

EARLY EXPRESSION OF ANGIOGENESIS FACTORS IN ACUTE MYOCARDIAL ISCHEMIA AND INFARCTION

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ABSTRACT

Background When the myocardium is deprived of blood, a process of ischemia, infarction, and myocardial remodeling is initiated. Hypoxia-inducible factor 1 (HIF-1) is a transcriptional activator of vascular endothelial growth factor (VEGF) and is critical for initiating early cellular responses to hypoxia. We investigated the temporal and spatial patterns of expression of the α subunit of HIF-1 (HIF-1 α) and VEGF in specimens of human heart tissue to elucidate the early molecular responses to myocardial hypoxia.

Methods Ventricular-biopsy specimens from 37 patients undergoing coronary bypass surgery were collected. The specimens were examined by microscopy for evidence of ischemia, evolving infarction, or a normal histologic appearance. The specimens were also analyzed with the reverse-transcriptase polymerase chain reaction for HIF-1 α and VEGF messenger RNA (mRNA) expression and by immunohistochemical analysis for the location of the HIF-1 α and VEGF proteins.

Results HIF-1 α mRNA was detected in myocardial specimens with pathological evidence of acute ischemia (onset, <48 hours before surgery) or early infarction (onset, <24 hours before surgery). In contrast, VEGF transcripts were seen in specimens with evidence of acute ischemia or evolving infarction (onset, 24 to 120 hours before surgery). Patients with normal ventricles or evidence of infarction in the distant past had no detectable levels of either VEGF mRNA or HIF-1 α mRNA. HIF-1 α immunoreactivity was detected in the nuclei of myocytes and endothelial cells, whereas VEGF immunoreactivity was found in the cytoplasm of endothelial cells lining capillaries and arterioles.

Conclusions An increase in the level of HIF-1 α is an early response to myocardial ischemia or infarction. This response defines, at a molecular level, one of the first adaptations of human myocardium to a deprivation of blood. HIF-1 α is a useful temporal marker of acutely jeopardized myocardium. (N Engl J Med 2000;342:626-33.)

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HYPOXIA is a potent regulator of a variety of biologic processes, including angiogenesis, vascular contractility, and erythropoiesis.¹⁻⁴ When a coronary artery is partially or totally occluded, metabolic and contractile changes are initiated in the heart within seconds.⁵ Some of these early changes facilitate cellular preservation and functional survival of the heart. If the my-

ocardium remains deprived of blood, changes of progressively greater severity eventually culminate in cell death, tissue necrosis, and myofibrillar remodeling.⁶

Hypoxia-inducible factor 1 (HIF-1) is a transcriptional factor that is expressed in response to a decrease in the partial pressure of cellular oxygen and activates genes involved in angiogenesis, glycolysis, modulation of vascular tone, and erythropoiesis.⁷⁻¹¹ It is a heterodimer composed of α and β subunits, both of which are members of the family of basic helix-loop-helix peptides.¹² HIF-1 α is an 826-amino-acid protein that functions as a *trans*-acting transcriptional activator of vascular endothelial growth factor (VEGF), inducible nitric oxide synthase, lactate dehydrogenase, and erythropoietin.¹³⁻¹⁶ HIF-1 β is a constitutively expressed nuclear translocator protein that forms heterodimers with HIF-1 α as well as other nuclear proteins.¹⁷

Several studies have found increased levels of HIF-1 α messenger RNA (mRNA) in hypoxic cultured cells and in organs (the retina and lung) of animals exposed to short- or long-term hypoxia.¹⁸⁻²⁰ We hypothesized that an increase in the steady-state levels of HIF-1 α mRNA is one of the earliest responses to myocardial ischemia and infarction in humans and that it potentially is an important stimulus of angiogenesis and myocardial-cell survival. To investigate this possibility, we examined HIF-1 α mRNA expression in relation to changes in steady-state levels of VEGF mRNA. VEGF is an inducible factor that controls capillary growth and angiogenesis in several organ systems.²¹ The temporal and spatial patterns of expression of HIF-1 α and VEGF proteins were also studied to identify molecular markers of the myocardial response to ischemia.

METHODS

Selection of Patients

Between November 1997 and April 1998, 37 patients (27 men and 10 women; mean age, 65.9 years; range, 55 to 75 years) who were undergoing coronary bypass surgery were enrolled in the study. Seven of these patients had a clinical history, electrocardiographic findings, and creatine kinase and troponin I levels indi-

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cating that myocardial infarction had occurred within the preceding 24 hours (early infarction); 8 patients had evidence, on the basis of the same variables, that myocardial infarction had occurred during the preceding 24 to 120 hours (evolving infarction); and 10 patients had evidence of myocardial ischemia of less than 48 hours' duration (acute ischemia), defined as angina or heart failure without Q waves on the electrocardiogram and without an increase in serum levels of creatine kinase and troponin I. Twelve patients underwent coronary bypass surgery but had not had angina or heart failure within the preceding 10 days. According to usual practice at our institution, myocardial infarction was defined as a total creatine kinase level of more than 150 U per liter (normal range, 10 to 150) or a troponin I level of more than 0.6 ng per milliliter (normal range, less than 0.6).²²

The criteria for enrollment included the need for urgent or elective coronary bypass surgery, an age between 55 and 75 years, and written informed consent for heart biopsy. The study was approved by the University of California, San Diego, institutional review board.

Biopsy of Myocardium

After the induction of anesthesia and median sternotomy, the heart of each patient was examined, and 3-mm, partial-thickness biopsy specimens were taken from the left ventricle. In patients with early or evolving infarction, specimens were taken from the area of presumed infarction as well as from an area of the ventricle free of coronary disease that could have caused ischemia or infarction. Likewise, in patients with acute ischemia, specimens were taken from the area of ischemia as well as from an area of normal ventricular tissue. In this way, each patient with ischemia or infarction served as his or her own control. In patients without evidence of ischemia or infarction, a single ventricular-biopsy specimen was obtained. All biopsies were performed before cardiopulmonary bypass, during ventilation with a fraction of inspired oxygen of 40 percent and peripheral oxygen saturations of greater than 95 percent. Biopsy sites were closed with polypropylene sutures.

Extraction of RNA and Analysis of Specimens

Half of each biopsy specimen was fixed in formalin, sectioned to a thickness of 5 μ m, mounted on slides, and stained with hematoxylin and eosin. The mounted specimens were then examined for evidence of acute ischemia and early or evolving infarction.²³ The other half of each specimen was frozen in liquid nitrogen at -140°C . Portions of the frozen samples were lyophilized, and then RNA was extracted by the acid guanidinium thiocyanate-phenol-chloroform technique, as previously described.^{24,25}

The recovered RNA pellet was dried under vacuum conditions for 10 to 15 minutes and then dissolved in diethyl pyrocarbonate-treated deionized distilled water. The concentration and purity of the RNA were determined by spectrophotometric analysis (Ultrospec II, Biochrom, Cambridge, England) at 260 and 280 nm. The samples were stored at -80°C until analyzed.

Measurement of RNA

The reverse-transcriptase polymerase chain reaction (PCR) was used to analyze each ventricular specimen for the presence of transcripts encoding HIF-1 α , HIF-1 β , VEGF, and cyclophilin. Cyclophilin mRNA was studied as a marker to control for variation in RNA concentration and RNA degradation as potential confounding variables. Five micrograms of total RNA was used to synthesize complementary DNA (cDNA) with Super Script II Reverse Transcriptase and oligo(dT)¹²⁻¹⁸ (GIBCO BRL, Gaithersburg, Md.). The synthesized primers had the following sequences: for HIF-1 α , 5'CTGTGATGAGGCTTACCATCAGC3' and 5'CTCGGCTAGTTAGGGTACACTC3'; for HIF-1 β , 5'CAGGTCGGATGATGAGCAGACA3' and 5'CTCATGGAAGACTGCTGACCTTC3'; for VEGF, 5'GGATGTCTATCAGCGCAGCTAC3' and 5'TCACCGCTCGGCTTGTACATC3'; and for cyclophilin, 5'GTGACTTCACACGCCATAATGCG3' and 5'GGTGCTCTCCTGAGCTACAGAAGG3'.

Duplicate amplification reactions were carried out with a single-block thermocycler (Ericomp, San Diego, Calif.) containing 2 μ l of first-strand cDNA, 1 μ l of each primer, deoxynucleotide triphosphates (at 10 mM each), 25 mM magnesium chloride, 0.5 U of *Taq* DNA polymerase, and 36.5 μ l of autoclaved distilled water. Each sample underwent initial denaturation at 95°C for 5 minutes, 35 cycles of denaturation at 95°C for 30 seconds, annealing at 55°C for 1 minute, extension at 72°C for 1 minute, and a final extension at 72°C for 10 minutes. The PCR products were electrophoresed on 1.8 percent agarose gels containing 3 percent ethidium bromide in TRIS-acetate-EDTA buffer. The gels were photographed with an electrophoresis photodocumentation camera (Fisher Scientific, Pittsburgh) on black-and-white film (3000ISO, Polaroid, Cambridge, Mass.).

Immunohistochemical Staining for HIF-1 α and VEGF

Portions of the frozen biopsy specimens were fixed in 10 percent formalin and prepared as 5- μ m-thick tissue sections on slides. The paraffin was then removed with a xylene substitute (Hemo-De, Fisher Scientific) and the sections were rehydrated with ethanol gradient washes. The sections of affected tissue and normal tissue from patients with ischemia or infarction and the sections from patients without ischemia or infarction were incubated with either mouse antihuman HIF-1 α IgG (IgG2v, Novus Biological, Littleton, Colo.) or mouse antihuman VEGF IgG (IgG_{2a}, Santa Cruz Biotechnology, Santa Cruz, Calif.) at a 1:100 dilution. Control sections were incubated with diluted normal horse serum (Vector Laboratories, Burlingame, Calif.) instead of the primary antibody. All the sections were subsequently incubated with biotinylated secondary antimouse antibodies and stained with an immunoperoxidase technique (Vectastain Elite ABC reagents, Vector Laboratories). Sections were dried and mounted (Gel Mount, Biomed, Foster City, Calif.), examined with a photomicroscope, and photographed on color film (Fujicolor 100, Tokyo, Japan).

Statistical Analysis

Data for each continuous variable were examined with the Shapiro-Wilk W test to determine whether assumptions of normality were valid. When continuous variables were compared among the groups of patients, an independent Student's t-test and one-way analysis of variance were used for normally distributed data, and the Wilcoxon rank-sum test and the Kruskal-Wallis test were used for non-normally distributed data. For all the tests, the significance level was 5 percent. When significant differences were found among the groups, pairwise comparisons were made to identify the source of the differences. Overall type I error rates of 5 percent were controlled with use of the Tukey-Kramer honestly-significant-differences test (with analysis of variance) or the Nemenyi test (with the Kruskal-Wallis test). Descriptive data for continuous variables are reported as means \pm SD or as medians and ranges. Categorical variables are presented as numbers and percentages. Data were analyzed with JMP software (version 3.2.1, SAS Institute, Cary, N.C.) or with a program written in S+ (version 5.0, release 3, MathSoft, Seattle).

RESULTS

Classification of Ventricular Specimens and Preoperative Characteristics of the Patients

All ventricular-biopsy specimens were examined by light microscopy for evidence of ischemia or infarction by a cardiac pathologist who was unaware of the patients' identity. Seven specimens had pathological evidence of acute myocardial infarction that had occurred less than 24 hours before biopsy (designated the early-infarction group), 8 specimens had evidence of acute infarction that had occurred 24 to 120 hours before biopsy (the evolving-infarction group),

10 specimens had evidence of acute ischemia that had occurred less than 48 hours before biopsy (the ischemia group), and 12 specimens had no evidence of ischemia or infarction (the control group). For each patient in the first three groups, the second ventricular-biopsy specimen, taken from an area remote from the ischemic or infarcted area, was found on microscopical examination to be normal.

The characteristics and cardiac measurements of the patients before coronary bypass surgery and heart biopsy are shown in Table 1. There were no apparent differences in age or sex distribution among the four groups of patients. There were no significant differences in the peak levels of troponin I and creatine kinase between the seven patients in whom acute myocardial infarction had occurred less than 24 hours before biopsy (early infarction) and the eight patients in whom infarction had occurred 24 to 120 hours before biopsy (evolving infarction). The seven patients with early infarction had higher pulmonary-capillary wedge pressures ($P < 0.001$), had lower ejection fractions ($P < 0.01$), and were in higher New York Heart Association functional classes than those with ischemia occurring less than 48 hours before biopsy and those without ischemia or infarction.

Pathological Analysis of Ventricular Specimens

There were direct correlations between clinical course (onset of chest pain and electrocardiographic changes) and the pathological classifications of the affected specimens. Figure 1 shows representative biopsy specimens from the four groups of patients. There were no correlations between the levels of troponin I or creatine kinase and the severity of myocardial necrosis in any of the specimens. This lack of correlation may reflect a sampling bias, since only a single affected biopsy specimen was obtained from each patient.

Molecular Analysis of Ventricular Specimens

Figure 2 shows the results of the PCR analysis of samples of RNA from ventricular specimens from the four groups of patients. All seven patients with early infarction had detectable steady-state levels of HIF-1 α mRNA in the specimen from the infarcted region and did not have detectable levels of HIF-1 α mRNA in the normal ventricular specimen. VEGF transcripts were not detected in any biopsy specimens from this group. Patients with evolving infarction had both HIF-1 α transcripts and VEGF transcripts in specimens from the infarcted area of the ventricle only.

TABLE 1. CHARACTERISTICS OF THE PATIENTS UNDERGOING CORONARY-ARTERY BYPASS SURGERY ACCORDING TO THE PRESENCE OR ABSENCE OF INFARCTION OR ISCHEMIA IN VENTRICULAR-BIOPSY SPECIMENS.*

VARIABLE	INFARCTION		ACUTE ISCHEMIA (<48 HR BEFORE SURGERY)	NO ISCHEMIA OR INFARCTION	P VALUE†
	EARLY (<24 HR BEFORE SURGERY)	LATE (24–120 HR BEFORE SURGERY)			
No. of patients	7	8	10	12	
Age — yr	64.6±4.1	64.0±5.6	65.6±7.2	68.2±5.5	NS
Male sex — no. (%)	6 (86)	6 (75)	7 (70)	8 (67)	
Ejection fraction — %	31.4±6.9	40.0±6.5	43.5±6.7	44.2±6.7	<0.01
Pulmonary-artery pressure — mm Hg					
Systolic	42.1±12.0	29.9±7.6	25.9±6.7	26.4±4.2	<0.001
Diastolic	22.0±6.7	16.6±3.7	12.7±3.4	12.6±3.0	<0.001
Pulmonary-capillary wedge pressure — mm Hg					<0.001
Median	20	14	12	11	
Range	20–30	10–20	10–18	9–18	
Systolic blood pressure — mm Hg	103.6±14.4	127.5±10.3	136.5±15.4	133.1±10.8	<0.001
New York Heart Association class — no. (%)					
I	0	0	3 (30)	7 (58)	
II	0	4 (50)	4 (40)	5 (42)	
III	1 (14)	4 (50)	3 (30)	0	
IV	6 (86)	0	0	0	
Peak troponin I — ng/ml					NS
Median	10	9			
Range	7–21	7–15			
Peak creatine kinase — U/liter	1267.3±105.4	1246.3±264.0			NS

*Plus-minus values are means ±SD. NS denotes not significant.

†P values are for the comparison between patients with early infarction and patients with acute ischemia or no ischemia or infarction.

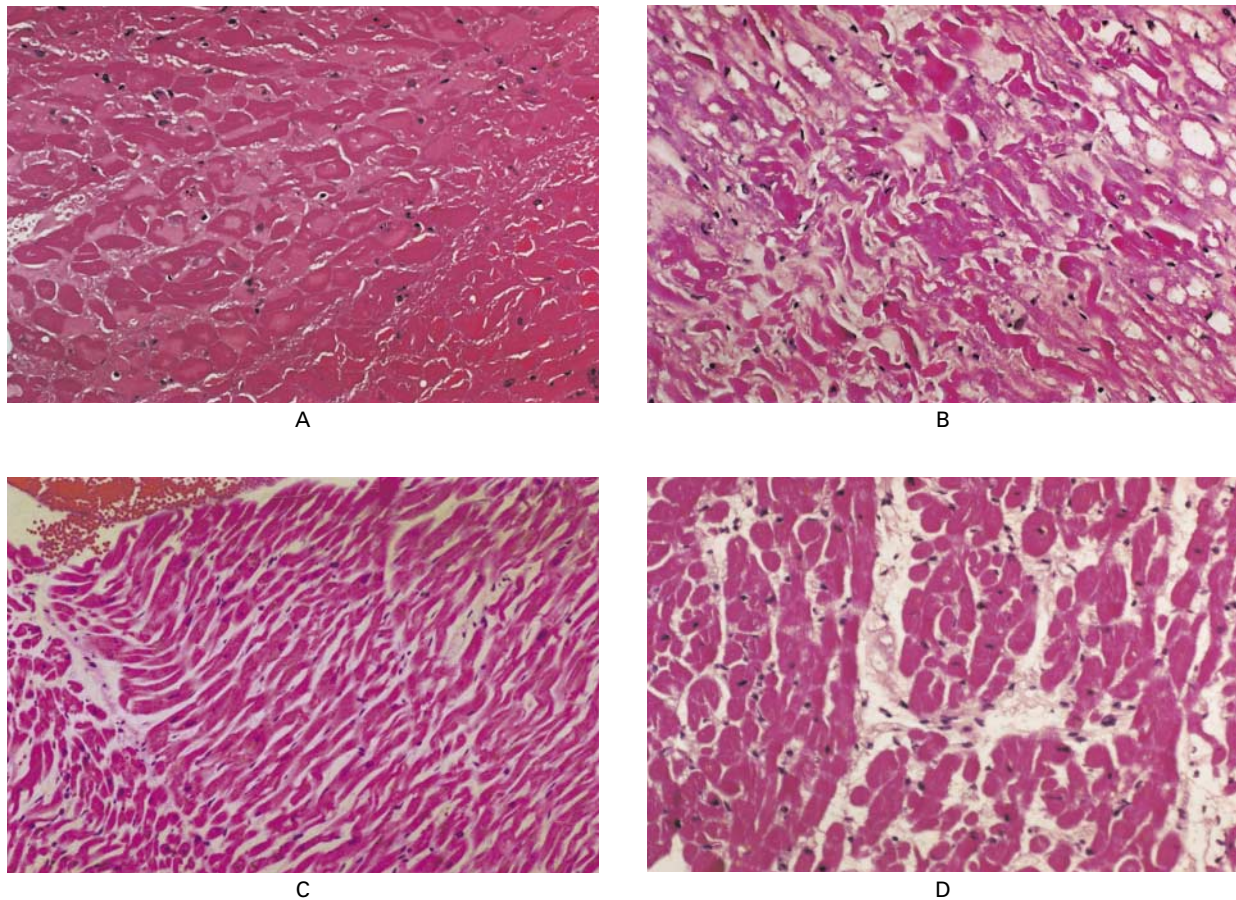


Figure 1. Pathological Changes in Representative Ventricular-Biopsy Specimens (Hematoxylin and Eosin, $\times 200$).

The specimen from a patient with early transmural myocardial infarction (onset, <24 hours before surgery) shows wavy fibers, coagulation necrosis with hyper-eosinophilia, and loss of myofibrils (Panel A). The specimen from a patient with evolving transmural myocardial infarction (onset, 24 to 120 hours before surgery) shows disintegrating myofibers and myocytolysis, disintegrating neutrophils, and infiltration of monocytes and macrophages (Panel B). The specimen from a patient with focal acute ischemia (onset, <48 hours before surgery) shows wavy fibers and intact nuclei in myocytes (Panel C). The specimen from a patient with no ischemia or infarction has a normal cellular appearance (Panel D).

Likewise, patients with acute ischemia had HIF-1 α and VEGF transcripts in specimens from the affected myocardial territory but not in control specimens. Patients with no infarction or ischemia had no detectable expression of HIF-1 α or VEGF mRNA in their single specimens.

The HIF-1 α mRNA detected in all the affected specimens was 383 bp long. The VEGF mRNA detected in specimens from patients with evolving infarction or ischemia was present as two transcripts, 445 and 517 bp long. These two VEGF transcripts correspond to the known protein isoforms VEGF165 and VEGF182. All the samples contained HIF-1 β mRNA, indicating that the β moiety is not sensitive to hypoxia in the heart. We found that levels of cyclophilin mRNA were consistently equal among the samples studied.

Localization of HIF-1 α and VEGF Proteins in Hypoxic Myocardium

Immunohistochemical staining with antibody to HIF-1 α of sectioned biopsy specimens from patients with early or evolving infarction or ischemia revealed HIF-1 α protein throughout areas of infarcted or ischemic myocardium. Specifically, immunoreactivity was seen in the nuclei of cardiomyocytes and endothelial cells lining the small vessels (Fig. 3). HIF-1 α protein was not present in noninfarcted or nonischemic myocardium (data not shown). The level of expression of HIF-1 α was higher in the myocardium than in the endothelium.

VEGF immunoreactivity was seen in biopsy specimens with evidence of evolving infarction and in those with evidence of acute ischemia (onset, <48 hours before surgery). In contrast to HIF-1 α , VEGF

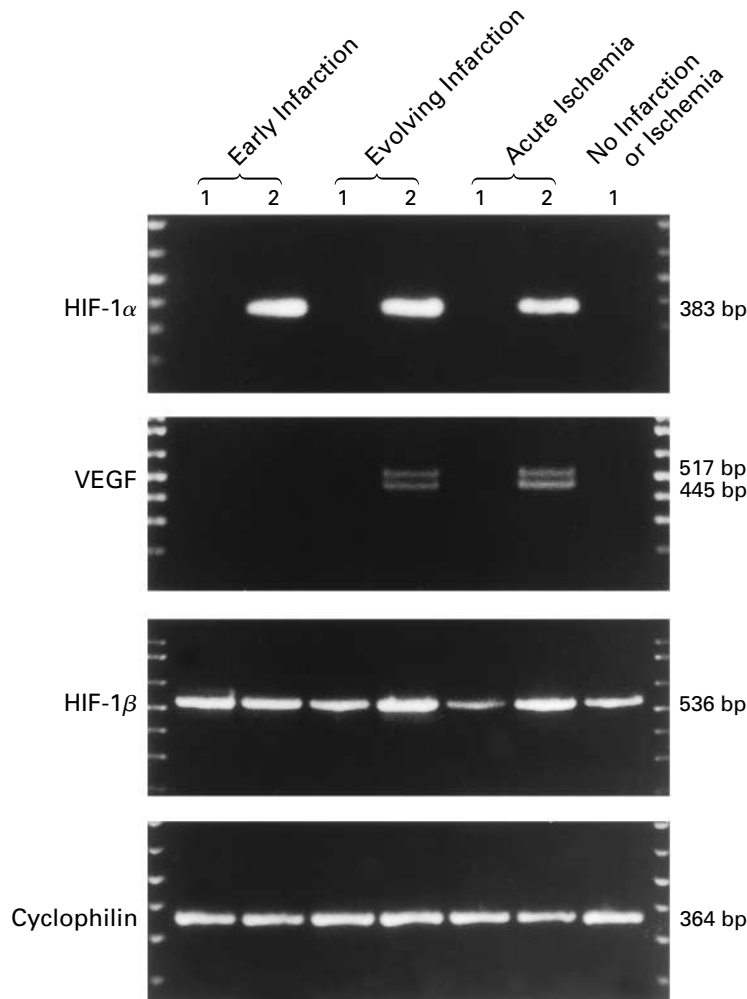


Figure 2. Results of Analysis of Ventricular-Biopsy Specimens by the Polymerase Chain Reaction. In specimens in the early-infarction group, the onset of infarction was less than 24 hours before surgery; in those in the evolving-infarction group, the onset of infarction was 24 to 120 hours before surgery; and in those in the ischemia group, the onset of ischemia was less than 48 hours before surgery. In each pair, 1 denotes the specimens taken from an area of normal ventricular tissue, and 2 the specimens taken from an area of ischemic or infarcted ventricular tissue. The lengths of the transcripts detected are shown on the right.

protein in these specimens was found only in the cytoplasm of endothelial cells lining the small vessels and was not present in cardiomyocytes (Fig. 3). VEGF protein was not detected in specimens with early infarction but was detected in specimens with evolving infarction or specimens with ischemia, in which it was confined to the myocardial vasculature. We did not detect HIF-1 α protein or VEGF protein by Western blot analysis of the peripheral blood of any of the patients (data not shown), suggesting that these proteins and their effects are confined to the heart.

DISCUSSION

To survive periods of stress and ischemia, the human heart has developed mechanisms to adapt to

changes in its environment. One of these mechanisms is the ability to promote growth of new blood vessels into ischemic areas, thus limiting regions of impairment and ultimately preserving myocardial function.²⁶ The decrease in the partial pressure of cellular oxygen induced by ischemia is a potent stimulator of neovascularization in several organ systems. Semenza has shown in both in vitro and in vivo models of ischemia that one of the first genes up-regulated by hypoxia is the gene encoding HIF-1.⁷ HIF-1 protein is composed of two distinct peptides. Expression of the gene for HIF-1 α is exquisitely sensitive to the onset of cellular hypoxic conditions, making it one of the earliest effectors of the response to ischemia.²⁷ HIF-1 β , the other component of the HIF-1 protein, is a

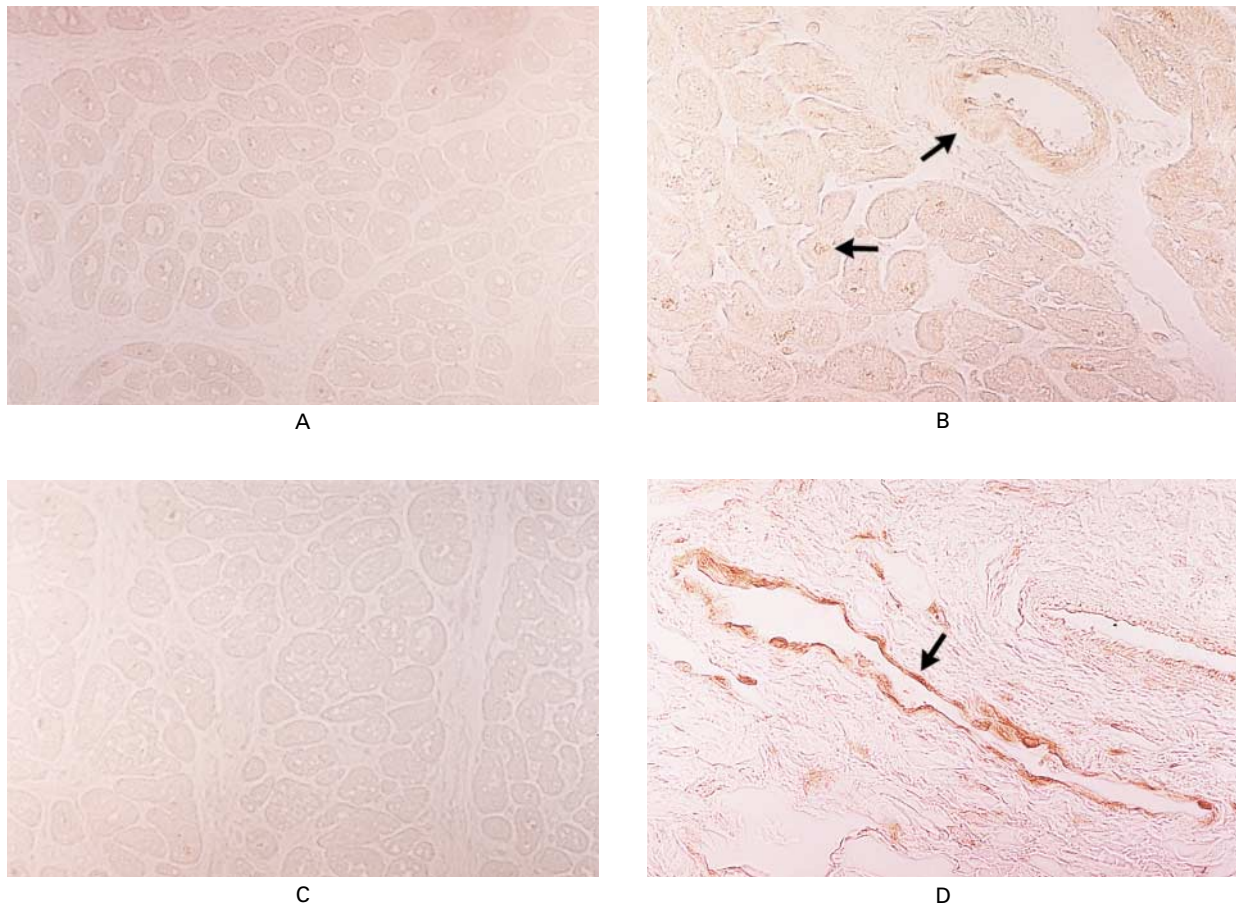


Figure 3. Localization of HIF-1 α and VEGF Proteins in Ventricular-Biopsy Specimens (Immunohistochemical Staining, $\times 400$).

Immunohistochemical analysis of ischemic or infarcted ventricular-biopsy specimens was performed on permanent sections without antibody to HIF-1 α (Panel A), with antibody to HIF-1 α (Panel B), without antibody to VEGF (Panel C), and with antibody to VEGF (Panel D). The results show localization of HIF-1 α in the nuclei of cardiomyocytes and endothelial cells in the section analyzed with antibody to HIF-1 α (Panel B, arrows) and localization of VEGF in the cytoplasm of endothelial cells in the section analyzed with anti-VEGF antibody (Panel D, arrow).

high-affinity protein that binds to HIF-1 α in the cytosol and transports HIF-1 α into the nucleus, where HIF-1 α may exert its *trans*-acting effect.²⁸ Expression of HIF-1 β is constitutive, not sensitive to hypoxia, in several types of tissue culture and in solid organs.²⁹

After it is activated by a low partial pressure of cellular oxygen, HIF-1 binds to a specific hypoxia-responsive element in the regulatory regions of several hypoxia-sensitive genes, leading to their transcriptional activation. We hypothesized that one of the most crucial actions of HIF-1 is to regulate the gene encoding the angiogenesis factor VEGF and thus ultimately to trigger the cascade of angiogenesis.

The goal of this study was to examine specimens of human heart tissue affected by various degrees of ischemic insult and to correlate the physiologic and pathological state of the heart with the temporal and spatial expression of HIF-1 and VEGF. In our patients,

we detected increased steady-state levels of HIF-1 α mRNA during the early period (the first 24 hours) after acute myocardial infarction or during acute myocardial ischemia. This accumulation of mRNA was limited to the region of affected myocardium. No HIF-1 α transcripts were detectable by PCR analysis in specimens of nonischemic or noninfarcted tissue. These results suggest that HIF-1 α is an early molecular marker of myocardial ischemia or infarction. The production of this protein and its effects appear to be limited to the heart, since it was not detected in the peripheral blood of our patients.

Immunoreactivity to HIF-1 α was detected in both myocardial and endothelial cells in all specimens of human heart affected by ischemia or infarction. Since the half-life of HIF-1 α protein has been estimated to be on the order of minutes,³⁰ we surmise that HIF transcription or stabilization of HIF mRNA contin-

ues throughout early ischemia or infarction to generate protein at levels that are detectable by antibody staining.

Two important limitations of this study should be recognized. First, by using the PCR to detect steady-state levels of HIF-1 α and VEGF mRNA, we did not measure the amount of transcript present in each tissue specimen. Rather, we determined whether mRNA was present or absent at the defined sensitivity of the assay (1 or more mRNA molecules per 1000 cells).³¹ Our study did not distinguish whether the spatial and temporal accumulation of HIF-1 α and VEGF mRNA in the heart reflected enhanced transcription or enhanced stabilization of mRNA. Evidence from cultured cell lines^{32,33} and animal models³⁴ suggests that both mechanisms may be important in the regulation of hypoxia-sensitive genes. Second, since our study examined specimens from human subjects, it was necessarily limited in scope and time course. Despite our inability to perform serial biopsies in individual patients, we found clear evidence that HIF-1 α expression is confined to the region of acute hypoxia in the heart; that it is initiated within hours of the onset of myocardial ischemia or infarction, or even earlier; and that detectable levels of HIF-1 α mRNA are transient. Our results suggest that HIF-1 induced by ischemia may be a signal mechanism for controlling the early-to-intermediate expression of genes that initiate angiogenesis during myocardial hypoxia.

VEGF has an important role in stimulating the growth of new capillaries in several organ systems and thus is a good candidate for the role of stimulating neovascularization to limit damage from infarction in the heart. Although the mechanism of enhanced VEGF expression remains to be determined, it is worth noting that the gene for VEGF has an HIF-1 regulatory consensus sequence (a hypoxia-responsive element) in its promoter region.³⁵ These observations, together with the previous finding that HIF-1 is responsible for the increase in VEGF in cultured hypoxic myocytes,³⁶ suggest that the increase in myocardial HIF-1 protein that we detected in ischemic and infarcted tissue is necessary, at least in part, for the enhanced expression of myocardial VEGF in states of ischemia.

We found in specimens of human heart tissue that steady-state levels of VEGF mRNA were present in the initial periods of ischemia (<48 hours after onset) and in the intermediate periods of infarction (24 to 120 hours after onset). Expression of VEGF persisted for a longer time after the onset of myocardial ischemia or infarction than did HIF-1 α expression. This suggests that the response of HIF-1 α to ischemia occurs early and is transient, whereas the VEGF response is of longer duration and is probably necessary for preservation of the myocardium and limitation of hypoxic cellular destruction. VEGF protein in the myocardium was found only in the endothelium that

lined medium and small arterioles and capillaries, in contrast to HIF-1 protein, which was expressed in both vascular endothelial cells and myocardial cells. This observation suggests that the angiogenic effects of HIF-1 and VEGF are limited to regions of terminal small vessels in the myocardium. The importance of the difference between the types of cells that express HIF-1 α (endothelial and myocardial cells) and those that express VEGF (endothelial cells) remains to be determined. It is possible that in myocardial cells HIF-1 α controls hypoxia-responsive genes other than the gene encoding VEGF.

In conclusion, we defined at a molecular level the sequential expression of HIF-1 α and VEGF in the human heart during ischemia. The genes encoding these two proteins are molecular temporal and spatial markers of ischemic myocardium. The presence of HIF-1 α mRNA and subsequently the presence of VEGF mRNA in the heart tissue of patients with infarction provide compelling new evidence that HIF-1 α contributes to limitation of infarct size by promoting angiogenesis and vascular remodeling and that it does so by increasing steady-state levels of VEGF mRNA. The expression of HIF-1 α by both myocardial cells and endothelial cells in the hypoxic heart raises the possibility that HIF-1 α has a broad role in myocardial disease associated with ischemia and infarction. Although elucidation of the pathophysiologic importance of HIF-1 α in these conditions awaits the availability of specific HIF-1 antagonists, the present study provides new information about variations in local synthesis and distribution of HIF-1 and VEGF in human heart disease. Further elucidation of the effects of these proteins may reveal clues for approaches to limiting infarct size and the sequelae of hypoxic damage to the myocardium.

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REFERENCES

1. Ladoux A, Frelin C. Hypoxia is a strong inducer of vascular endothelial growth factor mRNA expression in the heart. *Biochem Biophys Res Commun* 1993;195:1005-10.
2. Hashimoto E, Ogita T, Nakaoka T, Matsuoka R, Takao A, Kira Y. Rapid induction of vascular endothelial growth factor expression by transient ischemia in rat heart. *Am J Physiol* 1994;267:H1948-H1954.
3. Firth JD, Ebert BL, Pugh CW, Ratcliffe PJ. Oxygen-related control elements in the phosphoglycerate kinase 1 and lactate dehydrogenase A genes: similarities with the erythropoietin 3' enhancer. *Proc Natl Acad Sci U S A* 1994;91:6496-500.
4. Melillo G, Musso T, Sica A, Taylor LS, Cox GW, Varesio L. A hypoxia-responsive element mediates a novel pathway of activation of the inducible nitric oxide synthase promoter. *J Exp Med* 1995;182:1683-93.
5. Heusch G, Schulz R. Features of short-term myocardial hibernation. *Mol Cell Biochem* 1998;186:185-93.
6. Hearse DJ. Myocardial protection during ischemia and reperfusion. *Mol Cell Biochem* 1998;186:177-84.

7. Semenza GL. Hypoxia-inducible factor 1: master regulator of O₂ homeostasis. *Curr Opin Genet Dev* 1998;8:588-94.
8. Palmer LA, Semenza GL, Stoler MH, Johns RA. Hypoxia induces type II iNOS gene expression in pulmonary artery endothelial cells via HIF-1. *Am J Physiol* 1998;274:L212-L219.
9. Forsythe JA, Jiang BH, Iyer NV, et al. Activation of vascular endothelial growth factor gene transcription by hypoxia-inducible factor 1. *Mol Cell Biol* 1996;16:4604-13.
10. Semenza GL, Roth PH, Fang HM, Wang GL. Transcriptional regulation of genes encoding glycolytic enzymes by hypoxia-inducible factor 1. *J Biol Chem* 1994;269:23757-63.
11. Wang GL, Semenza GL. Desferrioxamine induces erythropoietin gene expression and hypoxia-inducible factor 1 DNA-binding activity: implications for models of hypoxia signal transduction. *Blood* 1993;82:3610-5.
12. Jiang BH, Rue E, Wang GL, Roe R, Semenza GL. Dimerization, DNA binding, and transactivation properties of hypoxia-inducible factor 1. *J Biol Chem* 1996;271:17771-8.
13. Iyer NV, Kotch LE, Agani F, et al. Cellular and developmental control of O₂ homeostasis by hypoxia-inducible factor 1 α . *Genes Dev* 1998;12:149-62.
14. Martin C, Yu AY, Jiang BH, et al. Cardiac hypertrophy in chronically anemic fetal sheep: increased vascularization is associated with increased myocardial expression of vascular endothelial growth factor and hypoxia-inducible factor 1. *Am J Obstet Gynecol* 1998;178:527-34.
15. Semenza GL, Wang GL. A nuclear factor induced by hypoxia via de novo protein synthesis binds to the human erythropoietin gene enhancer at a site required for transcriptional activation. *Mol Cell Biol* 1992;12:5447-54.
16. Semenza GL, Jiang BH, Leung SW, et al. Hypoxia response elements in the aldolase A, enolase 1, and lactate dehydrogenase A gene promoters contain essential binding sites for hypoxia-inducible factor 1. *J Biol Chem* 1996;271:32529-37.
17. Salceda S, Beck I, Caro J. Absolute requirement of aryl hydrocarbon receptor nuclear translocator protein for gene activation by hypoxia. *Arch Biochem Biophys* 1996;334:389-94.
18. Yu AY, Frid MG, Shimoda LA, Wiener CM, Stenmark K, Semenza GL. Temporal, spatial, and oxygen-regulated expression of hypoxia-inducible factor-1 in the lung. *Am J Physiol* 1998;275:L818-L826.
19. Ozaki H, Yu AY, Della N, et al. Hypoxia inducible factor-1 α is increased in ischemic retina: temporal and spatial correlation with VEGF expression. *Invest Ophthalmol Vis Sci* 1999;40:182-9.
20. Wang GL, Jiang BH, Rue EA, Semenza GL. Hypoxia-inducible factor 1 is a basic-helix-loop-helix-PAS heterodimer regulated by cellular O₂ tension. *Proc Natl Acad Sci U S A* 1995;92:5510-4.
21. Ferrara N, Davis-Smyth T. The biology of vascular endothelial growth factor. *Endocr Rev* 1997;18:4-25.
22. Antman EM, Tanasijevic MJ, Thompson B, et al. Cardiac-specific troponin I levels to predict the risk of mortality in patients with acute coronary syndromes. *N Engl J Med* 1996;335:1342-9.
23. Cotran RS, Kumar V, Collins T, eds. *Robbins pathologic basis of disease*. 6th ed. Philadelphia: W.B. Saunders, 1999:554-64.
24. Chomczynski P, Sacchi N. Single-step method of RNA isolation by acid guanidinium thiocyanate-phenol-chloroform extraction. *Anal Biochem* 1987;162:156-9.
25. Puissant C, Houdebine LM. An improvement of the single-step method of RNA isolation by acid guanidinium thiocyanate-phenol-chloroform extraction. *Biotechniques* 1990;8:148-9.
26. Sabia PJ, Powers ER, Ragosta M, Sarembock IJ, Burwell LR, Kaul S. An association between collateral blood flow and myocardial viability in patients with recent myocardial infarction. *N Engl J Med* 1992;327:1825-31.
27. Jiang BH, Zheng JZ, Leung SW, Roe R, Semenza GL. Transactivation and inhibitory domains of hypoxia-inducible factor 1 α : modulation of transcriptional activity by oxygen tension. *J Biol Chem* 1997;272:19253-60.
28. Wood SM, Gleadle JM, Pugh CW, Hankinson O, Ratcliffe PJ. The role of the aryl hydrocarbon receptor nuclear translocator (ARNT) in hypoxic induction of gene expression: studies in ARNT-deficient cells. *J Biol Chem* 1996;271:15117-23.
29. Rowlands JC, Gustafsson JA. Aryl hydrocarbon receptor-mediated signal transduction. *Crit Rev Toxicol* 1997;27:109-34.
30. Wenger RH, Gassmann M. Oxygen(es) and the hypoxia-inducible factor-1. *Biol Chem* 1997;378:609-16.
31. Kawasaki ES. Amplification of RNA. In: Innis MA, Gelfand DH, Sninsky JJ, White TJ, eds. *PCR protocols: a guide to methods and applications*. San Diego, Calif: Academic Press, 1990:21-7.
32. Levy AP, Levy NS, Goldberg MA. Hypoxia-inducible protein binding to vascular endothelial growth factor mRNA and its modulation by the von Hippel-Lindau protein. *J Biol Chem* 1996;271:25492-7.
33. Wenger RH, Kvietikova I, Rolfs A, Gassmann M, Marti HH. Hypoxia-inducible factor-1 α is regulated at the post-mRNA level. *Kidney Int* 1997;51:560-3.
34. Deindl E, Schaper W. Gene expression after short periods of coronary occlusion. *Mol Cell Biochem* 1998;186:43-51.
35. Shima DT, Kuroki M, Deutsch U, Ng YS, Adamis AP, D'Amore PA. The mouse gene for vascular endothelial growth factor: genomic structure, definition of the transcriptional unit, and characterization of transcriptional and post-transcriptional regulatory sequences. *J Biol Chem* 1996;271:3877-83.
36. Levy AP, Levy NS, Loscalzo J, et al. Regulation of vascular endothelial growth factor in cardiac myocytes. *Circ Res* 1995;76:758-66.