Nitric oxide (NO) is produced from the guanidino group of L-arginine in an NADPH-dependent reaction catalyzed by a family of NO synthase (NOS) enzymes. There are at least 3 distinct isoforms of NOS: neural NOS (nNOS), inducible NOS (iNOS), and endothelial NOS (eNOS). The neuronal isoform is highly expressed in neuronal cells and skeletal muscle, whereas the inducible isoform is expressed in many cell types primarily in response to inflammatory cytokines. The endothelial isoform originally was identified in endothelial cells. NO produced by eNOS plays an important role in the regulation of cell growth, apoptosis, and tissue perfusion. Recent studies showed that mice deficient in eNOS developed abnormal aortic bicuspid valves. The aim of the present study was to additionally investigate the role of eNOS in heart development.

**Methods and Results**—We examined postnatal mortality, cardiac function, and septum defects in eNOS−/−, eNOS+/+, and wild-type mice. Postnatal mortality was significantly increased in eNOS−/− (85.1%) and eNOS+/− (38.3%) compared with wild-type mice (13.3%, P<0.001). Postmortem examination found severe pulmonary congestion with focal alveolar edema in mice deficient in eNOS. Heart shortening determined by ultrasound crystals was significantly decreased in eNOS−/− compared with wild-type mice (P<0.05). Congenital atrial and ventricular septal defects were found in neonatal hearts. The incidence of atrial or ventricular septal defects was significantly increased in eNOS−/− (75%) and eNOS+/− (32.4%) neonates compared with those of the wild-type mice (4.9%). At embryonic days 12.5 and 15.5, cardiomyocyte apoptosis and myocardial caspase-3 activity were increased in the myocardium of eNOS−/− compared with wild-type embryos (P<0.01), and increases in apoptosis persisted to neonatal stage in eNOS−/− mice.

**Conclusions**—Deficiency in eNOS results in heart failure and congenital septal defects during cardiac development, which is associated with increases in cardiomyocyte apoptosis. Our data demonstrate that eNOS plays an important role in normal heart development. *(Circulation. 2002;106:873-879.)*

**Key Words:** nitric oxide ■ heart failure ■ heart defects, congenital ■ heart septal defects ■ apoptosis
that mice deficient in eNOS developed aortic bicuspid valves.\textsuperscript{17} In the present study, we additionally demonstrated that deficiency in NO results in congenital atrial and ventricular septal defects in mice. Our results suggest that NO plays an important role during cardiac development.

**Methods**

**Animals**

Breeding pairs of eNOS\textsuperscript{−/−} (stock No. 002684) and wild-type C57BL/6 (eNOS\textsuperscript{+/+}) mice were purchased from Jackson Laboratory (Bar Harbor, Maine). A breeding program was carried out to produce neonates. To generate eNOS\textsuperscript{−/−} mice, eNOS\textsuperscript{−/+} animals were bred with eNOS\textsuperscript{−/+} mice. Genotyping of eNOS\textsuperscript{−/−} and eNOS\textsuperscript{−/+} mice was performed by a polymerase chain reaction (PCR) method using genomic DNA prepared from tail biopsies. All procedures involving mouse husbandry and manipulation were in accordance with the guidelines of the Canadian Council of Animal Care and approved by the Animal Use Subcommittee at the University of Western Ontario, Canada.

**Histology, Microdissections, and Scanning Electron Microscopy**

Neonatal eNOS\textsuperscript{−/−}, eNOS\textsuperscript{−/+}, and eNOS\textsuperscript{+/+} mice were used for analysis. Neonatal hearts and lungs were isolated and fixed in 10% buffered formalin, dehydrated, and embedded in paraffin. Serial heart sections were made, stained with hematoxylin and eosin, and examined by light microscopy. To quantify the incidence of septal defects, neonatal hearts (36 eNOS\textsuperscript{−/−}, 34 eNOS\textsuperscript{−/+}, and 41 eNOS\textsuperscript{+/+}) were fixed in 10% buffered formalin, and a standard procedure for microdissection of the heart was applied according to methods described previously.\textsuperscript{18,19} Briefly, the heart was exposed and examined under an operating microscope. The right ventricle was dissected with crafted microscissors proceeding from the apex to the pulmonary artery trunk. Similarly, the left ventricle was opened from the apex toward the base of heart and its internal relief examined. Subsequently, the parietal segments of ventricles and atria were isolated by extending the previously mentioned cuts of the right and left ventricles beyond the base of the heart. The ventricular cavity and the septum were scrutinized for anomalies. Hearts were dehydrated by graded methanol solutions, dried by a critical point dryer (Polaron E3000, Watford Hertfordshire), sputtered with gold coating, and examined by a field emission scanning electron microscope (S-4500, Hitachi).

**Measurement of Neonatal Cardiac Shortening In Vivo**

Postnatal day 1 (P1) mice were anesthetized with sodium pentobarbital (75 mg/kg, IP). After tracheotomy, the trachea was cannulated with a PE10 catheter, which was connected to a ventilator (SAR-830, CWE Inc). Mice were artificially ventilated with room air. Tidal volume was set at 25 \( \mu \)L with 90 breaths/min and 40/60 inspiration/expiration ratio. Body temperature was maintained at 37°C. The heart was exposed through a midline sternotomy. The crystals (0.7 mm) were fixed on the heart surface to allow short-axis examination. The crystals were connected to a ventilator (SAR-830, CWE Inc). Mice were artificially ventilated with room air. Tidal volume was set at 25 \( \mu \)L with 90 breaths/min and 40/60 inspiration/expiration ratio. Body temperature was maintained at 37°C. The heart was exposed through a midline sternotomy. The crystals were fixed on the heart surface to allow short-axis measurement similarly, as we previously described in adult mice.\textsuperscript{20} The ultrasound signals were measured by a Digital Sonomicrometer (Sonometrics). Maximum and minimum distances as well as percent shortening were calculated.

**Enzyme Immunoassay for Cytoplasmic Histone-Associated DNA Fragments**

For quantitative determination of apoptosis, we measured cytoplasmic histone-associated DNA fragments (mononucleotides and oligonucleotides) in E12.5, E15.5, and P1 mouse hearts using a photometric enzyme immunoassay (Cell Death Detection ELISA, Roche Molecular Biochemicals), as we described previously.\textsuperscript{21}

**Caspase-3 Activity**

Fetal myocardial caspase-3 activity was measured using a caspase-3 fluorescent assay kit according to manufacturer’s protocol (BIOMOL Research Laboratories). Briefly, 5 to 7 hearts isolated from E12.5 or E15.5 mice were pooled together and homogenized, and protein concentration was determined by Bradford method.\textsuperscript{22} Samples (50 \( \mu \)g protein) in duplicates were incubated with caspase-3 substrate Ac-DEVD-AMC or Ac-DEVD-AMC plus inhibitor AC-DEVD-CHO at 37°C for 2 hours before measurements were made by a fluorescent spectrophotometer (excitation at 380 nm, emission at 405 nm). Signals from inhibitor-treated samples served as background.

**Statistical Analysis**

Data are presented as mean±SEM. Student’s \textit{t} test, \( \chi^2 \) analysis, and ANOVA followed by Student-Newman-Keuls test were performed. Survival curves were created by the method of Kaplan and Meier and compared by log-rank test. \( P<0.05 \) was considered statistically significant.

**Results**

**Postnatal Survival and Cardiac Function**

Postnatal survival was followed for 21 days in eNOS\textsuperscript{−/−}, eNOS\textsuperscript{−/+}, and eNOS\textsuperscript{+/+} mice (n=74, 81, and 60, respectively). Survival was significantly decreased in eNOS\textsuperscript{−/−} and eNOS\textsuperscript{−/+} compared with eNOS\textsuperscript{+/+} mice with the same genetic background (\( P<0.001 \)). Within 10 days after birth, 85.1% (63 of 74) of eNOS\textsuperscript{−/−} and 38.3% (31 of 81) of eNOS\textsuperscript{−/+} mice died, whereas only 13.3% (8 of 60) of eNOS\textsuperscript{−/+} mice died during the same period (\( P<0.001 \), Figure 1A). These results demonstrated a dose-dependent effect between eNOS gene deficiency and postnatal mortality.

To determine if higher mortality observed in eNOS\textsuperscript{−/−} was attributable to cardiac dysfunction, in vivo heart shortening was measured using the ultrasound crystals in eNOS\textsuperscript{−/−}, eNOS\textsuperscript{−/+}, and eNOS\textsuperscript{+/+} mice at P1 (n=5 per group). Basal heart rate was similar among 3 groups (257±10, 284±18, and 252±15 beats/min, \( P=NS \)). Percent shortening of the heart was significantly decreased, whereas heart to chest ratio was increased in eNOS\textsuperscript{−/−} compared with eNOS\textsuperscript{−/+} mice (Figures 1B and 1C, \( P<0.05 \)). Diastolic dimensions of the heart were significantly increased in eNOS\textsuperscript{−/+} compared with eNOS\textsuperscript{−/−} and eNOS\textsuperscript{−/+} mice (3.37±0.04 versus 3.04±0.10 and 2.69±0.22 mm, respectively, \( P<0.05 \)). Furthermore, LV and RV chamber size measured from serial sections of paraffin-embedded hearts at P1 was significantly increased in eNOS\textsuperscript{−/+} compared with eNOS\textsuperscript{−/−} mice (Figures 1D and 1E, \( n=5 \) per group, \( P<0.05 \)). Dose-dependent relationship was evident between eNOS gene deficiency, heart shortening, and heart chamber size (Figures 1B through 1E). Postmortem examination showed that whereas lungs of eNOS\textsuperscript{−/+} mice had normal and clear alveoli (Figure 1F), eNOS\textsuperscript{−/−} mice had severe pulmonary congestion with focal alveolar edema (Figure 1G).
Congenital Septal Defects
Hearts were enlarged in eNOS−/− compared with eNOS+/− and eNOS+/+ mice (Figure 2A). Serial heart sections were made in eNOS−/− and eNOS+/− mice at P2 (n=10 per group). A normal structure of the heart from an eNOS+/+ mouse is shown in Figure 2B. Atrial or ventricular septal defects were found in 6 of 10 eNOS−/− mice, and only 1 of 10 eNOS+/− mice showed an atrial septal defect. Atrial septal defects were typical of ostium secundum defects (Figure 2C), ventricular septal defects were membranous and muscular defects in eNOS−/− mice (Figures 2D and 2E). Ventricular hypertrophy and enlargement of atria were obvious in eNOS−/− compared with eNOS+/+ mice with congenital septal defects (Figures 2C through 2E).

Microdissections were performed in all mice at P1. In mice with atrial or ventricular septal defects, clear openings were observed in the atrial or ventricular septum that were not covered by any tissues. Congenital septal defects were additionally confirmed by scanning electron microscopy (Figure 3). The incidence of atrial or ventricular septal defects was significantly increased in eNOS−/− (75%) and eNOS+/− (32.4%) neonates compared with those of the eNOS+/+ (4.9%, P<0.001). Whereas 11.2% of eNOS−/− neonates had ventricular septal defects, none were observed in the eNOS+/− and eNOS+/+ mice (Table). These data demonstrated a dose-dependent relationship between eNOS gene deficiency and septal defects. No obvious defects were observed in tricuspid and mitral valves in eNOS−/− mice.

Caspase Activity and Apoptosis in the Developing Heart
To investigate possible mechanisms responsible for development of heart failure and congenital septal defects in eNOS−/− mice, we studied caspase-3 activity and myocardial apoptosis during embryonic development. To measure myocardial caspase-3 activity, embryonic hearts were collected from 4 pregnant eNOS−/− (22 hearts) and 3 pregnant eNOS+/− mice (21 hearts) at E12.5. Fetal hearts were also collected from 3 pregnant eNOS−/− (18 hearts) and 3 pregnant eNOS+/− mice (21 hearts) at E15.5. Caspase-3 activity was significantly higher in E12.5 and E15.5 myocardium from eNOS−/− compared with eNOS+/+ mice (Figure 4, P<0.05). To determine apoptosis in the embryonic heart, TUNEL staining was performed in E12.5 hearts isolated from eNOS−/−, eNOS+/−, and eNOS+/+ mice (n=5 to 7 per group). Representative TUNEL staining of fetal hearts from 3 groups is shown in Figure 5. Apoptosis was detected in the heart, including atrioventricular endothelial cushions, septum primum, and right and left ventricular myocardium in all 3 groups (Figure 5). However, apoptosis in these regions was significantly
increased in eNOS−/− compared with eNOS+/+ fetal hearts (Figure 6A, P<0.01). To additionally quantify the level of apoptosis during heart development, cell death detection ELISA assay was used. At E12.5, E15.5, and P1, apoptosis was significantly increased in the myocardium of eNOS−/− compared with eNOS+/+ mice (Figure 6B, P<0.05).

**Discussion**

Ventricular and atrial septal defects are the most common forms of congenital heart disease (30% to 40%), affecting 1 to 2 in 200 live births in the United States.23,24 Although the embryology of heart development has been described in some detail, the molecular mechanisms governing cardiac growth and morphogenesis remain largely unknown. The present study demonstrated for the first time that deficiency of eNOS led to significant increases in cardiomyocyte apoptosis and cardiac dysfunction. Furthermore, deficiency of eNOS gene increased congenital septal defects and postnatal mortality in a gene dosage–dependent manner. These results suggest that NO production from eNOS plays an important role in normal heart development.
Congenital Septal Defects in eNOS+/+, eNOS+/−, and eNOS−/−
Neonatal Mice at P1

<table>
<thead>
<tr>
<th>Genotype</th>
<th>eNOS+/+</th>
<th>eNOS+/−</th>
<th>eNOS−/−</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>38 (95.1)</td>
<td>23 (67.6)</td>
<td>9 (25.0)</td>
</tr>
<tr>
<td>ASD</td>
<td>2 (4.9)</td>
<td>11 (32.4)</td>
<td>23 (63.8)</td>
</tr>
<tr>
<td>VSD</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>2 (5.6)</td>
</tr>
<tr>
<td>ASD and VSD</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>2 (5.6)</td>
</tr>
<tr>
<td>Total</td>
<td>41 (100)</td>
<td>34 (100)</td>
<td>36 (100)</td>
</tr>
</tbody>
</table>

Values are n (%). ASD indicates atrial septal defects; VSD, ventricular septal defects. *P<0.001 vs eNOS+/+ by χ² analysis.

We started the present study by breeding the eNOS−/− and corresponding eNOS+/+ controls, and we consistently obtained fewer eNOS−/− mice compared with eNOS+/+ animals that survived to adulthood. Therefore, we began to monitor their breeding closely. To our surprise, most of the eNOS−/− newborns died within 6 days after birth. Mortality was markedly increased in eNOS−/− compared with the eNOS+/+ neonates (85.5% versus 13.3%). To investigate if there is a dose-dependent effect between eNOS gene deficiency and cardiac dysfunction, as measured by in vivo heart shortening. There was also a dose-dependent effect between eNOS deficiency and cardiac dilatation. Postmortem examination in mice that died after birth showed severe pulmonary congestion and edema in eNOS−/− mice. Our data indicate that death of eNOS−/− mice is most likely attributable to heart failure.

Congenital septal defects were observed in mice deficient in the eNOS gene. The septal defects include ostium secundum defects, ventricular septal defects (membranous and muscular type), and atrioventricular septal defects. Quantitative analysis demonstrated that congenital septal defects were found in 75% of eNOS+/+, 32.4% of eNOS+/−, and 4.9% of eNOS−/− mice. Our data showed a clear dose-dependent effect between eNOS gene deficiency and congenital septal defects, demonstrating an important role of eNOS in heart development. Although most eNOS−/− mice had atrial septal defects, it is unlikely that atrial septal defects alone resulted in cardiac dysfunction and high mortality in these animals. The lack of a complete penetrance also suggested that, in addition to eNOS, other modifier genes are involved in heart failure and congenital septal defects during development.

Mechanisms by which heart failure and congenital septal defects develop in eNOS−/− mice are not known. Apoptosis is an important physiological process in organ development. During early embryonic and postnatal heart development, apoptosis is demonstrated in several areas, including atrioventricular endothelial cushions, the outflow tract, septum, and trabeculae, as well as papillary muscles of ventricles. It is a highly regulated process, because increased apoptosis may result in congenital heart defects. Studies demonstrated that intra-amniotic treatment of cyclophosphamide increased apoptosis in atrioventricular endothel-
Atrial and ventricular myocardium in including atrioventricular endothelial cushions, septum pri-
vating heart development. Apoptosis was significantly in-
creased at all time points in eNOS−/− mice. A, Apoptosis determined by TUNEL staining at
E12.5. Apoptosis was significantly increased in atrioventricular
endothelial cushion and septum primum (septum) and right and
left ventricular myocardium (RV and LV) in eNOS−/− compared
with eNOS+/+ and eNOS+/− mice (n = 5 to 7, *P < 0.01). B, Quan-
titative analysis of apoptosis by cell death detection ELISA in
the heart at E12.5, E15.5, and P1 (neonate). Apoptosis was sig-
nificantly increased at all time points in eNOS−/− compared
with eNOS+/− mice (n = 6 to 9 per group, *P < 0.05).

In the present study, we demonstrated that caspase-3 activity
increased apoptosis during embryonic development represents
one of the mechanisms that leads to heart failure and
congenital septal defects in eNOS−/− mice.

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References
1. Feng Q, Hedner T. Endothelium-derived relaxing factor (EDRF) and
nitric oxide (NO), I: physiology, pharmacology and pathophysiological
isozymes: characterization, purification, molecular cloning, and
expression and role during cardiacangiogenesis. Cardiovasc Res.
4. Balligand JL, Kelly RA, Marsden PA, et al. Control of cardiac muscle cell
function by an endogenous nitric oxide signaling system. Proc Natl Acad
5. Kanai AJ, Mesaros S, Finkel MS, et al. β-adrenergic regulation of
1997;273:C1371–C1377.
angiogenesis in response to tissue ischemia. J Clin Invest. 1998;101:
2567–2578.
nitric oxide via inhibition of interleukin-1β-converting enzyme (ICE)-like
185:661–667.
10. Kim Y-M, Talanian RV, Billiar TR. Nitric oxide inhibits apoptosis by
preventing increases in caspase-3-like activity via two distinct mech-
11. Pexieder T. Cell death in the morphogenesis and teratogenesis of the
and shortening of the cardiac outflow tract involves myocyte programmed
formation of the ventricular wall during mouse heart organogenesis. Anat
14. Zhao Z, Rivkees SA. Programmed cell death in the developing heart:
expression of the protooncogene bcl-2 in myocytes during postnatal
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