Committee of Medical Journal Editors.

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REFERENCES

For e-references please refer to the additional references listed below.


ADDITIONAL REFERENCES


