CASE RECORDS of the MASSACHUSETTS GENERAL HOSPITAL

Case 8-2024: A 55-Year-Old Man with Cardiac Arrest, Cardiogenic Shock, and Hypoxemia

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CME

PRESENTATION OF CASE

Dr. Man Piu Wong: A 55-year-old man was evaluated at this hospital after a witnessed out-of-hospital cardiac arrest.

The patient had been eating at a restaurant late at night when he lost consciousness. A first responder used an automated external defibrillator to deliver a shock, and cardiopulmonary resuscitation (CPR) was initiated. Four minutes later, emergency medical services identified ventricular fibrillation, and defibrillation was performed. Intravenous amiodarone and epinephrine and intranasal naloxone were administered. Unstable ventricular tachycardia occurred, and the patient underwent cardioversion. He was transported to the emergency department of this hospital. The results of electrocardiography (ECG) performed before arrival at the hospital were suggestive of inferior ST-segment elevation myocardial infarction.

A review of systems could not be performed. The patient had no known medical history. He was not known to take any medications. He reportedly lived alone, worked in the service industry, and did not use tobacco or drink alcohol. His family history was unknown.

On the patient's arrival at the emergency department, the heart rate was 123 beats per minute, the blood pressure 188/107 mm Hg, the respiratory rate 26 breaths per minute, and the oxygen saturation 88% while he was receiving supplemental oxygen through a bag–valve–mask device at a rate of 15 liters per minute. The weight was 73 kg, and the body-mass index (the weight in kilograms divided by the square of the height in meters) was 27.0. The patient was awake but not oriented. He did not spontaneously move the arms or legs or respond to tactile stimuli; he had increased work of breathing and posturing. The pupils were 3 mm in diameter and sluggishly reactive. Auscultation revealed sinus tachycardia and diffuse lung crackles. There was no leg edema. The remainder of the examination was normal.

Dr. Ada C. Stefanescu Schmidt: ECG showed sinus tachycardia, Q waves and 2-mm ST-segment elevations in the inferior leads, and upsloping ST-segment depressions in the lateral and precordial leads (Fig. 1A).

Dr. Wong: Laboratory test results are shown in Table 1. The white-cell count and differential count were normal, as were the levels of magnesium, bilirubin, and globulin. The high-sensitivity troponin T level was 3169 ng per liter (reference range, 0 to 14), and the N-terminal pro–B-type natriuretic peptide (NT-proBNP) level was 5679 pg per milliliter (reference value, <900). Urinalysis showed 3+ blood and 5 erythrocytes per high-power field. Blood was obtained for culture.

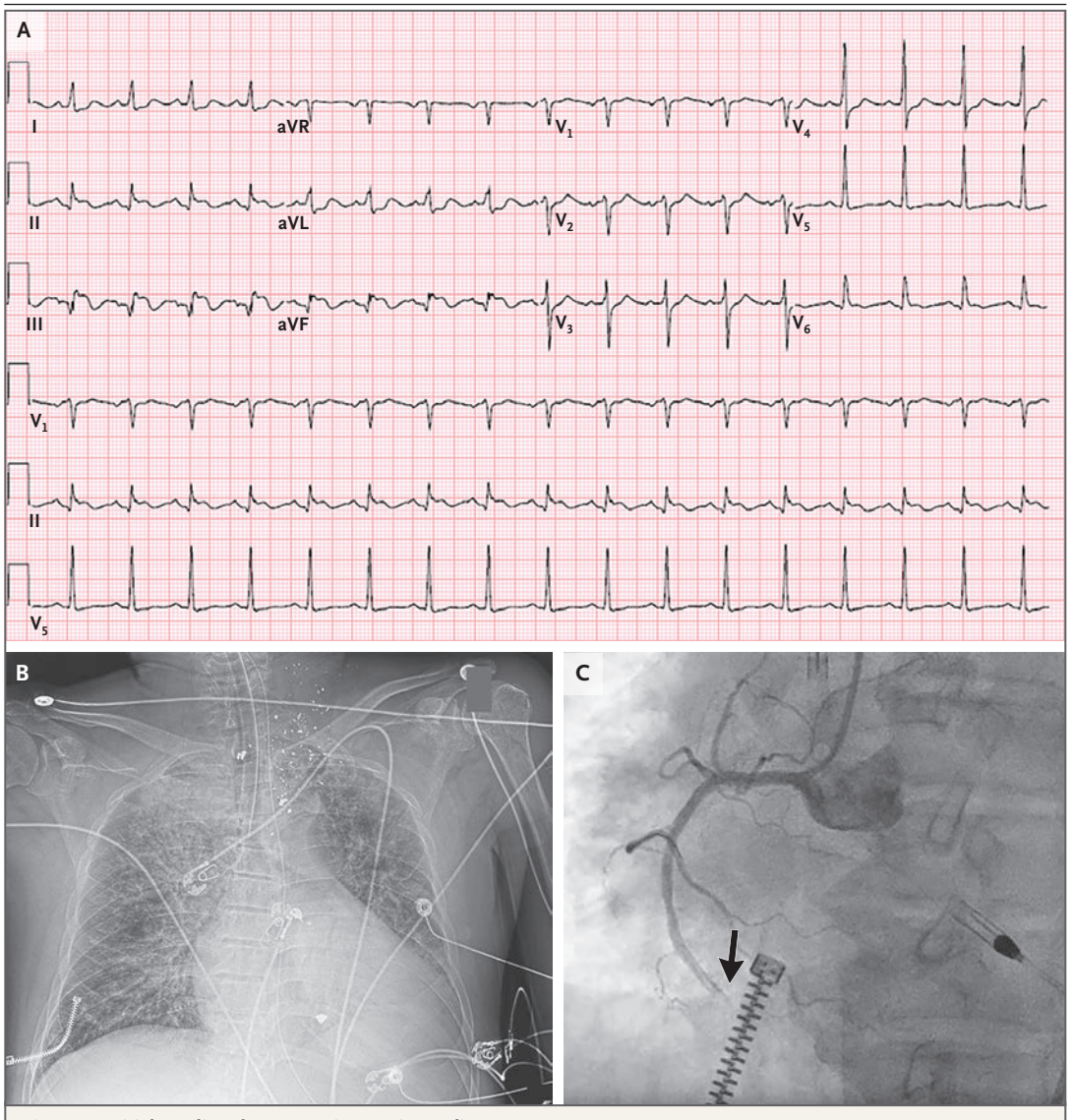


Figure 1. Initial Cardiopulmonary Diagnostic Studies.

An electrocardiogram (Panel A) shows sinus tachycardia, Q waves and 2-mm ST-segment elevations in the inferior leads, and reciprocal ST-segment depressions in the lateral and precordial leads. A chest radiograph (Panel B) shows an enlarged cardiac silhouette, as well as diffuse interstitial opacities in both lungs and an asymmetric consolidation in the right upper lobe; endotracheal and enteric tubes are in appropriate positions, and multiple metallic densities most likely related to a previous gunshot injury are projected over the left hemithorax. A coronary angiogram (Panel C) shows a thrombotic occlusion of the right coronary artery (arrow); a percutaneous left ventricular assist device is visible.

Table 1. Laboratory Data.*

Variable	Reference Range, Adults†	On Initial Evaluation, Hospital Day 1	During Cardiac Catheterization, Hospital Day 1	On CICU Admission, Hospital Day 2	6 Hr after CICU Admission, Hospital Day 2	14 Hr after CICU Admission, Hospital Day 2
Blood						
Hemoglobin (g/dl)	13.5–17.5	10.8	—	10.7	9.4	8.2
Hematocrit (%)	41.0–53.0	33.3	—	33.3	28.3	8.2
White-cell count (per μl)	4500–11,000	13,240	—	17,510	21,860	22,630
Platelet count (per μl)	150,000–400,000	330,000	—	447,000	371,000	257,000
Sodium (mmol/liter)	135–145	137	—	135	135	132
Potassium (mmol/liter)	3.4–5.0	3.2	—	3.5	3.6	5.1
Chloride (mmol/liter)	98–108	104	—	105	105	102
Carbon dioxide (mmol/liter)	23–32	15	—	20	14	12
Urea nitrogen (mg/dl)	8–25	12	—	17	25	24
Creatinine (mg/dl)	0.60–1.50	1.07	—	1.40	1.85	2.04
Glucose (mg/dl)	70–110	208	—	209	269	220
Calcium (mg/dl)	8.5–10.5	8.1	—	7.5	7.4	7.8
Ionized calcium (mmol/liter)	1.14–1.30	1.16	1.07	1.05	1.01	1.03
Albumin (g/dl)	3.3–5.0	3.0	—	2.5	2.4	2.4
Alanine aminotransferase (U/liter)	10–55	82	—	83	—	1018
Aspartate aminotransferase (U/liter)	10–40	88	—	98	—	1777
Alkaline phosphatase (U/liter)	45–115	132	—	121	—	102
Lactate (mmol/liter)	0.5–2.0	—	2.9	3.5	3.6	9.3
Glycated hemoglobin (%)	4.3–5.6	—	—	—	—	6.0
Prothrombin time (sec)	11.5–14.5	16.8	—	20.4	20.8	26.1
International normalized ratio	0.9–1.1	1.4	—	1.8	1.8	2.4
Partial-thromboplastin time (sec)	22.0–36.0	—	—	>150.0	47.4	87.0
Venous blood gas						
pH	7.30–7.40	7.17	—	—	—	—

Arterial blood gas						
Fraction of inspired oxygen	—	—	1.0	1.0	1.0	1.0‡
pH	7.35–7.45	—	7.24	7.22	7.28	7.14
Partial pressure of carbon dioxide (mm Hg)	35–42	—	42	49	40	35
Partial pressure of oxygen (mm Hg)	80–100	—	74	87	63	234
Urine						
Urine output (ml/hr)	—	—	140	150	40	0

* To convert the values for urea nitrogen to millimoles per liter, multiply by 0.357. To convert the values for creatinine to micromoles per liter, multiply by 88.4. To convert the values for glucose to millimoles per liter, multiply by 0.05551. To convert the values for calcium to millimoles per liter, multiply by 0.250. To convert the values for lactate to milligrams per deciliter, divide by 0.1110. CICU denotes cardiac intensive care unit.
† Reference values are affected by many variables, including the patient population and the laboratory methods used. The ranges used at Massachusetts General Hospital are for adults who are not pregnant and do not have medical conditions that could affect the results. They may therefore not be appropriate for all patients.
‡ In addition to mechanical ventilation, intravenous cisatracurium and inhaled nitric oxide (at a rate of 40 parts per million) were administered.

Intravenous norepinephrine and vasopressin were administered. Bedside ultrasonography revealed bilateral lung sliding and reduced left ventricular function. The trachea was intubated, and the oxygen saturation was 88% while the patient was receiving mechanical ventilation on a volume-controlled mode (tidal volume, 440 ml; respiratory rate, 20 breaths per minute; positive end-expiratory pressure [PEEP], 14 cm of water; fraction of inspired oxygen [FIO_2], 1.0).

Dr. Milena Petranovic: Portable chest radiography (Fig. 1B) revealed an enlarged cardiac silhouette, as well as diffuse interstitial opacities in both lungs and an asymmetric consolidation in the right upper lobe. Endotracheal and enteric tubes were in appropriate positions, and multiple metallic densities related to a previous gunshot injury were projected over the left hemithorax.

Dr. Stefanescu Schmidt: Unstable ventricular tachycardia recurred, and defibrillation was performed. Emergency cardiac catheterization was performed, and a percutaneous left ventricular assist device (LVAD) was placed through the right femoral artery. Coronary angiography (Fig. 1C) revealed a thrombotic occlusion of the right coronary artery, as well as 60 to 70% stenosis of the left anterior descending artery and a diagonal branch. The left ventricular end-diastolic pressure was 34 mm Hg. Intraprocedural transesophageal echocardiography (TEE) revealed a dilated, hypokinetic left ventricle with akinesis of the inferior and septal walls. Mild-to-moderate mitral regurgitation and tricuspid regurgitation were present, and there was no pericardial effusion.

The thrombosis of the right coronary artery was difficult to wire and cross. Percutaneous coronary intervention (PCI) was undertaken with the use of two drug-eluting stents in the middle and distal portions of the right coronary artery. Ventricular tachycardia recurred before reperfusion, and the patient underwent two cardioversions. Intravenous cangrelor, heparin, amiodarone, vancomycin, and cefepime were administered. Data from pulmonary artery catheterization, performed after PCI, are shown in Table 2. After the initiation of treatment with the percutaneous LVAD and reperfusion of the right coronary artery, the patient received low-dose norepinephrine.

Dr. Wong: The patient was admitted to the

Table 2. Data from Invasive Hemodynamic Monitoring and Pulse Oximetry.

Variable	Reference Range, Adults*	On Initial Evaluation, Hospital Day 1	During Cardiac Catheterization, Hospital Day 1	On CICU Admission, Hospital Day 2	6 Hr after CICU Admission, Hospital Day 2	14 Hr after CICU Admission, Hospital Day 2
Central venous pressure (mm Hg)	0–6	—	18	17	17	15
Right ventricular pressure (mm Hg)						
Systolic	20–30	—	68	—	—	—
End diastolic	0–6	—	15	—	—	—
Pulmonary artery pressure (mm Hg)						
Systolic	15–30	—	69	52	30	42
Diastolic	6–15	—	29	22	15	11
Mean	8–20	—	44	33	22	22
Pulmonary capillary wedge pressure (mm Hg)	6–14	—	20	—	—	—
Pulmonary artery pulsatility index	—	—	2.2	1.8	0.9	2.1
Central venous oxygen saturation (%)	70.0–80.0	—	56.6	—	—	—
Mixed venous oxygen saturation (%)	65.0–75.0	—	76.8	—	76.5	90.1
Arterial oxygen saturation (%)	94.0–99.0	91.5	93.0	94.2	96.9	99.1
Cardiac output by thermodilution (liters/min)	4.0–8.0	—	—	—	3.0	5.4
Cardiac index by thermodilution (liters/min/m^2)	2.4–4.0	—	—	—	1.7	3.0†

* Reference values are affected by many variables, including the patient population and the laboratory methods used. The ranges used at Massachusetts General Hospital are for adults who are not pregnant and do not have medical conditions that could affect the results. They may therefore not be appropriate for all patients.

† The measurement was obtained while the patient was receiving intravenous epinephrine at a rate of 5 μg per minute.

cardiac intensive care unit early on the morning of the second hospital day. The temporal temperature was 36.7°C, the heart rate 98 beats per minute, and the blood pressure 81/72 mm Hg while he was receiving intravenous norepinephrine at a rate of 4 μg per minute and maximal support from the percutaneous LVAD. The oxygen saturation was 92% while he was receiving mechanical ventilation on a volume-controlled mode. The heart sounds were tachycardic and distant and were obscured by the mechanical hum of the LVAD. There was bleeding at the site of the right femoral arteriotomy. The arms and legs were cool. When sedation was temporarily discontinued, the pupils were sluggishly reactive, without corneal reflexes or blinking in response to threat; there was no response to noxious stimuli, and the plantar reflexes were mute.

A screening test for severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) RNA was positive, and intravenous dexamethasone and remdesivir were administered. Aspirin was also administered. Results from laboratory testing and hemodynamic monitoring are shown in Table 1 and Table 2. The protocol for temperature management after cardiac arrest was initiated.

Dr. Petranovic: Chest radiography showed that the endotracheal tube, cardiac catheter, percutaneous LVAD, and enteric tube were in appropriate positions. There were diffuse alveolar opacities, which were greater on the left side than the right side, as well as a left pleural effusion.

Dr. Wong: During the 6 hours after admission to the cardiac intensive care unit, the blood pressure decreased to 74/72 mm Hg while the patient was receiving intravenous norepinephrine at a rate of 9 μg per minute and maximal support from the percutaneous LVAD. The urine output decreased, and the cardiac index measured by means of thermodilution was 1.7 liters per minute per square meter of body-surface area; other results are shown in Table 1 and Table 2. Treatment with intravenous epinephrine was initiated at a rate of 2 μg per minute. The oxygen saturation was 81% while he was receiving mechanical ventilation; intravenous cisatracurium and inhaled nitric oxide were administered.

By the afternoon, the patient was anuric. On examination, there was a systolic murmur, and the arms and legs remained cool and were mottled. He received doses of intravenous epinephrine at a rate of up to 5 μg per minute, and the blood pressure was 70/66 mm Hg. Laboratory test results are shown in Table 1 and Table 2.

Diagnostic test results were received, and management decisions were made.

DIFFERENTIAL DIAGNOSIS

Dr. Robert O. Roswell: The patient was a 55-year-old man who presented after a witnessed out-of-hospital cardiac arrest with ST-segment elevations in the inferior leads and reciprocal ST-segment depressions in the lateral leads on ECG. His syndrome included cardiogenic shock with acute hypoxemic respiratory failure, dysfunction of the left side of the heart, and elevated filling pressures. Despite stenting of a thrombosed right coronary artery, support from a percutaneous LVAD, and the administration of inotropes, the cardiogenic shock and hypoxemia worsened.

ACUTE RESPIRATORY FAILURE

Cardiologists who practice in the contemporary intensive care unit must be well versed in the management of respiratory failure and consider its effects on the heart and the differential diagnosis.[1,2] Clinicians must be mindful of the possibility that acute hypoxemic respiratory failure may have more than one cause, that new causes may develop during the course of acute illness, and that each cause may require attention, including appropriate treatments and approaches to ventilatory support.

The evaluation of patients with acute hypoxemic respiratory failure and bilateral opacities on chest radiography includes consideration of acute respiratory distress syndrome (ARDS) when an acute risk factor for its development, such as coronavirus disease 2019 (Covid-19) or aspiration pneumonitis after cardiac arrest, is present. The diagnosis of ARDS also requires the presence of severe hypoxemia, as determined by the ratio of partial pressure of arterial oxygen (PaO_2) to FIO_2. A recently proposed updated definition of ARDS allows for the ratio of oxygen saturation to FIO_2 to be used, as well, and does not require the presence of PEEP in the absence of invasive or noninvasive ventilation.[3]

It is important to note that the diagnosis of ARDS requires that pulmonary edema not be exclusively or primarily attributable to cardiogenic pulmonary edema.[3]

This patient had a positive test for SARS-CoV-2 infection, bilateral infiltrates, and an extremely low PaO_2:FIO_2 ratio (an initial ratio of 74 that worsened to 63 despite a PEEP of 14 cm of water). He also had clear evidence of prominent cardiogenic pulmonary edema, including an elevated NT-proBNP level (5679 pg per milliliter), a dilated, hypokinetic left ventricle on TEE, and a left ventricular end-diastolic pressure of 34 mm Hg — findings that preclude a confirmatory diagnosis of ARDS.

CARDIOGENIC SHOCK

Chest pain is the most common presenting symptom of acute coronary syndrome.[4] The patient's history from the time before the cardiac arrest could not be obtained to assess for antecedent chest pain. However, the presence of Q waves on the initial ECG suggests a subacute process. The presence of difficult-to-cross thrombosis in the right coronary artery lends credence to the hypothesis that he may have had a late-presenting ST-segment elevation myocardial infarction with cardiogenic shock. Acute myocardial infarction complicated by cardiogenic shock is defined by a systolic blood pressure of less than 90 mm Hg, end-organ hypoperfusion, and a cardiac index of less than 2.2 liters per minute per square meter; cardiogenic shock can occur hours to days after the myocardial infarction.[5,6]

Use of the Society for Cardiovascular Angiography and Interventions (SCAI) shock stage classification can help in discerning the risk of death from cardiogenic shock, with the stages ranging from A (least severe) to E (most severe).[7] This patient had refractory stage E shock on the basis of the minimal intrinsic cardiac pulsatility and hypotension despite intervention with mechanical and pharmacologic therapy, persistent severe lactic acidosis, and evolving hepatic and renal dysfunction. Stage E shock is associated with in-hospital mortality of at least 60% and 30-day mortality of at least 77%.[7,8]

Features of cardiogenic shock in this patient included a narrow pulse pressure, cool arms and legs, lactic acidemia, anuria, and a cardiac index measured by means of thermodilution of 1.7 liters per minute per square meter. In such a scenario, the mixed venous oxygen saturation would typically be low, perhaps approximately 40%. Yet, the concurrent mixed venous oxygen saturation in this patient was 76.5%. This finding corresponds to a cardiac index calculated according to Fick's principle of 4.9 liters per minute per square meter, which is discordant with the clinical picture. However, a cardiac index calculated according to Fick's principle can be erroneous because the calculation relies on an assumed oxygen consumption value, which is likely to be aberrant in a critically ill patient.[9]

Nevertheless, the higher-than-expected mixed venous oxygen saturation must be investigated, in part because it may help to explain the cause of acute myocardial infarction complicated by cardiogenic shock. With the pulmonary artery catheter in the appropriate position, the possible causes for a higher-than-expected mixed venous oxygen saturation in the context of acute myocardial infarction complicated by cardiogenic shock are extracardiac arteriovenous shunting, cardiogenic shock with concurrent distributive shock, acute severe mitral regurgitation from papillary muscle rupture, or ventricular septal rupture.

This patient had a history of a gunshot wound, which can cause the formation of arteriovenous fistulae from trauma. Arteriovenous fistulae can lead to a high mixed venous oxygen saturation but can also cause high-output heart failure. He had SARS-CoV-2 infection, which can cause distributive shock. Distributive shock can increase the mixed venous oxygen saturation owing to dysfunctional oxygen extraction.[10]

The patient might have had a late-presenting ST-segment elevation myocardial infarction with the development of a systolic murmur after presentation. Both ischemic papillary muscle rupture and ventricular septal rupture are mechanical complications of myocardial infarction. Intraprocedural TEE showed mild-to-moderate mitral regurgitation; it is possible that the severity of the mitral regurgitation was underestimated, given that the jet may be directed eccentrically. However, a ruptured papillary muscle is typically evident on TEE. A decrease in the pulmonary artery pulsatility index from 2.2 to 0.9

reflects right ventricular dysfunction, which could be due to ventricular septal rupture but could also be caused by new, severe, acute mitral regurgitation.

It is important to note that the central venous oxygen saturation was 56.6% while the mixed venous oxygen saturation was 76.8%. This combination of findings could indicate a "step-up" in oxygen saturation from the right atrium to the right ventricle due to extant left-to-right interventricular shunting, which would be suggestive of ventricular septal rupture. The administration of inhaled nitric oxide would lead to vasodilation of the pulmonary beds and offloading of the right ventricle, thereby increasing the flow across the left-to-right interventricular shunt and increasing the mixed venous oxygen saturation. In this patient, the mixed venous oxygen saturation was 90.1% after the administration of inhaled nitric oxide.

Given the patient's clinical history, echocardiography focused on the ventricular septum would be indicated. Because he had severe concurrent respiratory failure and SCAI stage E cardiogenic shock, venoarterial extracorporeal membrane oxygenation (ECMO) would be the next intervention to stabilize his condition, and additional treatment would be directed toward possible mechanical complications of myocardial infection as well as SARS-CoV-2 infection.

DR. ROBERT O. ROSWELL'S DIAGNOSIS

Ventricular septal rupture in the context of acute myocardial infarction complicated by cardiogenic shock.

ECHOCARDIOGRAPHIC STUDY

Dr. Emily K. Zern: Transthoracic echocardiography (TTE) revealed aneurysmal deformity of the inferoposterior aspect of the left ventricle. There was a 16-mm serpiginous defect in the inferoseptum with left-to-right interventricular shunting (Fig. 2A and 2B; and Videos 1 and 2, available with the full text of this article at NEJM.org). This finding is diagnostic of ventricular septal rupture. The peak interventricular flow velocity was at least 2.7 m per second. The right ventricle was dilated and hypokinetic, and the tip of the percutaneous LVAD was visible 39 mm from the aortic valve. Mild mitral regurgitation, moderate tricuspid regurgitation, mildly elevated right ventricular systolic pressure, and a small anterior pericardial effusion were detected.

ECHOCARDIOGRAPHIC DIAGNOSIS

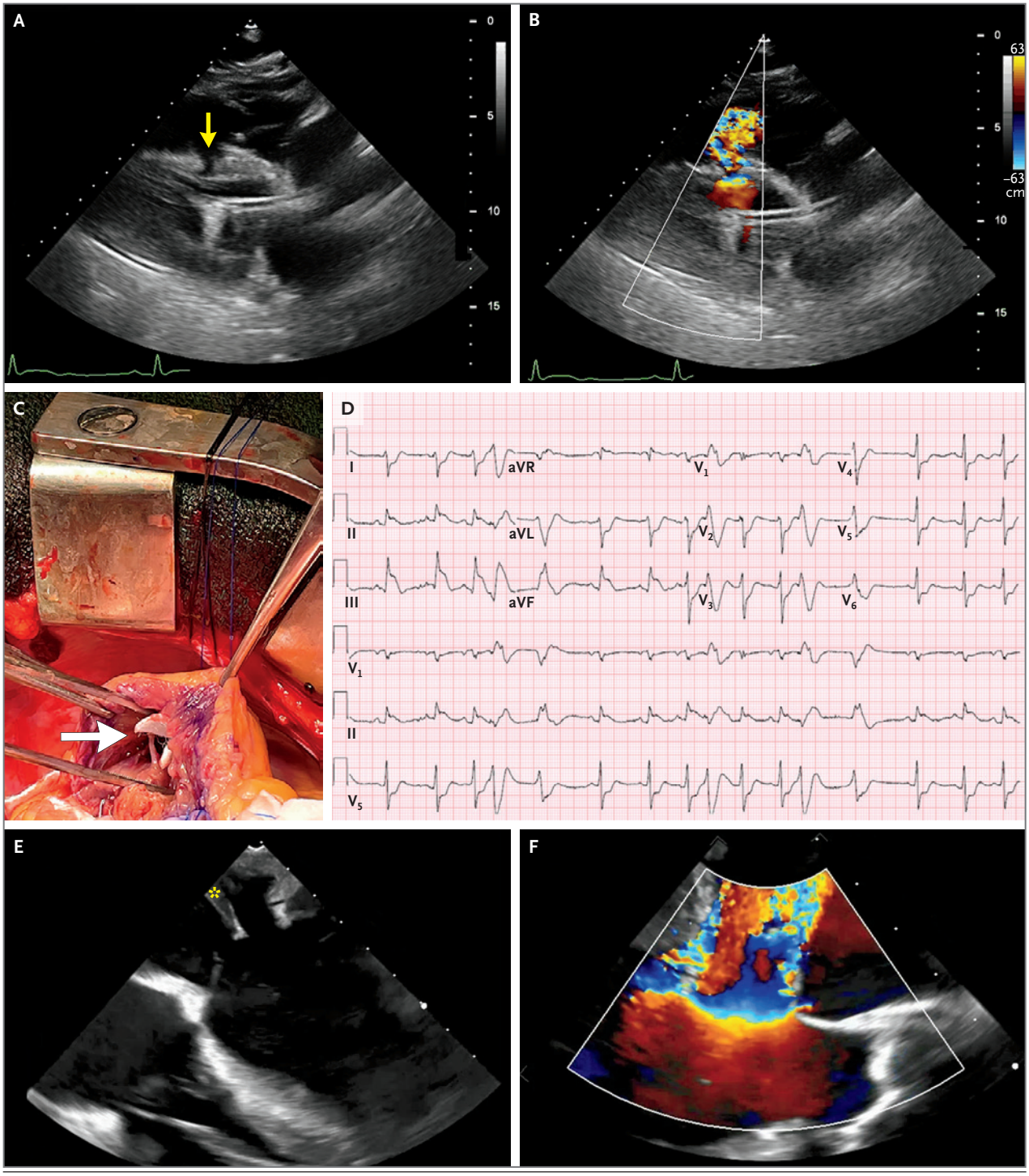
Ventricular septal rupture.

DISCUSSION OF MANAGEMENT

Dr. Daniel Burkhoff: Preoperative stabilization before the definitive surgical treatment of ventricular septal rupture typically involves medical therapy or temporary mechanical circulatory support. Hemodynamic goals for such therapies include normalizing the blood pressure and forward cardiac output, maintaining the pulmonary artery pressure and central venous pressure within the normal ranges, and reducing the flow through the pulmonary vasculature. In patients with acute ventricular septal rupture with left-to-right shunting, the flow through the pulmonary vasculature can reach 2 to 3 times the normal rate (e.g., 8 to 10 liters per minute), with the ratio of pulmonary to systemic flow typically ranging from 3 to 4. However, patients with ventricular septal rupture have a wide range of hemodynamic profiles, depending on the size of the ventricular septal rupture and the degree to which ventricular contractility is compromised by the infarction. This variability necessitates a customized approach to therapeutic decision making that can be guided, in part, by hemodynamic data obtained on pulmonary artery catheterization when feasible.

Treatment with vasopressors can unfavorably decrease forward systemic blood flow; the increased vascular resistance disproportionally increases the flow through the ventricular septal rupture into the lower-pressure right ventricle and through the pulmonary vasculature. In contrast, treatment with vasodilators can favorably decrease pulmonary flow and increase forward flow through the aorta, such that the blood pressure may not decrease despite the reduction of systemic vascular resistance. However, this approach may not be feasible if the patient has clinically significant hypotension. The administration of inotropes may be of limited

Videos showing echocardiographic studies are available at NEJM.org



value in overcoming the marked decrease in right and left ventricular function due to the infarction. The left ventricular ejection fraction may be misleading as an index of left ventricular contractility because the left ventricle is ejecting against a markedly reduced effective afterload and is receiving a higher preload from recirculated blood.

Because medical therapies are typically insufficient in patients with acute myocardial infarction

Figure 2 (facing page). Additional Cardiac Diagnostic Studies.

One day after the out-of-hospital cardiac arrest, a transthoracic echocardiographic (TTE) image obtained from a parasternal long-axis window (Panel A) shows a ventricular septal rupture (arrow); a percutaneous left ventricular assist device is in place. A TTE image obtained with color Doppler (Panel B) shows extensive left-to-right shunting across the ventricular septal rupture during ventricular systole. In a photograph obtained during surgical repair (Panel C), the apex of the heart is reflected cephalad, and a ventriculotomy established to the left of the posterior descending coronary artery provides access to the infarct zone; the ventricular septal rupture is visible through a left ventriculotomy (arrow). After resuscitation was performed for a subsequent in-hospital cardiac arrest, an electrocardiogram (Panel D) shows sinus rhythm with ventricular ectopic beats, ST-segment elevations of up to 6 mm in the inferior leads, and 5-mm ST-segment depressions in the lateral and precordial leads. A transesophageal echocardiographic (TEE) image obtained from the midesophageal four-chamber view (Panel E) shows a ruptured papillary muscle of the mitral valve, as evidenced by the presence of papillary muscle tissue in the left atrium (asterisk) during systole. A TEE image obtained with color Doppler from the midesophageal long-axis view, at a different omniplane angle (Panel F), shows severe mitral regurgitation due to the papillary muscle rupture.

complicated by cardiogenic shock and ventricular septal rupture, temporary mechanical circulatory support is often considered. Case reports and small case series of mechanical circulatory support[11] include the use of an intraaortic balloon pump,[12,13] a percutaneous transaortic ventricular assist device,[14] a transeptal bypass system from the left atrium to the femoral artery (e.g., TandemHeart),[15] or ECMO.[11] Owing to a lack of data, there is no agreed-upon approach to the treatment of ventricular septal rupture as a complication of myocardial infarction. The choice therefore largely depends on device availability, local expertise, the severity of hemodynamic compromise, and whether supplemental oxygenation of the blood is needed. The following sequence of therapies may be a reasonable approach: initial medical therapy, followed by the use of an intraaortic balloon pump, and then followed by the use of either a ventricular assist device or ECMO. Given the multiorgan failure and severity of hypotension in this patient, and despite the presence of a percutaneous LVAD, the next step was ECMO.

Dr. Wong: Peripheral venoarterial ECMO and continuous venovenous hemodialysis were initiated. Second and third tests for SARS-CoV-2 RNA were negative. The patient's family members confirmed that he had received two vaccines against Covid-19 in previous months. Treatment with dexamethasone and remdesivir was stopped after 3 days, and the patient underwent surgical repair of the ventricular septal rupture. Intraoperative TEE again showed the ventricular septal rupture with left-to-right shunting (Video 3).

Dr. Thoralf M. Sundt: Repair of the inferoposterior ventricular septal rupture (Fig. 2C) was conducted with the patch technique with infarct exclusion.[16] A large bovine pericardial patch was sewn to the inside of the left ventricle, eliminating the need for débridement of the myocardium. The flexible patch simply bridges the defect, leaving intact any viable myocardium that may still be able to contract and maintain ventricular geometry. The patch also serves to exteriorize the ventricular septal rupture, such that with a simple linear closure of the myocardium, hemostasis can be established with only right ventricular pressure on the suture line.

The left anterior descending artery was bypassed. The posterior descending artery was oversewn because the subtended myocardium had been infarcted and was patched. The ECMO equipment and percutaneous LVAD were removed.

Dr. Wong: The trachea was extubated and mechanical ventilation was discontinued on postoperative day 1. Treatment with inotropes and vasopressors was stopped on postoperative day 2, and continuous venovenous hemodialysis was discontinued on postoperative day 3 with recovery of renal function. Once the patient was able to provide his medical history, he recalled having had new chest pressure for approximately 3 days before the cardiac arrest.

After the repair, aspirin, clopidogrel, atorvastatin, and metoprolol were administered. On postoperative day 7, TTE showed no evidence of residual interventricular shunting. A dilated left ventricle (left ventricular ejection fraction, 35%) with regional inferior dysfunction, a dilated right ventricle with dysfunction, mild-to-moderate mitral regurgitation and tricuspid regurgitation with biatrial dilatation, and a pleural effusion were detected.

On postoperative day 13, the patient had dyspnea and became unresponsive after urinating. The initial cardiac rhythm was consistent with pulseless electrical activity with sinus bradycardia. CPR was initiated, and intravenous atropine and epinephrine were administered. The subsequent cardiac rhythm was consistent with ventricular tachycardia, and three shocks and intravenous epinephrine, lidocaine, amiodarone, and sodium bicarbonate were administered. The trachea was intubated for mechanical ventilation, and venoarterial ECMO was initiated with right femorofemoral cannulation. Subsequent ECG showed sinus rhythm with ventricular ectopic beats, ST-segment elevations of up to 6 mm in the inferior leads, and ST-segment depressions in the lateral and precordial leads (Fig. 2D).

TEE, performed during ECMO cannulation, revealed a ruptured papillary muscle of the mitral valve with severe mitral regurgitation (Fig. 2E and 2F and Videos 4 and 5). Serial ECGs showed resolution of the ST-segment elevations.

Dr. Sundt: The patient underwent surgical exploration, and the posteromedial head of the papillary muscle that supplies chordae tendineae to the anterior leaflet was ruptured. The affected segment of the anterior leaflet and associated papillary muscle head were excised. The remainder of the anterior leaflet was detached at its base from the aortomitral continuity and reflected posteriorly, such that it was included with the intact posterior leaflet in the valve sutures. A 29-mm porcine bioprosthetic mitral valve was implanted with preservation of the remaining chordal attachments.

PATHOLOGICAL DISCUSSION

Dr. Cynthia K. Harris: On microscopic examination of the surgical specimen (Fig. 3), the cardiomyocytes of the papillary muscle were devoid of nuclei, a finding consistent with coagulative necrosis. There was abundant neutrophilic inflammation, with no histologically significant histiocytic inflammation. Acute hemorrhage and surface fibrin deposition were also seen.

This patient's case shows a well-characterized progression of histologic findings that develop after acute myocardial infarction. Coagulative necrosis begins within 4 hours after the infarction

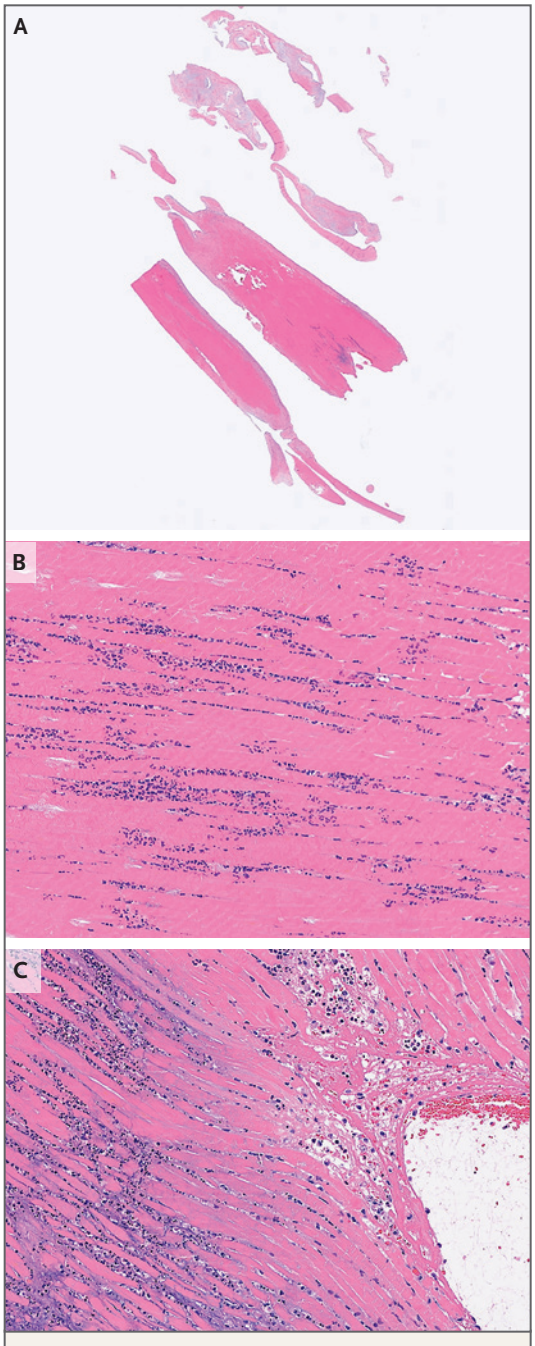


Figure 3. Histologic Examination of the Surgical Specimen.

Hematoxylin and eosin staining shows fragments of papillary muscle with attached chordae tendineae and valve tissue (Panel A). The cardiomyocytes of the papillary muscle are devoid of nuclei, a finding consistent with coagulative necrosis (Panel B). Abundant neutrophilic inflammation, acute surface hemorrhage, and surface fibrin deposition are shown (Panel C).

and peaks 2 to 5 days after the infarction.[17,18] Neutrophilic infiltration begins 1 day after the infarction. By day 3 to 7, the myofibers begin to disintegrate, the neutrophils break down, and macrophages infiltrate the tissue to phagocytose the dying cells. The histologic changes present in the papillary muscle in this patient indicate that the infarct had occurred 1 to 3 days earlier.

PATHOLOGICAL DIAGNOSIS

Papillary muscle and chordae tendineae with acute infarction, neutrophilic inflammation, and surface fibrin.

MECHANICAL COMPLICATIONS OF MYOCARDIAL INFARCTION

Dr. Patrick T. O'Gara: Pump failure due to severe left ventricular systolic dysfunction is the leading cause of acute myocardial infarction complicated by cardiogenic shock, accounting for nearly 80% of cases. Mechanical complications of myocardial infarction — such as rupture of the ventricular septum, papillary muscle, or left ventricular free wall — account for approximately 12% of cases.[19] The incidence of mechanical complications has decreased considerably over the past four decades, in temporal association with the increasing use of early reperfusion therapy, particularly primary PCI.[20,21]

The time course of myocardial rupture is bimodal, with one peak occurring within the first 24 hours and the other peak occurring 3 to 5 days after myocardial infarction.[22] Shared risk factors for the various types of myocardial rupture include older age, female sex, hypertension, a first infarction, the absence of a collateral blood supply, and the use of medications that may interfere with wound healing, such as glucocorticoids or nonsteroidal antiinflammatory drugs.

Mechanical complications of myocardial infarction can be distinguished from each other on the basis of the findings on physical examination, echocardiography, and cardiac catheterization. Ventricular septal rupture with shock can complicate the course of both anterior and inferior myocardial infarction. With anterior myocardial infarction, the rupture typically involves the anterior apical septum, whereas with inferior myocardial infarction, the rupture involves the inferior basal septum and has a worse prognosis. Ventricular septal rupture can be accompanied by a harsh systolic murmur at the middle or lower left sternal border, left-to-right shunting detected on echocardiography or contrast ventriculography, and a step-up in oxygen saturation from the right atrium to the right ventricle — findings that were all present in this patient. In patients with acute myocardial infarction complicated by cardiogenic shock and ventricular septal rupture, hemodynamic stabilization is usually established with mechanical circulatory support before definitive surgical repair, the timing of which is individualized. Transcatheter repair can be considered in selected patients with ventricular septal rupture who are considered to be poor candidates for surgical repair.

Thirteen days after this patient had undergone surgical repair of the ventricular septal rupture and concomitant coronary artery bypass, he had posteromedial papillary muscle rupture with severe acute mitral regurgitation, electrical instability, and cardiogenic shock. The systolic murmur associated with papillary muscle rupture is usually soft or absent owing to equalization of the pressures between the left atrium and the left ventricle. Rupture of the posteromedial papillary muscle is more common than rupture of the anterolateral papillary muscle; the posteromedial muscle has a singular coronary blood supply, whereas the anterolateral muscle has a dual coronary blood supply. The infarct that causes posteromedial papillary muscle rupture may therefore be relatively small, involving an isolated obtuse marginal branch or posterolateral ventricular branch, and may be accompanied by only modest ST-segment depressions in the precordial or lateral leads. Large V waves may be inscribed on the tracing of the pulmonary capillary wedge pressure. The diagnosis can be established by means of echocardiography or contrast ventriculography. In this patient, mechanical circulatory support was reinitiated after the papillary muscle rupture, and bioprosthetic mitral valve replacement was performed.

The occurrence of two sequential mechanical complications of myocardial infarction in the same patient is exceedingly rare. The late papillary

muscle rupture could have resulted from impaired wound healing after the initial injury associated with his inferior myocardial infarction. Alternatively, it could have been an unintended consequence of further compromise of blood flow in the distal right coronary artery during surgical repair of the ventricular septal rupture.

FOLLOW-UP

Dr. Wong: Two days after the patient underwent mitral valve replacement, ECMO was discontinued. A tracheostomy was maintained, and mechanical ventilation was continued for 6 weeks after the procedure, in the context of ventilator-associated pneumonia due to carbapenem-resistant enterobacteriaceae. Renal replacement therapy was administered for 3 months, until renal recovery was achieved. After 1 month of rehabilitation, the patient was discharged home with prescriptions for aspirin, ticagrelor, atorvastatin, bumetanide, metoprolol, sacubitril–valsartan, empagliflozin, and spironolactone. Discharge occurred 145 days after his initial presentation.

At an outpatient follow-up visit 12 months after the initial presentation, the patient reported that he walked 45 minutes daily, which resulted in mild fatigue but no orthopnea or edema. Echocardiography showed a left ventricular ejection fraction of 27% and a hypokinetic right ventricle. The prosthetic mitral valve was functioning well, and there was no evidence of residual interventricular shunting.

FINAL DIAGNOSIS

Inferior myocardial infarction with ventricular septal rupture and acute papillary muscle rupture.

This case was presented at the Harvard Medical School postgraduate course "5C: Concepts in Contemporary Critical Care Cardiology," directed by Dr. David M. Dudzinski.

Disclosure forms provided by the authors are available with the full text of this article at NEJM.org.

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