Achievements in Congenital Heart Defect Surgery:
A Prospective, 40 Year Study of 7038 Patients

Running title: Erikssen et al.; Postoperative mortality and reoperations

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Abstract

Background—To update results achieved by modern surgery in congenital heart defects (CHD) over the last 40 years regarding survival and need for reoperations, especially focusing on the results from the two last decades.

Methods and Results—From 1971 to 2011, all 7038 patients under age 16 years undergoing surgical treatment for CHD at Rikshospitalet (Oslo, Norway) were enrolled prospectively. CHD-diagnosis, date and type of all operations were recorded, as was all-cause mortality until December 31, 2012. CHDs were classified as “simple” (3751/7038 = 53.2%), “complex” (2918/7038 = 41.5%) or “miscellaneous” (369/7037 = 5.2%). Parallel to a marked, sequential increase in operations for complex defects, median age at first operation decreased from 1.6 years in 1971-1979 to 0.19 years in 2000-2011. In total, 1033 died prior to January 1, 2013. Cumulative survival until age 16 years in complex CHD operated in 1971-1989 vs. 1990-2011 was 62.4% vs. 86.9% (p< 0.0001). Comparing patients operated in 2000-04 vs. 2005-11, one year survival was 90.7% vs. 96.5% (p=0.003), and five year cumulative survival 88.8% vs. 95.0% (p=0.0003). In simple vs. complex defects, 434 (11.6%) vs. 985 (33.8%) needed at least one reoperation before age 16 years. In complex defects, five years cumulative freedom of reoperation among patients operated in 1990-1999 vs. 2000-2011 was 66% vs. 73% (p=0.0001).

Conclusions—Highly significant, sequential improvements in survival and reductions in reoperations after CHD surgery were seen. A future challenge is to find methods to reduce the need for reoperations and further reduce long term mortality.

Key words: congenital heart disease, surgery, survival, reoperations
Introduction

Following the surgical closures of patent ductus arteriosus (PDA) in 1938\(^1\) and atrial septal defect (ASD) in 1953,\(^2\) major treatment advances have made surgical palliation or correction\(^3\) of nearly all congenital heart defects (CHDs) possible. Still, 232,000 deaths globally were attributed to CHD in 2010,\(^4\) and most victims were young. Trends in the western countries indicate, however, that this number may be substantially reduced. Nieminen et al reported major improvements in survival of children in Finland undergoing CHD surgery up to 1989.\(^5\) Later, few population based studies have specifically targeted long-term survival after CHD surgery.\(^6,7\)

In Norway, CHD surgery was introduced at Oslo University Hospital, Rikshospitalet, and the number of patients operated for CHD increased rapidly during the early 1970-ies. Up until 2003, about 80\% of all Norwegian CHD surgery was carried out at this hospital, and after 2003 Rikshospitalet has been responsible for all operations. All CHD operations in patients aged < 16 years were registered prospectively from 1971, providing a basis for a population based study of the changes in survival after surgery, age at operation and reoperations. Based on the 7038 patients operated on from 1971 to 2011, and mortality data until Dec 31, 2012, we want to update these trends for different types of CHDs, especially focusing on the last two decades.

Methods

Data collection

The study was conducted at the Departments of Thoracic Surgery, Pediatric Cardiology, and Cardiology at Oslo University Hospital (OUS), Rikshospitalet. All operations from June 21, 1971, to December 31, 2011, were registered prospectively using a hand-written protocol from 1971 to 1989 (transferred to our electronic Datacor® database in 1990) and directly into
Datacor® thereafter. All-cause mortality until December 31, 2012, was obtained from our files and from the Norwegian population registry in Statistics Norway. The study was approved by the Data Protection Officer at OUS.

Data handling was facilitated by using each patient’s unique eleven digit social security number, which includes individual birth date. CHD diagnoses were based on ICD-9 until 1998, and ICD-10 thereafter. The date of the first operation, number of operations, and type(s) of surgical correction(s) were recorded. A maximum of three diagnoses were given, and each patient was classified by the most severe diagnosis according to a diagnosis hierarchy as applied previously.5

Data on the number of operations performed at other Norwegian hospitals from 1994 to 2003 were obtained from the Norwegian Cardiovascular Surgery Registry (operative from 1994) revealing that 80.1% of all CHD operations in Norway were performed at Rikshospitalet during this period. After 2003, all CHD operations have been performed at Rikshospitalet.

From 1987 through 1998, 51 patients with hypoplastic left heart syndrome (HLHS) had their Fontan circulation completed at a surgical centre in the United States (25 survivors).8 These operations have not been included in our database. Data on mortality in all congenital heart defects in Norway from 1971 to 2011 were obtained through open access to official Norwegian mortality statistics at Statistics Norway.

Rapid development occurred in the availability of diagnostic tools during the long study period. In the 1970-ies, primary pre-operative CHD diagnoses necessary for planning the operations were mainly based on clinical findings and invasive studies, but from the early 1980-ies diagnostics increasingly relied on echo-Doppler techniques and computer tomography, and from the late 1980-ies also on magnetic resonance imaging. Significant refinements in all these
techniques are still taking place. However, final diagnoses (i.e. applied in this paper) were ultimately obtained during surgery.

**Complex defects**

A CHD was defined as a defect in the structure of the heart and/or the great vessels that was present at birth. If more than one CHD was present, patients were classified by the most severe diagnosis according to a diagnosis hierarchy as applied previously. The following diagnostic criteria were used for “complex defects” (table 1):

1. Univentricular hearts (UVH) were characterized by the presence of one rudimentary and one dominant ventricle (left or right), regardless of whether it had a double-inlet left or right ventricle or a single atrioventricular inlet.
2. Truncus arteriosus communis (TAC) was diagnosed according to Van Praagh, including TAC associated with an interrupted aortic arch.
3. Cases with interrupted or hypoplastic aortic arch (I/HAA) with or without coarctation of the aorta (COA) were grouped together. Aortic arch hypoplasia was defined according to Moulaert et al.
4. Patients with simple or complex transposition of the great arteries (TGA) and biventricular anatomy were grouped together.
5. Atrioventricular septal defect (AVSD) included both the incomplete and complete forms.
6. Patients with totally anomalous pulmonary venous drainage (TAPVD) were assigned to this group if this was their dominant defect.
7. Cases with pulmonary atresia (PA), with or without coexisting ventricular septal defect (VSD), were assigned PA as their primary diagnosis if biventricular correction was performed.
8. Tetralogy of Fallot (TOF) was defined according to convention. Double outlet right
ventricle (DORV) included both simple and complex forms.\textsuperscript{11}

According to the diagnosis hierarchy in \textbf{table 1}, patients e.g. with both UVH and TAPVD were classified as UVH.

\textbf{Simple defects}

VSD and COA were defined conventionally. Valvular aortic stenosis was classified as AS, valvular pulmonary stenosis as PS, and stenosis or insufficiency of the mitral valve as MV. Cases with drainage to the right atrium from one or more – but not all – pulmonary veins, were classified as PAPVD. ASD included ASD secundum and superior and inferior sinus venosus defect, but not partial AVSD. PDA was diagnosed in the presence of an open ductus $> 2$ weeks after birth.

\textbf{Miscellaneous defects}

The MISC group ($n=369$) included DORV ($n=95$), subvalvular and supravalvular aortic stenosis ($n=65$ and 21, respectively), Ebstein’s anomaly ($n=11$), congenitally corrected TGA ($n=4$), coronary artery anomalies ($n=18$), cor triatriatum ($n=11$), and vascular rings ($n=48$). A total of 97 patients (26.4\% of all 369 patients in the MISC group and 1.4\% of all 7038 patients in the study) had defects lacking dominant features that justified classification into any of the previously mentioned categories.

Only patients who had their first operation before their 16\textsuperscript{th} birthday were included because this is the age threshold of the pediatric population in Norway. The term “early mortality” is used for all deaths that occurred $< 30$ days after the first operation, and “late mortality” denotes deaths occurring later.

\textbf{Reoperations}

Dates and descriptions of all operations were recorded prospectively. The first operation was
denoted the “index operation”. Operations both with and without cardiopulmonary bypass (CPB) were included, and operations were classified according to whether they could be considered as “corrections” or “palliations”. Palliative procedures mainly included shunt operations or banding of the pulmonary artery – either as destination therapy or as steps in staged procedures aimed at final correction. Accordingly, e.g. the Norwood I operation and Glenn operations were classified as a palliative procedures. E.g. Fontan operations, on the other hand, were classified as corrections. The few reoperations due to acute surgical complications have not been included.

**Statistical analysis**

We used Kaplan-Meier analyses to study survival after first operation (< 30 days and until age 16 years), and reoperation-free “survival”. In the latter case, patients who died without reoperation were censored at the time death. The log-rank test (Mantel-Cox) was used to test for differences in survival between eras.

Kaplan-Meier probabilities of 5 years reoperation-free survival were computed separately for all complex defects in patients who had their first operation in 1990-1999 vs. 2000-2011. Five years was chosen somewhat arbitrarily because patients operated in 1990-1999 had longer follow-up than patients operated in 2000-2011, and since the great majority of reoperations were performed during the first few years after the first operation in both eras (see Results).

The Mann-Whitney test was used when comparing variables not necessarily normally distributed. The binomial test was used when testing for differences in numbers of various types of operations in different eras.

Two-sided p-values <0.05 were considered significant. The statistical packages Statview® 5.0 and JMP® 10 were used for analyses.
Results

A total of 7038 CHD patients underwent 9380 operations during the data collection period. One hundred and eight patients (1.5%) had incomplete social security number and were lost to follow-up after discharge.

Index operations

Table 2 shows the numbers and proportions of patients who had their index operation during the four decades of 1971-1979, 1980-1989, 1990-1999, and 2000-2011. The number of patients operated for complex defects increased from 37 per year in 1971-1979 to 109 per year in 2000-2011. Surgery for simple defects only increased from 80 per year in 1971-1979 to 92 per year in 2000-2011.

Age at operation

The age at first operation decreased markedly. In complex defects, median age was 1.6 years in 1971-1979, 0.35 years in 1980-1989, 0.27 years in 1990-1999, and 0.19 years in 2000-2011 (p(1990-1999 vs. 2000-2011) = 0.0002). In 2000-2011, median age at first operation was less than 3 weeks in all complex defects excluding AVSD and TOF. No significant trends towards further reductions in age at first operation were seen after year 2000. Patients with simple defects were generally operated on at a higher age (median 5.7 years in 1971-1979 and 0.39 years in 2000-2011).

Long-term survival trends

Substantial, gradual improvements in survival were seen over the whole study period for all complex defects (figure 1 and table 3a). In general, most of the improvements occurred early after surgery, but also late mortality improved sequentially - particularly in UVH, TGA, and PA. Taking into account all complex defects, early survival was 79.7% in patients who underwent
surgery in 1971-1989 vs. 94.6% in 1990-2011 (p<0.0001), and cumulative survival to age 16 years was 62.4% vs. 86.9% (p<0.0001), respectively. Moreover, highly significant improvements were also found for simple defects like VSD and COA.

**Survival differences in patients operated in 1990-1999 and 2000-2011**

Table 3b focuses on survival among patients who underwent surgery during the last two decades. Improvements were found particularly for the most severe defects. Early survival in complex defects among patients operated in 1990-1999 vs. 2000-2011 was 90.7% vs. 97.2% (p<0.0001), and cumulative survival until age 16 years was 80.2% vs. 91.2% (p<0.0001).

Significant improvements also occurred in simple defects.

**Survival differences in patients operated in 2000-2004 and 2005-2011**

Survival in complex defects improved significantly even among patients operated after year 2000 (figure 2). Thus, early survival in patients operated in 2000-2004 vs. 2005-2011 was 93.6% vs. 99.1% (p<0.0001), one year survival 90.7% vs. 96.5% (p<0.0001), and five year cumulative postoperative survival 88.8% vs. 95.0% (p=0.0003). One year postoperative survival among patients operated in 2005-2009 vs. 2010-2011 was 95.3% vs. 99.6% (p=0.003).

Among patients with UVH operated in 2000-2004 (n=98) vs. 2005-2011 (n=155) one year postoperative survival was 82.5% vs. 94.0 (p=0.0002), and in patients with HLHS, one-year survival was 69.8% (n=53) vs. 93.3% (n=60) (p=0.0007).

**Reoperations**

The 2918 patients with complex defects had 4500 operations before the age of 16 years. At least one reoperation was performed in 985 (33.8%), at least two in 389 (13.3%), and at least three in 131 (4.5%). In those with simple defects, 434 (11.6%) patients underwent at least one reoperation.
Among patients with complex defects who had their index operation in 1990-1999 vs. 2000-2011 (767 vs. 1291 patients), 308 vs. 353 (40.2% vs. 27.3%) had at least one reoperation, 156 vs. 113 (20.3% vs. 8.8%) at least two, and 54 vs. 30 (7.0% vs. 2.3%) at least three. Furthermore, there were 15 vs. 29 catheter interventions (p=NS). The Kaplan-Meier plots in figure 3 show that the great majority of reoperations were performed within a few years after the index operation, and that significantly fewer patients needed reoperation in 2000-2011 than in 1990-1999 – even when catheter interventions are taken into account. The estimates in table 4 indicate trends towards increased reoperation-free survival for most complex defects, especially in patients with I/HAA and PA.

CPB was used in 72.5% of the index operations in patients with complex defects in 1990-1999, and in 86.9% in 2000-2011 (p<0.01). Corresponding percentages for (first) reoperations were 83.9% and 92.8% (p<0.01). The proportions of index operations classified as “corrections” were 70.5% in 1990-1999, and 78.6% in 2000-2011 (p<0.01).

Discussion

To our knowledge, this is the first long term prospective study of its kind. Our data demonstrate that over the last 40 years, there have been substantial improvements in postoperative survival within all subgroups of complex congenital heart defects - with early mortality now approaching zero. Parallel to these improvements, there has been a decrease in the need for reoperations. This development has taken place despite the fact that increasing proportions of complex cases have been operated, and despite a marked decrease in age at first operation. In children with defined simple defects, survival was already so high in the late 1970-ies that only moderate further improvements were possible. In the following, we have therefore focused on children with
complex defects.

**Number of patients**

The birth incidence of CHD appears constant,\(^1^2\) possibly excluding the most complex defects (e.g. HLHS) in some countries due to abortions after prenatal echocardiography.\(^1^3\) The increasing number of operations for complex defects therefore implies that an increasing proportion of patients underwent surgery following improvements in pre-operative diagnostics, surgical techniques, anesthesiology and intensive care. Improved pre-operative diagnostics has facilitated both the identification and characterization of patients that may be amenable for surgery. Surgical corrections that were judged impossible or too dangerous in the past, or which had not yet been developed, may now be performed with good results and acceptable risk.

Notably, among recent advances are new surgical techniques such as the Norwood procedures in patients with HLHS,\(^1^4\) the arterial switch procedure in patients with TGA,\(^1^5\) staged palliation for patients with UVH,\(^1^6\) and one-stage palliation in patients with I/HAA and VSD.\(^1^7\) Few CHDs are now beyond the reach of surgical treatment, even at a very young age, exemplified by the fact that median age at first operation in patients with complex defects was 1.6 years in 1971-1979 and only 0.19 years in 2000-2011. A sizeable proportion of children with CHD succumbed at an early age during the early phases of the study, especially those with the most severe defects. Most of these children now undergo surgery shortly after birth, thereby increasing the size and complexity of the population offered operation.

The decrease in the number of patients with certain simple CHD undergoing surgery probably follows an increase in invasive catheter treatment. E.g. the number of pulmonary balloon valvuloplasty procedures increased from 89 in 1990-1999 to 150 in 2000-2011, device closures of ASD from 29 to 260 and balloon dilatations of COA from 9 to 17. An increasing
availability of these techniques may have lowered the threshold for treating PS and ASD, but not COA.

Approximately 80% of all CHD surgery in Norway was performed at Rikshospitalet until 2003, and 100% from 2004 to 2011. Accordingly, the reported increase in the number of patients from 1990-1999 to 2000-2011 (table 2) was somewhat larger than it would have been without the policy change in 2004. However, the increase in the number of complex cases was steeper than what would have been expected from a purely proportional expansion of the total patient population.

Survival

In addition to a report from our hospital on a sub-cohort of 970 children operated for CHD between 1990 and 1999,7 three other studies specifically targeting survival after CHD surgery have been published during the last decade - all based on retrospective data. Nieminen et al.5 reported that, among patients < 15 years of age who underwent surgery in 1953-1989 (75% in 1970-1989), 15-year survival in patients with UVH, TGA, and TOF was 45%, 65%, and 82%, respectively. In our study, 15-year survival among patients < 15 years of age who were operated for UVH in 1971-1989 was 36.2%, for TGA 64.7%, and for TOF 87.5%. In a study including 850 children in Denmark, Larsen et al.6 reported that, among all CHD patients < 15 years of age who underwent surgery in 1996-2002, 8-year survival was 86%. In our study, overall survival after 8 years was 90.2% among patients < 15 years of age who were operated in 1996-2002.

Based on a population from 38 American states, Marelli et al.18 found that 30-day postoperative survival in all CHD patients < 18 years of age who were operated in 2000, 2003, and 2006 was 95·8%, 95·5%, and 96·5%, respectively. However, the study did not discriminate between different CHD diagnoses, and no data on long term follow-up were given. In our study, 30-day
postoperative survival in 2000, 2003 and 2006 when taking all CHD subgroups (table 1) together was 96.3%, 96.3%, and 97.6%.

Four additional studies on CHD survival have been published during the last decade on children with “severe” or “critical” CHD, all of whom probably underwent CHD operations, but no specific data on surgery were reported.

Based on the most recent data available in 2001, Warnes et al. estimated that children with “complex” CHD born in the eighties had a one-year survival rate of 85%. Our data show marked further improvements in survival during the following two decades in all complex CHD subgroups (figure 1). In fact - since the era studied by Warnes et al., one-year survival in complex defects has increased almost linearly - now approaching the 100% limit (figure 4).

Despite the early gain in survival, no increase in late mortality was seen. Especially, this appeared to be the case among the patients operated on from 2000 to 2011. Because nearly all (99.1%) of the children with complex defects operated in 2005-2011 survived the early 30 days postoperative period, further reductions in mortality can be achieved almost exclusively from improvements in late survival. However, the potential for further improvements is narrowing – as suggested by the fact that CHD-related mortality in Norwegian children was approximately constant after 2005 (figure 5) – in good agreement with data from the UK.

Reoperations
About one third of the patients with complex defects who were initially operated in 1990-2011 needed reoperation before age 16 years, similar to findings reported from studies in the UK and in the US. However, parallel to the improvements in postoperative survival (figure 2), there was also a significant increase in reoperation-free survival from 1990-1999 to 2000-2011. We are not aware of other studies reporting on sequential changes in reoperations during this
period. Further studies are needed to explore the full clinical impact of these developments - e.g. on quality of life.

Table 4 demonstrates increases in reoperation-free survival in most complex CHD subgroups, particularly marked in patients with I/HAA and PA, and table 2 shows that there was a particularly marked increase in the number of patients with I/HAA, PA and UVH being operated during the study period. However, the reoperation-free survival figures given for patients with UVH should be interpreted with caution, since in 1990-1999 not all patients with HLHS were operated in Norway. Among patients who typically underwent primary correction (like TGA, AVSD and TAPVD), changes in reoperation-free survival were modest.

These developments coincided with declining age at first operation and increasing proportions of corrections rather than palliations. The lower age at first operation has contributed to increasing numbers of operations in the most complex cases – since many of these patients previously succumbed at an early age. Early corrections may prevent complications caused by the hazards associated with the defects themselves. Once it has been proved that primary corrections can be performed successfully with low risk, the need for palliations and reoperations will obviously be reduced.

In summary, our data indicate that in general, an aggressive surgical strategy aimed at primary correction instead of palliation during the very first few weeks after birth may be advocated.

Limitations

We divided CHDs into “complex” and “simple” defects based on a diagnosis complexity hierarchy adopted by Nieminen et al. acknowledging that the degree of severity varies widely within the complex subgroup - and even within each diagnostic category. Table 3a shows that
the complex vs. simple scheme fits best for patients operated on from 1971 to 1989. However, even in patients operated on from 1990 to 2011, all complex defects except TOF had a poorer prognosis than “simple” defects, which may justify the complex vs. simple classification.

Importantly, the assumed complexity of a certain defect depends on the assumed complexity of surgical correction, which probably changed for most heart defects during the long study period. Since risk assessment scores based on surgical complexity have been used internationally for only about 10 years,27 such scores were not applied in the present study.

Some previous studies classified TOF as “critical”22 or “severe”,21 whereas others judged it to be “moderately severe”.19,23 Despite successful surgical corrections in the 1970s, we find it difficult to categorize TOF as anything but a complex defect.

The data presented show outcomes in a single, medium sized center with low selection bias, since access to health services in Norway is free, and since Norwegian children with few exceptions are born in hospitals. Accordingly, it is likely that the great majority of cases with complex CHD were early diagnosed and immediately referred for care. However, before 2003, some of the most severe complex cases were transferred to our institution, suggesting that postoperative mortality in children operated before 2003 was higher than it might have been in an unselected population.

The ethincal distribution in Norway changed during the 40-year study period because of considerable immigration. Among children operated in 2000-2011, about one sixth had names suggesting Asian or African origin, whereas in 1971-1979 only one such patient was operated.

**Perspectives**

Essentially, our paper deals with data from a continuous, four-decade quality control and improvement project, acknowledging that controlled trials in children with CHD are difficult – if
not impossible,28 for ethical reasons. By continuously introducing “state of the art”

improvements in diagnostics, anesthesiology, surgical techniques, and postoperative care, a level

has been reached where virtually all CHDs are now within reach of surgical correction with

acceptable risk. This advance makes it easier for health professionals to communicate with

parents fearing for the life of their child.

Conclusion

This prospective study covering the last 40 years of more than 80% of CHD surgery in

Norwegian children with 98.5% complete follow-up demonstrates very marked, gradual

improvements in both short and long term postoperative survival despite increasing proportions

of complex cases becoming amenable for surgery, and despite a gradual and marked decline in

age at operation. Moreover, a significant reduction in the need for reoperations is observed,

probably mainly as a result of performing more primary corrections as opposed to primary

palliations. Future challenges include further refinements and education in surgical techniques29

and implementation of risk stratification algorithms.30-36

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the database in 1971.

Conflict of Interest Disclosures: None.

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Table 1. Diagnosis Hierarchy

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<th>C</th>
<th>1. Univentricular hearts (UVH)</th>
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<tr>
<td>O</td>
<td>2. Truncus arteriosus communis (TAC)</td>
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<td>M</td>
<td>3. Interrupted or hypoplastic aortic arch (I/HAA)</td>
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<td>4. Transposition of the great arteries (TGA)</td>
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<td>5. Atrioventricular septal defect (AVSD)</td>
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Table 2. The Number of Patients Operated for Congenital Heart Defects 1971-2011

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<td>32</td>
<td>0.5</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>E</td>
<td>PAPVD</td>
<td>88</td>
<td>1.2</td>
<td>21</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>ASD</td>
<td>705</td>
<td>10.0</td>
<td>138</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>PDA</td>
<td>890</td>
<td>12.6</td>
<td>179</td>
<td>16.2</td>
</tr>
<tr>
<td></td>
<td>All Simple</td>
<td>3751</td>
<td>53.2</td>
<td>724</td>
<td>65.2</td>
</tr>
<tr>
<td></td>
<td>MISC</td>
<td>369</td>
<td>5.2</td>
<td>45</td>
<td>4.1</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>7038</td>
<td>1106</td>
<td>1473</td>
<td>1887</td>
</tr>
</tbody>
</table>

*Abbreviations are given in Table 1.
Table 3A. Postoperative Survival in Patients Who Underwent Surgery 1971-1989 vs. 1990-2011

<table>
<thead>
<tr>
<th>CHD group*</th>
<th>Number of patients</th>
<th>Early (30-day) survival</th>
<th>Cumulative survival until age 16 years</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(n)</td>
<td>(n)</td>
<td>(%)</td>
<td>(%)</td>
</tr>
<tr>
<td>C</td>
<td>UVH</td>
<td>140</td>
<td>365</td>
<td>72.0</td>
</tr>
<tr>
<td>O</td>
<td>TAC</td>
<td>31</td>
<td>49</td>
<td>61.3</td>
</tr>
<tr>
<td>M</td>
<td>I/HAA</td>
<td>27</td>
<td>264</td>
<td>59.3</td>
</tr>
<tr>
<td>P</td>
<td>TGA</td>
<td>250</td>
<td>360</td>
<td>80.2</td>
</tr>
<tr>
<td>L</td>
<td>AVSD</td>
<td>98</td>
<td>468</td>
<td>78.4</td>
</tr>
<tr>
<td>E</td>
<td>TAPVD</td>
<td>35</td>
<td>74</td>
<td>77.1</td>
</tr>
<tr>
<td></td>
<td>PA</td>
<td>56</td>
<td>129</td>
<td>74.1</td>
</tr>
<tr>
<td></td>
<td>TOF</td>
<td>218</td>
<td>349</td>
<td>91.7</td>
</tr>
<tr>
<td></td>
<td>All complex</td>
<td>860</td>
<td>2058</td>
<td>79.7</td>
</tr>
<tr>
<td>S</td>
<td>VSD</td>
<td>425</td>
<td>831</td>
<td>92.0</td>
</tr>
<tr>
<td>I</td>
<td>COA</td>
<td>254</td>
<td>228</td>
<td>90.6</td>
</tr>
<tr>
<td>M</td>
<td>VALV†</td>
<td>165</td>
<td>165</td>
<td>93.3</td>
</tr>
<tr>
<td>P</td>
<td>ASD‡</td>
<td>367</td>
<td>426</td>
<td>99.2</td>
</tr>
<tr>
<td>L</td>
<td>PDA</td>
<td>395</td>
<td>495</td>
<td>98.2</td>
</tr>
<tr>
<td></td>
<td>All simple</td>
<td>1606</td>
<td>2145</td>
<td>95.1</td>
</tr>
<tr>
<td></td>
<td>MISC</td>
<td>113</td>
<td>256</td>
<td>84.1</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>2579</td>
<td>4459</td>
<td>89.5</td>
</tr>
</tbody>
</table>

*Abbreviations are given in Table 1. †Valvular aortic stenosis (AS), valvular pulmonary stenosis (PS), or mitral valve defect (MV). ‡Atrial septal defect or partially anomalous pulmonary venous drainage.
Table 3B. Postoperative Survival in Patients Who Underwent Surgery 1990-1999 vs. 2000-2011

<table>
<thead>
<tr>
<th>CHD group</th>
<th>Number of patients</th>
<th>Early (30-day) survival</th>
<th>Cumulative survival until age 16 years§</th>
</tr>
</thead>
<tbody>
<tr>
<td>C UVH</td>
<td>125 (n)</td>
<td>240 (%)</td>
<td>84.1 (%)</td>
</tr>
<tr>
<td>O TAC</td>
<td>23 (n)</td>
<td>26 (%)</td>
<td>65.2 (%)</td>
</tr>
<tr>
<td>M I/HAA</td>
<td>66 (n)</td>
<td>198 (%)</td>
<td>89.2 (%)</td>
</tr>
<tr>
<td>P TGA</td>
<td>152 (n)</td>
<td>208 (%)</td>
<td>90.8 (%)</td>
</tr>
<tr>
<td>L AVSD</td>
<td>176 (n)</td>
<td>292 (%)</td>
<td>94.4 (%)</td>
</tr>
<tr>
<td>E TAPVD</td>
<td>39 (n)</td>
<td>35 (%)</td>
<td>82.1 (%)</td>
</tr>
<tr>
<td>X PA</td>
<td>44 (n)</td>
<td>85 (%)</td>
<td>91.3 (%)</td>
</tr>
<tr>
<td>TOF</td>
<td>142 (n)</td>
<td>207 (%)</td>
<td>98.6 (%)</td>
</tr>
<tr>
<td>All complex</td>
<td>767 (n)</td>
<td>1291 (%)</td>
<td>90.7 (%)</td>
</tr>
<tr>
<td>S VSD</td>
<td>395 (n)</td>
<td>436 (%)</td>
<td>98.2 (%)</td>
</tr>
<tr>
<td>I COA</td>
<td>123 (n)</td>
<td>105 (%)</td>
<td>98.4 (%)</td>
</tr>
<tr>
<td>M VALV†</td>
<td>64 (n)</td>
<td>101 (%)</td>
<td>90.6 (%)</td>
</tr>
<tr>
<td>P ASD‡</td>
<td>239 (n)</td>
<td>187 (%)</td>
<td>99.2 (%)</td>
</tr>
<tr>
<td>L PDA</td>
<td>215 (n)</td>
<td>280 (%)</td>
<td>95.2 (%)</td>
</tr>
<tr>
<td>All simple</td>
<td>1036 (n)</td>
<td>1109 (%)</td>
<td>97.5 (%)</td>
</tr>
<tr>
<td>MISC</td>
<td>84 (n)</td>
<td>172 (%)</td>
<td>91.6 (%)</td>
</tr>
<tr>
<td>Total</td>
<td>1887 (n)</td>
<td>2572 (%)</td>
<td>94.4 (%)</td>
</tr>
</tbody>
</table>

*Abbreviations are given in Table 1. †Valvular aortic stenosis (AS), valvular pulmonary stenosis (PS), or mitral valve defect (MV). ‡Atrial septal defect or partially anomalous pulmonary venous drainage. §Maximum 13 years postoperative follow-up in patients operated on in 2000-2011.
Table 4. Freedom of Reoperation in Patients with Complex Defects Who Were Initially Operated in 1990-1999 vs. 2000-2011

<table>
<thead>
<tr>
<th>CHD Group*</th>
<th>1990-1999</th>
<th></th>
<th>2000-2011</th>
<th></th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Freedom of reoperation†</td>
<td>n</td>
<td>Freedom of reoperation†</td>
<td></td>
</tr>
<tr>
<td>UVH</td>
<td>125</td>
<td>0.16</td>
<td>240</td>
<td>0.15</td>
<td>0.22</td>
</tr>
<tr>
<td>TAC</td>
<td>23</td>
<td>0.42</td>
<td>26</td>
<td>0.56</td>
<td>0.43</td>
</tr>
<tr>
<td>I/HAA</td>
<td>66</td>
<td>0.79</td>
<td>198</td>
<td>0.87</td>
<td>0.0045</td>
</tr>
<tr>
<td>TGA</td>
<td>152</td>
<td>0.87</td>
<td>208</td>
<td>0.90</td>
<td>0.19</td>
</tr>
<tr>
<td>AVSD</td>
<td>176</td>
<td>0.84</td>
<td>292</td>
<td>0.86</td>
<td>0.38</td>
</tr>
<tr>
<td>TAPVD</td>
<td>39</td>
<td>0.89</td>
<td>35</td>
<td>0.91</td>
<td>0.67</td>
</tr>
<tr>
<td>PA</td>
<td>44</td>
<td>0.32</td>
<td>85</td>
<td>0.66</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>TOF</td>
<td>142</td>
<td>0.55</td>
<td>207</td>
<td>0.64</td>
<td>0.095</td>
</tr>
<tr>
<td><strong>All complex defects</strong></td>
<td>767</td>
<td>0.66</td>
<td>1291</td>
<td>0.73</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

*Abbreviations are given in Table 1.
†Kaplan-Meier estimates of 5-year probability of freedom from reoperation in patients with complex CHD who had their index operation during 1990-1999 vs. 2000-2011.

Figure Legends:

**Figure 1.** Cumulative postoperative survival until 16 years of age or the end of follow-up in patients with different complex congenital heart defects. UVH, univentricular hearts; TAC, truncus arteriosus communis; I/HAA, interrupted or hypoplastic aortic arch; TGA, transposition of the great arteries; AVSD, atrioventricular septal defect; TAPVD, totally anomalous pulmonary venous drainage; PA, pulmonary atresia; TOF, Tetralogy of Fallot.

Figure 3. Kaplan-Meier plots of reoperation-free “survival” in the combined group of patients with complex congenital heart defects who had their index operation in 1990-1999 vs. 2000-2011.


Figure 5. Number of deaths related to congenital heart defects (ICD-10 codes Q20-Q28) in Norway from 1971 to 2011. The red line includes patients aged 0-15 years at the time of their death, and the blue line patients aged 15+ years at the time of their death. Codes Q20-Q28 recoded from ICD-8 codes 746-747 (1971-1985) and ICD-9 codes 745-747 (1986-1995).
SURVIVAL IN DIFFERENT SUBGROUPS OF COMPLEX CONGENITAL HEART DEFECTS

Figure 1
POSTOPERATIVE SURVIVAL IN THE COMBINED GROUP OF PATIENTS WITH
COMPLEX CONGENITAL HEART DEFECTS

A

\[ p < 0.0001 \]

\[
\text{Cum. survival} \\
0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \quad 12 \quad 14 \quad 16
\]

- Operated 1971-1989 (n=860)
- Operated 1990-2011 (n=2058)

B

\[ p < 0.0001 \]

\[
\text{Cum. survival} \\
0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \quad 12 \quad 14 \quad 16
\]

- Operated 1990-1999 (n=767)
- Operated 2000-2011 (n=1291)

C

\[ p = 0.0003 \]

\[
\text{Cum. survival} \\
0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \quad 12 \quad 14 \quad 16
\]

- Operated 2000-2004 (n=484)
- Operated 2005-2011 (n=807)

D

\[ p = 0.002 \]

\[
\text{Cum. survival} \\
0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \quad 12 \quad 14 \quad 16
\]

- Operated 2005-2009 (n=579)
- Operated 2010-2011 (n=228)
PROBABILITY OF REOPERATION IN THE COMBINED GROUP OF PATIENTS WITH COMPLEX CONGENITAL HEART DEFECTS INITIALLY OPERATED IN 1990-1999 vs. 2000-2011

Figure 3
Figure 4

ONE-YEAR POSTOPERATIVE SURVIVAL IN COMPLEX CONGENITAL HEART DEFECTS ACCORDING TO YEARS OF BIRTH 1975-2011
MORTALITY RELATED TO CONGENITAL HEART DEFECTS IN NORWAY 1971-2011

Figure 5
Achievements in Congenital Heart Defect Surgery: A Prospective, 40 Year Study of 7038 Patients
Gunnar Erikssen, Knut Liestøl, Egil Seem, Sigurd Birkeland, Kjell Johan Saatvedt, Tom Nilsen Hoel, Gaute Døhlen, Helge Skulstad, Jan Ludvig Svennevig, Erik Thaulow and Harald Lauritz Lindberg

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