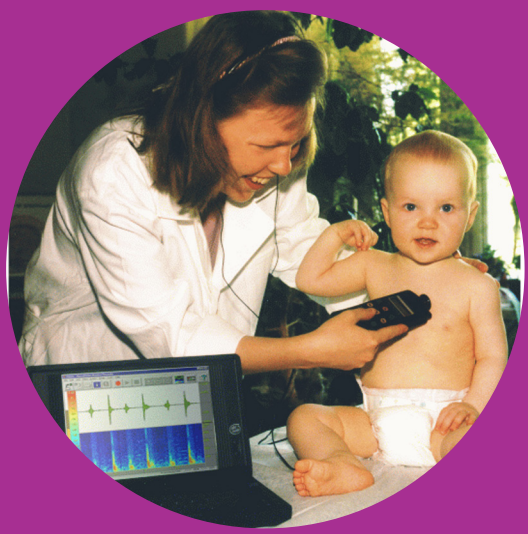
Department of Electronics

Phonocardiography: Development of a clinical system and its application to screening for paediatric heart murmurs

Sakari Lukkarinen



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Phonocardiography: Development of a clinical system and its application to screening for paediatric heart murmurs

Sakari Lukkarinen

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Abstract

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Abstract

Screening for heart murmurs in children is an area of healthcare in which significant gains can be made in terms of efficiency. Due to diagnostic uncertainties in primary healthcare, heart murmurs, most of which are innocent, are the most common reason for referrals to a paediatric cardiologist. The phonocardiographic system, updated with current technology, could provide the additional information necessary to screen for heart murmurs in children reliably.

In this thesis a prototype of a phonocardiographic system for non-cardiologist use was developed and its applicability to screening for heart murmurs in children was evaluated. A special feature of the system was the combined phonospectrographic view that could be used to analyse the features of the heart sounds and murmurs.

The system was used to collect two independent heart sound databases in cooperation with Helsinki University Hospital and Lund University Hospital. Experienced paediatric cardiologists examined the children and analysed their heart sounds. The timing, duration, and frequency contents of heart sounds and murmurs were extracted from the sound signals. Statistical analysis was used to find the most significant features for screening between pathological and physiological cases.

The system was capable of recording, displaying and replaying common heart murmurs in children. The characteristics of the heart murmurs in children were illustrated in phonospectrograms. The timing and quality of the cardiovascular sound events were measured from the graphical presentations. With the use of time interval and spectral analysis as well as a stepwise regression analysis model, all significant cardiac defects were correctly classified as pathological. In phonospectrographic analysis of heart murmurs in children, a sensitivity of 90% and specificity of 92% in screening for pathological heart murmurs were achieved.

The digital phonocardiographic system for screening for heart murmurs in children can be implemented rather simply using an electronic stethoscope and a personal computer. The enhanced phonospectrographic presentation of the heart sounds and murmurs provides more information than traditional auscultation or phonocardiography alone. Simple features extracted from the phonospectrogram may significantly improve the diagnostic quality of primary healthcare in screening for heart murmurs in children and thus lead to more efficient use of personnel and technical resources in the whole healthcare system.

Keywords Phonocardiography, Digital signal processing, Heart sounds, Heart murmurs, paediatric cardiology

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Tiivistelmä

Lasten sydänäänten seulonta terveydenhuollossa kaipaa tehostamista. Sydämen sivuääni, joka yleisimmin on viaton, on kaikkein yleisin tulosyy lastenkardiologiseen konsultaatioon. Fonokardiografia, modernisoituna, voisi tarjota tarvittavan lisäavun viattoman sivuäänen tunnistamiseen jo perusterveydenhuollon piirissä.

Tässä väitöstyössä kehitettiin prototyyppi fonokardiografiajärjestelmästä ei-kardiologiseen käyttöön ja sen soveltuvuutta lasten sydänäänien seulontaan testattiin. Järjestelmän erityispiirre on fonospektrografinen näyttö, jolla voidaan tutkia aiempaa tarkemmin sydämen sivuäänten ominaisuuksia.

Järjestelmää käytettiin kahden riippumattoman sydänäänitietokannan keräämiseen yhteistyössä Helsingin ja Lundin yliopistollisten keskussairaaloiden kanssa. Kokeneet lastenkardiologit tutkivat lapset ja analysoivat sydänäänet. Tilastollista analyysiä käyttäen etsittiin mitatuista signaalio minaisuuksista seulontaan sopivimmat.

Järjestelmän avulla kyettiin rekisteröimään, visualisoimaan ja uudelleen toistamaan yleisimmät lasten sydämen sivuäänet. Sivuäänten tyypillisimmät piirteet olivat erotettavissa fonospektrogrammeista. Sydän- ja sivuäänten ajoitus ja laatu pystyttiin mittaamaan graafisista esityksistä. Käytettäessä ajoitus- ja spektrianalyysiä sekä tilastollista regressioanalyysimallia kaikki merkittävimmät sydänviat pystyttiin tunnistamaan patologisiksi. Fonospektrografista analyysiä käyttämällä saavutettiin 90 % erottelykyky ja 92 % tarkkuus patologisten sydämen sivuäänten seulonnassa.

Digitaalinen sydänäänten rekisteröinti ja analysointi voidaan toteuttaa kohtuullisen yksinkertaisesti käyttäen elektronista stetoskooppia ja henkilökohtaista tietokonetta. Sydän- ja sivuäänten laajennettu fonospektrografinen esitystapa tarjoaa enemmän informaatiota seulontaa kuin perinteinen fonokardiografia tai auskultaatio yksinään. Fonospektrogrammista mitatut muutamat yksinkertaiset ominaisuudet voivat merkittävästi parantaa perusterveydenhuollon diagnostista laatua lasten sydänäänten seulonnassa ja näin johtaa koko terveydenhuollon resurssien tehokkaampaan käyttöön.

Avainsanat Fonokardiografia, digitaalinen signaalinkäsittely, sydänäänet, sydämen sivuäänet, lastenkardiologia

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Preface

There are about 58 million results for searching “heart sounds” in the Web. A lot is written and said about this topic. My favorite piece is written by a Finnish poet, Tommy Tabermann, and it goes: *“Sille, jota ruoho rakastaa, sille ruoho laulaa. Sille joka rohkenee kuunnella sydänääniä sille sydän laulaa.”* Freely translated to English: *“Whom the grass loves, for him it sings. Who dears to hear the heart sounds, for him the heart sings.*”

I have listened to the song of heart now almost 20 years. It is full of wonders. Sometimes its rhythmical beat lulls to innocent sleep, in other days it blows loudly and harshly like stormy autumn sea to rocks of shore. Day to day heart continues its story weaving new loops and connecting us to the fabric of life.

It took quite a long time to conclude this project. Maybe it could have been finalized earlier, maybe the elapsed moments have given more strength and depth to it. In any case, here it is now, and I want to express my gratitude to all of you who helped in this process. Although the final thesis is author's contribution, the credits belong to everyone involved. Thank you for your guidance, advice, encouragement, patience and blessings.

Lastly I want to devote this piece of work to all children. Despite the differences of our songs, the same Spirit is flowing through our hearts.

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I Lukkarinen S, Noponen A-L, Angerla A, Sikiö K, Sepponen R. A Recording Stethoscope in Study of Heart Sounds of Children, Medical and Biological Engineering and Computing. Vol. 34, Supplement 1, part 1, 1996, pp.97-98.

II Lukkarinen S, Korhonen P, Angerla A, Noponen A-L, Sikiö K, Sepponen R. Multimedia personal computer based phonocardiography, Engineering in Medicine and Biology Society, 1996. Bridging Disciplines for Biomedicine. Proceedings of the 18th Annual International Conference of the IEEE, 1996, Vol. 5, p. 2303-2304. DOI: 10.1109/IEMBS.1996.646545.

III Lukkarinen S, Noponen A-L, Sikiö K, Angerla A. A New Phonocardiographic Recording System, Computers in Cardiology 1997 Vol. 24, p. 117-120. DOI: 10.1109/CIC.1997.647844.

IV Lukkarinen S, Sikiö K, Noponen A-L, Angerla A, Sepponen R. Novel software for real-time processing of phonocardiographic signal, Engineering in Medicine and Biology Society, Proceedings of the 19th Annual International Conference of the IEEE, 1997, Vol. 4, p. 1455-1457, DOI: 10.1109/IEMBS.1997.756980.

V Lukkarinen S, Noponen A-L, Angerla A, Sikiö K, Sepponen R. Experiences with a Videoconference System in Heart Murmur Screening, Computers in Cardiology, 1998, Vol. 25, p. 53-56, DOI: 10.1109/CIC.1998.731712.

VI Noponen A-L, Lukkarinen S, Angerla A, Sikiö K, Sepponen R. How to Recognize the Innocent Vibratory Murmur, Computers in Cardiology 2000. Vol 27, pp. 561-564. DOI: 10.1109/CIC.2000.898583.

VII El-Segaier M, Pesonen E, Lukkarinen S, Peters K, Sörnmo L, Sepponen R. Detection of cardiac pathology: time intervals and spectral analysis, Acta Pædiatrica, 2007. Vol. 96, pp. 1036–1042. DOI: 10.1111/j.1651-2227.2007.00318.x.

VIII Noponen A-L, Lukkarinen S, Angerla A, Sepponen R. Phono-spectrographic analysis of heart murmur in children, BMC Pediatrics 2007. Vol. 7:23. DOI: 10.1186/1471-2431-7-23.

Author's contribution

Original idea, design, implementation and reporting of the phonocardiographic recording system in articles I, II, III, and IV. Design, specification and reporting of videoconferencing experiment V. Writing, technical preparation of the material and illustrations, discussion and conclusions in VI. Design and implementation of the recording system for Lund University Hospital. Technical guidance, comments, discussion and writing in article VII. Specifications, statistical analysis, reporting, writing and discussions in articles VIII.

In addition, the author instructed the following Master of Science theses: “The Design of a sound transducer for an electronic stethoscope” by Pekka Korhonen, 1996; “Design and Implementation of Biosignal Monitoring and Analysis Software” by Kari Sikiö 1999; “Development of Phonocardiographic Amplifier” by Johan Sjöholm, 2001; and gave the idea, guidance, comments and participated in discussion on Licentiate Thesis of “Digital Signal Analysis of Heart Sound Signals” by Huiying Liang, 1999, which all are closely related to author's own thesis.

List of symbols and abbreviations

A	Aortic
A2	Aortic component of S2
ACC	American college of cardiology
AHA	American heart association
ANN	Artificial neural network
AS	Aortic stenosis
ASD	Atrial septal defect
BD	Binomial distribution
bpm	beat per minute
CHD	Congenital heart disease
CoA	Coarctation of aorta
CWD	Choi-Williams distribution
dB	Desibel
E	Ejection sound
ECG	Electrocardiogram
FFT	Fast Fourier transformation
Fimax	The frequency of the maximum intensity of SM
Fm	Mean frequency
G.711	Standard for audio coding
G.722	Standard for speech coding
G.728	Standard for speech coding

HCM	Hypertrophic cardiomyopathy
HOCM	Hypertrophic obstructive cardiomyopathy
Imax	The maximum intensity of SM
IP	Internet protocol
LVOT	Left ventricular outflow tract
M	Mitral
M1	Mitral component of S1
MI	Mitral insufficiency
MS	Mitral stenosis
O	Opening sound
P	Pulmonic
P2	Pulmonic component of S2
PCG	Phonocardiogram
PDA	Patent ductus arteriosus
PM	Punctum maximum, the location on the chest, where the auscultated heart sound or murmur is loudest
PS	Pulmonary stenosis
R	R wave in ECG signal
RC	Resistor-capacitor
ROC	Receiver operating characteristic
RIFF	Resource interchange file format
S1	The first heart sound
S1SM	The time interval from the ending of S1 to the beginning of SM
S2	The second heart sound
ΔS2	The variation of the splitting of S2
S3	The 3rd heart sound
S4	The 4th heart sound
SDTimax	Standard deviations of Timax
SM	Systolic murmur
Sp	Mean spectral power of SM
STFT	Short time Fourier transformation
T	Tricuspid

T1	Tricuspidal component of S1
TI	Tricuspidal insufficiency
Timax	The time interval from the ending of S1 to the maximum intensity of SM
ToF	Tetralogy of Fallot
WD	Wigner distribution
VSD	Ventricular septal defect
WAV	Waveform audio file format
WAVE	See WAV

1 Introduction

1.1 Background

Screening for heart murmurs in children is an area of healthcare in which substantial efficiency gains can be made. Heart murmurs, extra sounds originating from the heart, are very common in children. Most of these murmurs are caused by the normal physiological functioning of the heart and are therefore benign. Only a small part of them are due to heart diseases or defects. Given the diagnostic uncertainties of primary healthcare and the lack of understanding or underestimation of the total costs of consultations, heart murmurs, most of them innocent, are the most common reason for referrals to paediatric cardiologists (Smythe et al. 1990; Bensky et al. 1999; Wong et al. 2005). These referrals pose an unnecessary burden on the financial, material and human resources of the healthcare system.

Clinical examination by an experienced paediatric cardiologist is an accurate means of assessing newly referred patients with murmurs (Smythe et al. 1990). Previous studies have reported high sensitivities (82…92 %) and specificities (76…99%) in the differentiation between innocent and pathological murmurs by paediatric cardiologists (Van Oort et al. 1994; McCrindle et al. 1996; Rajakumar et al. 1999; Benun et al. 2003). However, all specialist consultations, including by paediatric cardiologists, cost more than primary screening alone. A solution could be to provide echocardiography in primary healthcare and train the personnel to use the device. This option might cost even more than a consultation with a

cardiologist (Danford et al. 1993, 1995, 2002). In addition, echocardiography, although diagnostic when heart disease is suspected, is considered unnecessary in paediatric patients with clinically diagnosed innocent heart murmurs (Smythe et al. 1990; Bonow et al. 2006). An ideal solution would be to train primary healthcare personnel to recognise innocent (normal) heart murmurs by auscultation. This, however, would require either several years of practice or several hundreds repetitions of exercises (Barrett et al. 2004). As screening for heart murmurs is only a small portion of the clinical skills required in current primary healthcare, investing in such training is not likely to be cost-effective.

The idea that a phonocardiographic system could provide the necessary information to screen for heart murmurs in children arose from a personal discussion with a medical student years ago. The clinical training for recognising the heart sounds with auscultation is very short and leaves students lacking confidence in their skills. The standard instruction in cardiac auscultation consists of only a couple of hours of classroom lectures and bedside training, meaning that the ability of medical students to recognise common cardiac murmurs is poor (Barrett et al. 2004). A quest to find a solution that could help in the analysis of heart murmurs was initiated. This thesis is the outcome of that quest.

1.2 Aim and Scope

The main purpose of this thesis has been to develop a practical phonocardiographic system for use by non-cardiologists and to evaluate its applicability to screening for heart murmurs in children.

The scope of this thesis was limited to heart sounds, thus excluding several other areas of research, such as electrocardiographic analysis. An experienced paediatric cardiologist can make a reliable judgement on whether a heart murmur is innocent or pathological by auscultation only. This is because the sound itself contains all the necessary information to screen for heart murmurs in children. If the difference between the normal and diseased heart murmurs can be heard and distinguished, it must be possible to create a system to automate the process. The system should not require any additional information, like electrocardiography, apical or

venous pulse tracings, or any other signal related to the cardiovascular and respiratory cycle.

Second, the scope was limited to children. This thesis did not study typical auscultation findings, like third and fourth heart sounds, clicks and backflow murmurs, related to cardiac diseases in adults. The aim was to understand and analyse the heart sounds and the most common heart murmurs in children and to develop a system for improving screening for those cases.

Third, the scope was limited to screening. The major challenge in primary healthcare in the area of paediatric cardiology is to identify innocent heart murmurs with confidence. Most severe congenital heart defects are recognised during the first weeks of life. Such conditions are typically treated by specialists and the status and history of the patient are well known. A harsh and loud or diastolic murmur, usually caused by a congenital heart defect or disease, is usually easy to identify, even by non-experts. In contrast, distinguishing mild or slowly developing pathologies or diseases from the large amount of normal heart sounds and innocent murmurs is the real challenge in primary healthcare.

The aim has been to find answers for the following special questions:

- Does phonocardiography provide enough information to judge whether a heart sound or murmur is normal?
- Does phonocardiography improve diagnostics either in quality or efficiency in screening for heart murmurs in children?
- Is it possible to automate heart sound analysis and thus provide physicians with reliable information?
- What would the technical and clinical requirements of the phonocardiographic system for non-cardiologist use be?

In order to answer these questions, the study was divided into smaller research projects with the following targets:

- to develop a prototype of a phonocardiographic system for research and development purposes;
- to use the system to collect a heart sound database in parallel with technical research and improvements;
- to analyse the heart sounds and murmurs in more detail in order to identify the characteristic features of innocent and pathological murmurs; and

– to study and develop criteria for the detection and analysis of heart sounds and murmurs in children for screening purposes.

1.3 Contents

This thesis is divided into the following chapters:

– Chapter 1 (page 16) introduces the background, aim, scope and contents of this thesis.
– Chapter 2 (page 20) gives an introduction to the heart sounds, specifically in children.
– Chapter 3 (page 40) reviews the literature, history and current situation of existing technological tools, methods, and clinical observations in the field of phonocardiographic research.
– Chapter 4 (page 57) summarises the design and implementation of the phonocardiographic system.
– Chapter 5 (page 63) presents the setup and methods used in clinical experiments.
– Chapter 6 (page 70) presents the results of the clinical tests and evaluations of the phonocardiographic system developed.
– Chapter 7 (page 79) discusses the findings and the scope of this thesis and lastly,
– Chapter 8 (page 82) concludes by presenting the main achievements of this study and the contribution this dissertation offers the scientific community.

2 Heart sounds in children

From the point of view of screening, heart sounds and murmurs can be divided into two categories: normal and those considered having some degree of heart disease and thus requiring further treatment. Currently many children with normal heart sounds and murmurs children are over-examined. It is therefore crucial to understand the basic mechanisms and limits of normal heart sound events and their auscultatory and phonocardiographic findings in order to improve the efficiency of screening for heart murmurs in children.

2.1 Normal heart sound events

The movement and vibration of blood together with the movement and vibration of the heart structures produce audible heart sounds and murmurs (Rushmer 1970). The shorter vibrations are called heart sounds. The sounds having a longer duration due to continuous vibration are considered murmurs. The normal first and second heart sounds are produced by the deceleration of blood following the closure of the valves. Most heart murmurs are considered caused by turbulent blood flow (Allen et al. 2001; Walsh et al. 2011). Figure 2.1 illustrates normal heart sound events graphically.

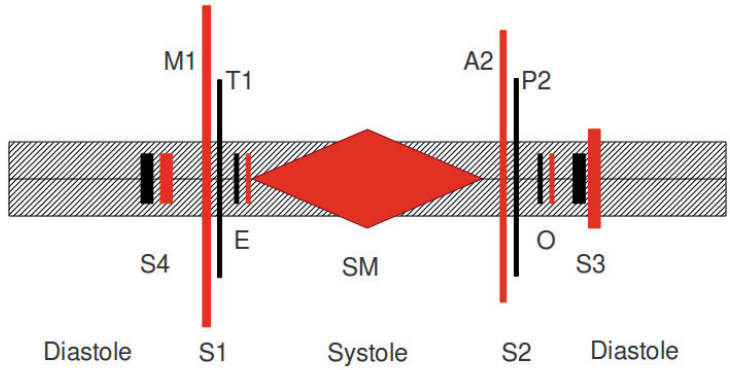

Figure 2.1. *Normal heart sound events presented graphically. The typical length of one heart cycle (from S1 to S1) in children varies from 550 to 750 ms (70-120 bpm). The red colour represents events on the left side of the heart, and the black colour events on the right side. The gray area is normally inaudible. S1 = the 1st heart sound, S2 = the 2nd heart sound, S3= the 3rd heart sound, S4 = the 4th heart sound, M1 = mitral valve component of S1, T1 = tricuspidal valve component of S1, A2 = aortic valve component of S2, P2 = pulmonary valve component of S2, E = ejection sound, SM = systolic murmur, O = opening sound. Adapted from Leatham (1970).*

Normal heart sound events can be divided into the following categories:

- loud and wide frequency transient sounds – the first (S1) and the second (S2) heart sound – associated with vibrations and sounds due to the sudden closing of the valves,
- soft or inaudible low frequency transient sounds - the third (S3) and fourth (S4) heart sound, related to early and late diastolic filling events of the ventricles,
- soft or inaudible low frequency transient sounds – the ejection sound (E) and the opening sound (O) – related to the vibrations due to the rush of the blood into ventricles or main arteries and the associated opening of the valves,
- soft and low or mid frequency longer duration sound – the systolic heart murmur (SM) – related to the main ejection of the blood from the ventricles to the arteries and the vibrations caused in the surrounding structures.

The loud, transient (70 - 110 ms) and wide-frequency (25-500 Hz) vibrations associated to the sudden closing of the heart valves and deceleration of the blood flow comprise the two major sound components of

the audible heart cycle, the first (S1) and the second (S2) heart sound. They are easily audible and recognisable in every healthy person. Both S1 and S2 are composed of two components related to the left and right side events of the heart. S1 contains the sounds caused by the closure of the mitral valve (M1) and the tricuspid valve (T1). The components of S2 the sounds caused by the closure of the aortic valve (A2) followed by the closure of the pulmonary valve (P2). S1 and S2 mark the transition between systole (work) and diastole (rest). In all normal and in most mild pathological cases in children there are no remarkable changes in the intensity or timing of S1 and S2. The only exception is the wide and fixed split of S2 (> 30 ms) in atrial septal defect (ASD). On auscultation, splitting of S2 is usually best heard at the second or third intercostal space (at the level of the semilunar valves).

The early diastolic ventricular filling – when the atrioventricular valves open, the blood flows into the relaxed chambers and is stopped rather suddenly when ventricles reaches their elastic limits – causes a soft, transient and low-frequency vibration, which constitutes the third (S3) heart sound. The S3 is a normal physiological finding in children. It is commonly found in thin almost underweight patients and is intensified in hyperkinetic situations. It can be made audible in any healthy normal person by increasing the heart's activity (cardiac output). The S3 is best heard at the apex in the left lateral position.

A forceful atrial contraction and associated distension and stretching of ventricular walls and structures in the late diastole generates the audible low-frequency fourth heart sound (S4; atrial systolic gallop, presystolic gallop). Normally the vibrations resulting from the atrial contraction are not audible but are usually found in phonocardiographic tracings. The presence of an S4 is usually an abnormal finding. The S4 is best heard at the apex with the patient turned in the left lateral position. It varies considerably with respiration, usually being loudest during expiration.

The sudden ejection of the blood from the ventricles to the main arteries may be associated with the early systolic ejection sound (E). It is normally inaudible, but is a typical finding in healthy children or young adults. The audible ejection sound is also found in valvular diseases, like stenosis, insufficiency or coarctation, hypertension or dilatation of the arteries.

The ejection of blood into the aorta and pulmonary artery is accompanied by a short systolic murmur (SM). It is usually audible in children. In most cases it is caused by normal or increased ejection. The innocent vibratory systolic murmur (Still's murmur, innocent precordial systolic murmur) is classified separately. Its qualitative difference from the other innocent systolic murmurs can be identified through auscultation, but traditional phonocardiographic analysis can not distinguish it from other normal systolic ejection murmurs.

The opening of the atrioventricular valves (O) is normally inaudible. Valvular stenosis, valvular abnormalities or increased atrioventricular flow may cause an audible early diastolic opening snap sound, which is always a pathological sign.

The continuous movement of blood, heart muscles and the surrounding tissues causes continuous a low frequency noise (rumbling), which constitutes the background or base line (gray area in Figure 2.1) for all other heart sound events.

2.2 Heart Murmurs

From the point of view of screening, heart murmurs could simply be classified as either normal or abnormal. The most common heart murmurs are normal systolic murmurs, and the clinical challenge is to differentiate them from the systolic murmurs caused by mild heart diseases.

All heart murmurs are considered to be the result of rapidly flowing turbulent blood that provides clear, functional and physical distinction between the heart sounds and murmurs (Rushmer 1970). Turbulence occurs when the velocity of the blood becomes critically high. The critical velocity can be estimated from the Reynold's number $\Re = \rho UD/\eta$, where ρ [kg/m³] is the density, η [Pa·s] the dynamic viscosity, U [m/s] the velocity of the fluid and D [m] is the diameter of the tube. Since the blood density and viscosity and the vascular diameter are relatively constant in normal situations, the major variable is the velocity of the blood flow. The critical level is normally exceeded in the roots of the aorta and the pulmonary artery during the rapid ejection phase of ventricular systole. On this basis,

virtually all persons have an early systolic murmur, even though its duration and intensity might be insufficient for its detection (Rushmer 1970). A high flow rate and thus turbulence is also found in several pathological cases such as constricted or irregular valves or orifices, backward flow through a regurgitant valves, septal defects, patent ductus arteriosus or any combination of these factors (Leatham 1970).

2.3 Characteristics of the murmur

The heart murmurs can be characterised on their intensity, pitch, quality, timing, duration, shape, location and radiation pattern on the chest wall.

Intensity

The intensity (loudness) of the murmur is graded with a scaling from 1 to 6 (Table 2.1) originally described by Freeman and Levine (1933). Most of the murmurs are in intensity of 1 to 3. A soft early-to-mid systolic murmur of grade 1 or 2 is a typical normal finding whereas loud murmur, grading 3 or more, should be studied more carefully. A palpable vibrations, thrills, are associated with the murmurs grading 4 or more.

The pathological or congenital heart defect may also alter the intensities and timings of the normal heart sounds (S1 and S2). Most common finding in children is the wide and fixed splitting of S2 found in patients with atrial septal defect (ASD).

The intensity of a murmur, however, may not be directly related to its haemodynamic importance, as a loud murmur may associate with a trivial lesion (e.g. a small ventricular septal defect) (Leatham 1970).

Pitch and quality

The frequency contents specify the pitch of the murmur. The frequency profile and thus the pitch (low, mid, high) has a direct relationship with the turbulent velocity energy profile of the blood flow (Sabbah and Stein 1976). The low-velocity flow through a large vessel produces a low-pitched rumbling murmur, whereas high-velocity jet-like flow through a small orifice, like in a small muscular ventricular septal defect, causes a high-

pitched murmur. The frequency components of normal systolic murmurs are typically below 200 Hz whereas murmurs caused by heart diseases, like pulmonary and aortic stenosis, may have higher frequency components (Walsh et al. 2011).

Table 2.1. Grading the intensity of a heart murmur

Grading	Description
1/6	Faint, can be heard only with special effort
2/6	Faint, can be heard easily
3/6	Moderately loud
4/6	Very loud
5/6	Extremely loud, can be heard if only the edge of the stethoscope is in contact with skin
6/6	Exceptionally loud. Can be heard with the stethoscope just removed from contact with the chest

The distance between the auscultation area and the source of the murmur affects on the quality of the murmur. The chest wall attenuates higher frequencies more effectively than the lower frequencies and the pitch of the murmur tends descend with increasing the distance (Durand and Pibarot 1995). In addition, the body habitus and the tissue properties affects both on the intensity and the quality of the murmur. The murmurs are typically louder and have higher pitch in children with thin habitus.

The quality of the murmur is typically described with terms like: noisy, harsh, rumbling and blowing. They all are related to the chaotic nature of the turbulence flow. Pathological or congenital heart defects cause typically noisy, harsh and wide frequency murmurs. In contrast some murmurs have a musical quality. This may be due to vibrations of a specific regular structure, like diseased valve, small ventricular defect or ventricular tendons. The most common musical murmur is the innocent vibratory murmur.

Timing, duration and shape

Timing, duration and shape are in major role in characterising heart murmurs. Based on their timing related to heart cycle the heart murmurs

can be divided into three main categories: systolic, diastolic or continous murmurs (Table 2.2).

Table 2.2. Classification of cardiac murmurs based on their timing and duration (Bonow et al. 2006)

1. Systolic murmurs
a. Holosystolic (pansystolic)
b. Midsystolic (systolic ejection)
c. Early systolic
d. Mid to late systolic
2. Diastolic murmurs
a. Early high-pitched
b. Middiastolic
c. Presystolic
3. Continuous

The duration of the systolic murmur and specially the termination of the murmur related to S2 is important (Figure 2.2). If the murmur is short, finishing before the both components of S2, it can be concluded to be an ejection type murmur (Leatham 1970). If the murmur continues until or over S2, it may be described as holosystolic (pansystolic). The holosystolic murmur due to regurgitant flow indicates heart disease. The midsystolic murmur due to ejection of blood across the left and right ventricle outflow tracts into the great vessels might be normal or abnormal.

A diastolic or continuous murmur, except venous hum, is considered to be related to pathological or congenital heart defect and thus is always abnormal finding.

The configuration or the shape of the intensity envelope is related to the blood flow velocity. Normal systolic murmurs are ejection type and thus follow the blood flow velocities. The commonest finding is a soft early-to-mid systolic ejection murmur which most probably is normal.

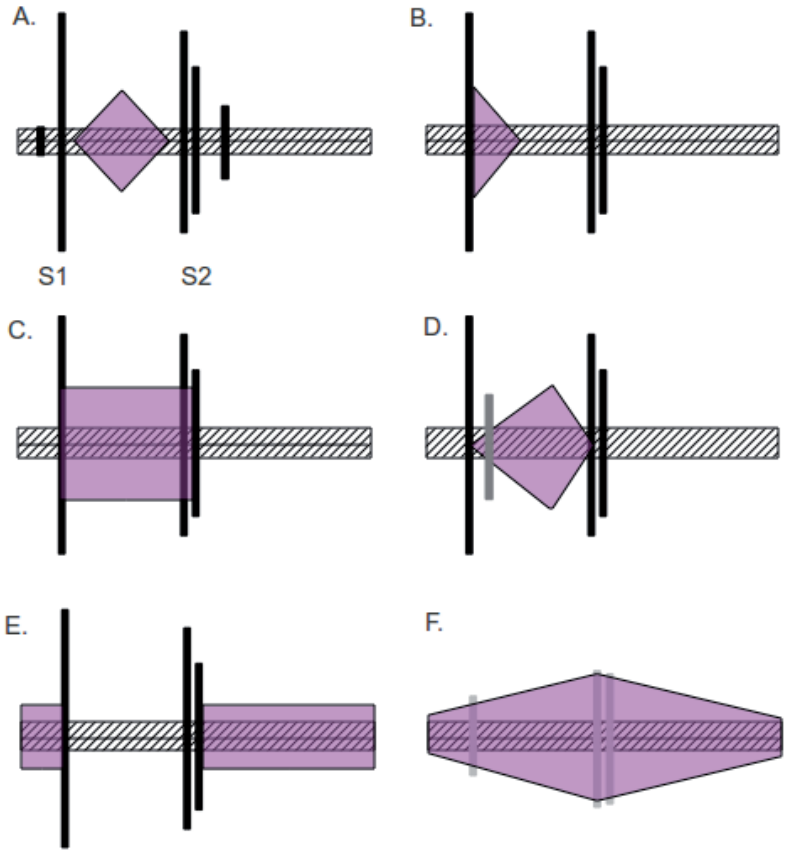

Figure 2.2. *Graphical illustrations of heart murmur timings: A) mid-systolic, B) early systolic, C) holosystolic, D) late systolic with ejection sound, E) diastolic (any timing), and F) continuous murmur.*

Location and radiation

The murmurs, like heart sounds, are loudest on the classical auscultation areas. The four primary areas of cardiac auscultation are named according to the locations on which the associated heart valves are heard best (Leatham 1970; Figure 2.3):

- the aortic area (A) in the second and third intercostal spaces on the right from the midline of the sternum,
- the pulmonary area (P) in the second intercostal space on the left from the midline of the sternum,
- the tricuspid area (T) in the fourth and fifth intercostal to the left sternal border, and
- the mitral area (M) at the cardiac apex.

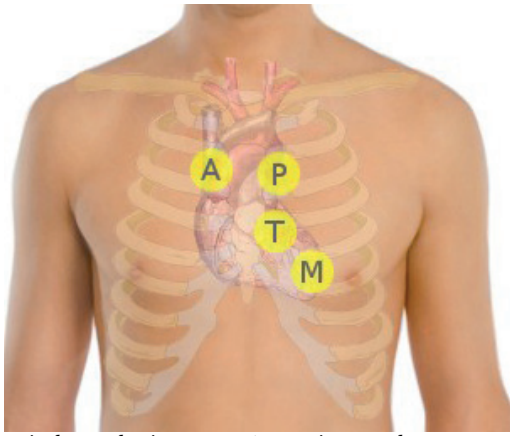

Figure 2.3. *Classical auscultation areas: A - aortic, P - pulmonary, T - tricuspid, and M - mitral (or apex) area. Adapted from: Surface anatomy of the heart, Häggström, 2009, http://en.wikipedia.org.*

The site of the origin, the intensity of the murmur, the direction of blood flow and the physical properties of the surrounding tissues determine the location and the radiation of the murmur (Walsh et al. 2011). The normal systolic heart murmurs are typically best heard at the pulmonary area, along the left sternal border (tricuspid area) and down to apex (mitral area).

2.4 Normal systolic heart murmurs

A normal systolic heart murmur (innocent systolic ejection murmur, innocent pulmonary/aortic ejection murmur, innocent ejection murmur, physiological ejection murmur) can be heard in most children and young adults. It is usually best heard at the pulmonary area and on the left sternal border. Sometimes it may be most intense at the apex or the aortic area. It is soft in intensity, typically grade of 1 or 2, sometimes 3. It can be accentuated by exercise, excitement or any stimulus causing increased stroke volume and rate of ejection. The pitch is low or mid frequency, frequency contents below 200 Hz. Its quality may be described as harsh or blowing. The shape follows the shape of the normal blood ejection having an early peak in intensity and degrading gradually and ending clearly before S2. It may be blended into the accentuated early ejection sound (E) thus making it sound like continuity from S1.

Table 2.3. Characteristics of normal innocent systolic heart murmur.

Character	**Description**
Location (best heard)	Pulmonary and tricuspidal area, sometimes aortic
Intensity (grade)	typically 1-2/6, sometimes 3/6
Pitch	Low or mid frequency
Timing and shape	Ejection type (Fig 2a or 2b)
Quality	Harsh or blowing
Other	Accentuated by exercise, excitement, increased stroke volume

Another type of normal systolic ejection murmur in childhood is the innocent vibratory murmur (precordial murmur, Still's murmur). It has been described as the most common murmur of early childhood. It is heard best at the apex or the lower left sternal border. The quality is musical or vibratory and the pitch is mid-to-high. The grading is between 1 and 3. The duration is early-to-mid systole, never pansystolic. As with normal systolic ejection murmur, the intensity of the vibratory murmur follows the ejection of the blood. It can be accentuated by increased stroke volume.

Table 2.4. Characteristics of innocent vibratory murmur.

Character	Description
Location	Tricuspidal or mitral (apex) area
Intensity	1-3/6
Pitch	Mid to high frequency
Timing and shape	Ejection type (Fig. 2a)
Quality	Vibratory, musical
Other	Accentuated by exercise, excitement and increased stroke volume

2.5 Common heart diseases in children

Although less than 1 % of all children have a congenital heart disease (CHD), the number of patients with CHD is increasing because of advances of medical treatment (Hoffman and Kaplan 2002; Figure 2.4). Most of the severe malformations are detected and managed during the infancy. Asymptomatic and gradually developing complications are captured later in the childhood. Only the common and mild congenital or acquired heart diseases cause trouble in heart murmur screening in children.

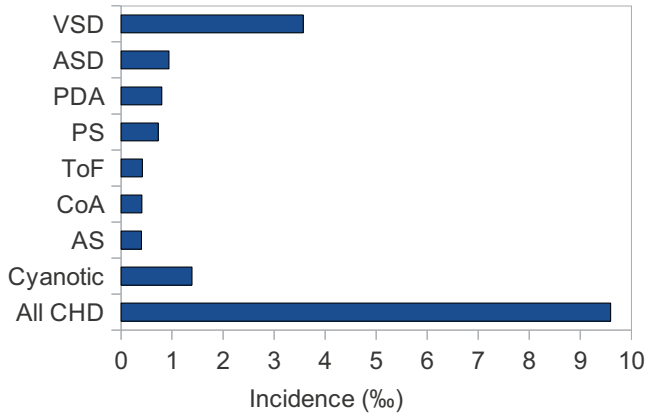

Figure 2.4. *Mean incidence of common congenital heart diseases (CHD) per thousand life births (Hoffman and Kaplan 2002). VSD = Ventricular septal defect, ASD = Atrial septal defect, PDA = Patent ductus arteriosus, PS = Pulmonary stenosis, ToF = Tetralogy of Fallot, CoA = Coarctation of aorta, AS = Aortic stenosis.*

The *ventricular septal defect (VSD)* is the most common detected congenital heart defect accounting up to 30% of all congenital heart diseases (Brown and Fulton, 2011). The incidence of the VSD among the pathological murmurs in outpatient clinical referral may be as high as 40% (Amaral and Granzotti 1999). A hole in the ventricular septum causes a whole systolic jet flow from the high pressure left ventricle to the low pressure right ventricle. The intensity of the jet and the murmur is proportional both to the pressure gradient over the defect and the size of the hole. Typically the systolic murmur of the VSD begins early after the end of S1 and continues the whole systole. The shape of the intensity follows the shape of the pressure gradient between the ventricles. The highest frequency components may rise up to 700-800 Hz and the quality of the murmur is harsh. Small muscular or membraneous VSD might close before the end of the systole giving only an early systolic murmur. VSDs are typically identified from the normal murmurs by their longer duration and harsh quality.

Table 2.5. Characteristics of the systolic murmur caused by VSD.

Character	**Description**
Location	Pulmonary and tricuspidal area
Intensity	1-6/6, typically 3-5/6
Pitch	Mid to high frequency
Timing and shape	Early or holosystolic (Fig. 2b or 2c)
Quality	Harsh, noisy
Other	

Pulmonary stenosis (PS) accounts about 10 % of all detected congenital heart defects (Brown and Fulton 2011). In pulmonary stenosis the pulmonary valve is unable to open completely restricting the blood flow properly from the right ventricle to the pulmonary artery, increasing the flow velocity across the valve and causing vibrations of the surrounding structures. The stenosis is most commonly at valvular level, but it can also occur in the right ventricle or in the pulmonary arteries. The systolic murmur is ejection type and due to the high turbulence the sound quality is harsh. The frequency contents and the intensity are related to the velocity contents of the turbulence. Typically the murmur is holosystolic and may

continue to diastole. Ejection sound may be present. The delayed ejection causes the murmur peak later in systole than in normal murmurs and may also result late pulmonary valve closure and splitting of S2. In mild cases the murmur may be soft (grade 1-3), low frequency and early systolic making it difficult to distinguish from normal murmur.

Table 2.6. Characteristics of the murmur caused by PS.

Character	**Description**
Location	Pulmonary area
Intensity	1-6/6
Pitch	Mid to high
Timing and shape	Early, holo- or late systolic (Fig 2b, 2c, or 2d)
Quality	Harsh, noisy
Other	May contain ejection sound or widely splitted S2

Tetralogy of Fallot (ToF) is a congenital heart disease which involves four related defects: ventricular septal defect (VSD), valvular or sub-valvular pulmonary stenosis (PS), overriding aorta, and right ventricular hypertrophy. It is the most common cyanotic heart defect accounting for 10% of all congenital heart diseases (Brown and Fulton 2011). In mild acyanotic cases, where the blood flows from the left ventricle to the right side, the auscultation findings resembles the findings in PS or VSD. The pulmonary component of S2 may occur late due to increased blood volume on the right side and S2 is widely splitted. A systolic ejection murmur is often heard. In mild cases it is harsh in quality and continues over the whole systolic period. With increasing the severity of the PS the murmur becomes shorter. Due to cyanosis moderate and severe cases are easily detected during the first days after birth. Mild acyanotic cases are usually found due their harsh, loud and holosystolic murmur.

Table 2.7. Characteristics of the murmur caused by ToF.

Character	Description
Location	Pulmonary or tricuspidal area
Intensity	1-6/6
Pitch	Mid to high
Timing or shape	Early, late or holosystolic (Fig. 2b, 2c, and 2d)
Quality	Harsh, noisy
Other	Similar to PS or VSD

The ductus arteriosus usually closes during the first days of living. In *patent ductus arteriosus (PDA)* it remains open connecting the left pulmonary artery and the aortic arch enabling a continuous flow from the system to the pulmonary circulation and causing a continuous harsh, machinery like, murmur heard best on the upper left sternal border (pulmonary area) and clavicular area (Walsh et al. 2011). Sometimes it is difficult to differentiate from the venous hum which also is continuous in character and heard in the same area. However, the intensity differences during the systole and diastole can be used to differentiate these two murmurs from each other. In PDA the flow is highest toward the end of the systole and in venous hum during the diastole. Due to its continuous timing PDA is very seldom confused with normal systolic murmur.

Table 2.8. Characteristics of the murmur caused by PDA.

Character	Description
Location	Pulmonary or clavicular area
Intensity	1-6/6
Pitch	Mid to high
Timing and shape	Continuous (Fig. 2f)
	Intensity highest at the end of systole
Quality	Harsh, machinery like
Other	May be confused with venous hum

In the *atrial septal defect (ASD)* an opening or hole between the right and left atrium causes blood flow from the high pressure left side to the low pressure right side increasing the pressure and work load to the right side structures of the heart (Brown and Fulton 2011). Majority of children with

ASD are asymptomatic as the heart is usually capable to compensate the changed blood flow. The defect seldom generates audible sound but the increased stroke volume on the right side might cause a mild ejection murmur in the pulmonary area. ASD is recognised in auscultation from widely and fixed split of S2 which is caused by the increased volume and the delayed right side systole ending. ASDs make up 6% of all detected heart abnormalities (Brown and Fulton 2011).

Table 2.9. Characteristics of the murmur caused by ASD.

Character	**Description**
Location (best heard)	Pulmonary area
Intensity (grade)	1-2/6, sometimes 3/6
Pitch	Low to mid
Type	Systolic ejection (Fig. 2a and 2b)
Quality	Harsh
Other	Constantly and widely splitted S2

In *aortic stenosis (AS)* the aortic valve opens only partially shrinking the outflow area and thus increasing the flow velocity. The stenosis may also be sub- or supra-valvular (Brown and Fulton 2011). The restricted outflow tract together with the increased flow velocity develops turbulence that in the interaction with membranous walls cause audible vibrations. The prevalence of AS is about 7% of the all children with congenital heart disease. The majority of the children with AS are discovered because of a systolic murmur leads to the referral to paediatric cardiology. The shape of the AS murmur is ejection type following the shape of the flow velocities as in the PS. The higher the velocities the higher the frequency contents of the murmur. As the aortic valve locates in the center of the heart base the vibrations are transmitted in wide area in precordium. The murmur can be heard in the aortic area, it can be spread through pulmonary artery to the pulmonary area or it can be transmitted through ventricles to the apex of the heart. A soft low-to-mid frequency murmur with early systolic timing of a mild AS may be heard only in the pulmonary area and it could be easily confused with normal murmur. Usually either duration or quality differentiates the murmur caused by AS from the normal heart murmurs. In

addition, a stiffened aortic valve may cause a systolic opening click, sometimes loud, which characterises valvular AS.

Table 2.10. Characteristics of the murmur caused by AS.

Character	Description
Location	Aortic area, radiates to all auscultation areas
Intensity	1-6/6
Pitch	Mid to high
Type	Systolic ejection (Fig. 2a and 2d)
Quality	Harsh, noisy
Other	May include ejection sound (systolic opening click)

Bicuspid aortic valve has only two leaflets instead of the normal 3. It usually develops before the birth but may also be caused if two normal leaflets are joined together as a result of a disease, like rheumatic fever. The incidence of the bicuspid aortic valve is about 2% in the general population making it most common congenital heart defect (Brown and Fulton 2011). As generally patients with uncomplicated bicuspid valve have no noticeable effect on the heart during the first years it may left undiagnosed. The bicuspid valve leaflets may thicken interfering the normal movement of the valve and causing a stenosis. It is usually diagnosed by a heart murmur associated to aortic stenosis. The most common finding in bicuspid aortic valve is a systolic ejection sound heard best at the apex. It's timing is rather constant, not affected by the breathing phase neither from any physical maneuvers. An associated mild valvular stenosis may produce a soft ejection murmur heard best on pulmonary area (Bayne 2009).

Table 2.11. Characteristics of the bicuspid aortic valve murmur.

Character	Description
Location	Mitral area (apex)
Intensity	1-3/6
Pitch	Mid to high
Type	Systolic ejection (Fig 2a and 2d)
Quality	Harsh, noisy
Other	Commonly associated to AS

Coarctation of aorta (CoA) is a narrowing of the aorta most commonly located at the beginning of the ascending aorta (Brown and Fulton 2011). It is a relatively common defect and usually (in 25 % of the cases) associated with a bicuspid aortic valve. A severe coarctations are recognised during the first days of life but a mild or slowly progressive coarctation may be missed for several years. The common findings for older child are hypertension in arms, diminished pulse on lower limbs and a systolic ejection murmur. When the narrowing has been less severe, the left ventricle may have been hypertrophied in order work against the higher work load. Coarctation of the aorta causes turbulence later in the systole due it's location later in the blood's pathway. The murmur associated to aortic coarctation is harsh and late systolic or continuous.

Table 2.12. Characteristics of CoA murmur.

Character	**Description**
Location	Back
Intensity	1-5/6
Pitch	Mid to high frequency
Type	Late systolic or continuous (Fig 2c and 2d)
Quality	Harsh, noisy
Other	Usually associated with bicuspid aortic valve

Mitral valve defects are usually a combination of *mitral insufficiency (MI)* and *mitral stenosis (MS)*. Mitral valve defects, like all other valvular defects, usually develop gradually making them more common among older children and young adults (Walch et al. 2011). The incidence of mitral insufficiency is about 5 % in normal population under 20 years. A mild MI is often detected with echocardiograpy in normal individuals. In MI the mitral valve leaks allowing the blood flow back to the left atrium causing a holosystolic high-frequency murmur. The murmur typically increases in intensity towards the end of the systole. If a midsystolic click is present it may indicate prolapse of the valve leaflets. Mitral stenosis causes a low-frequency diastolic murmur.

Table 2.13. Characteristics of the murmurs of mitral valve defects.

Character	Description
Location (best heard)	Back
Intensity (grade)	1-5/6
Pitch	High
Type	Holosystolic (Fig. 2d)
Quality	Harsh
Other	May have midsystolic clicks
	May have diastolic murmurs

In *hypertrophic cardiomyopathy (HCM)* the heart muscle cells increase in size resulting hypertrophied thickened myocardium often due inherited or congenital reasons. Commonly it affects the interventricular septum and 25 % of the cases have left ventricular outflow tract obstruction (*Hypertrophic obstructive cardiomyopathy (HOCM)*). Patients with HCM are often asymptomatic. It is best known for the predominant cause of the sudden deaths in young athletes (Maron 2001). The LVOT obstruction causes a systolic ejection murmur similar to innocent murmurs and heard best on the left sternal edge which may be confused with normal systolic murmur (Danford and McNamara 1990). Standing and Valsava maneuver increase the intensity of the murmur and squatting decreases which may be used to differentiate it from the normal murmurs.

Table 2.14. Characteristics of HCM and HCOM murmurs.

Character	Description
Location	Mitral area
	(pulmonary and tricuspid)
Intensity	1-4/6
Pitch	Mid to high
Type	Systolic ejection (Fig. 2a)
Quality	Harsh or vibratory
Other	Standing or Valsauva maneuver accentuate, squatting decreases the intensity

2.6 Evaluation of a paediatric patient with a heart murmur

Clinical examination through cardiac auscultation is the first and most commonly used method in the evaluation of paediatric patients with suspected heart disease (Bonow et al. 2006). With an experienced cardiologist, it is a cost-effective test for screening for heart murmurs in children. In many cases a heart murmur may be the only definite sign of organic heart disease, appearing long before any other symptoms are present (Rushmer 1970). Dynamic cardiac auscultation may give more insights into the origin and significance of the heart murmur (Bonow et al. 2006). Exercise and physical manoeuvres, positional changes and respiration phase alter the intensity of the murmur in specific cases. ECG and chest X-rays may be used to exclude abnormalities, such as ventricular hypertrophy. However, their use for testing asymptomatic paedatric patients with a soft mid-systolic murmur is not recommended (Bonow et al. 2006).

Echocardiography provides the most specific information about the significance of a heart murmur (Walsh et al. 2011). According to guidelines of the AHA, its use is *"recommended for all asympomatic patients with diastolic murmurs, continuous murmurs, holosystolic murmurs, late systolic murmurs, murmurs associated with ejection clicks (early systolic), murmurs that radiate to the neck, midpeaking murmur having grade 3 or louder, or any clinical evidence of structural heart disease."* However, its use is *"not recommended for patients having a grade 2 or softer midsystolic murmur identified as innocent or functional by an experienced observer"* (Bonow et al. 2006). Figure 2.5 summarises the strategy used for evaluating heart murmurs in paediatric patients.

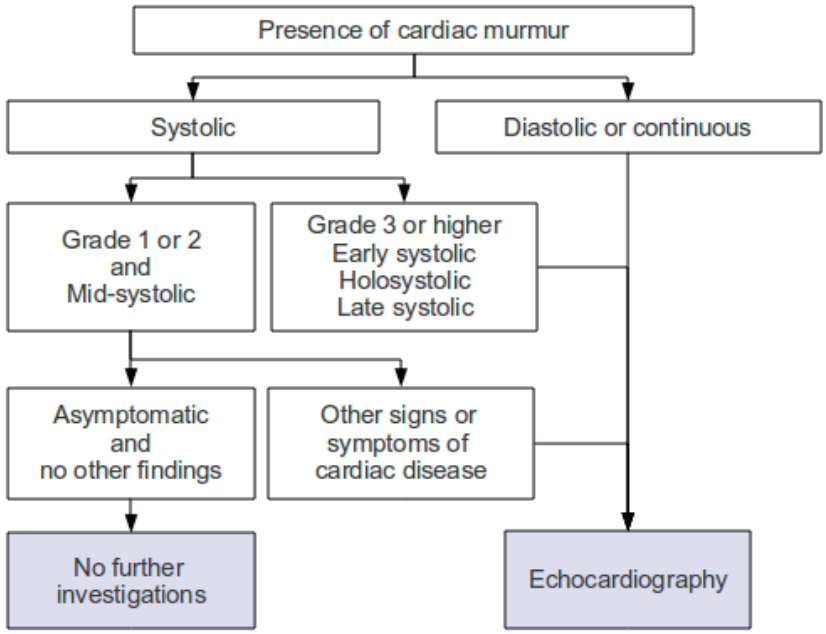

Figure 2.5. *Strategy for evaluating heart murmurs in peadiatric patients (Bonow et al. 2006; Walsh et al. 2011).*

2.7 Summary

A normal healthy heart produces sounds and murmurs. The loudest normal heart sounds, S1 and S2 are usually easily recognised, but normal systolic murmurs are often confused with their abnormal counterparts. In screening children for heart murmurs, it is essential to understand what the normal heart sound events are and how they differ from abnormal findings. The location, timing, intensity, pitch and quality of the murmur can be used to evaluate the significance of the auscultatory finding.

3 Literature review

3.1 History of phonocardiography device development

The history of phonocardiography can be traced back to the invention of telephone that opened the area to electric sound transmission (see Table 3.1). The first attempts to amplify heart and lung sounds were made as early as 1878 by Richardson and Hughes, the inventors of carbon granule microphone (Rappaport and Sprague 1941). The first graphical recordings of heart sounds were made in 1893 by Huertle. His apparatus consisted of a microphone connected to an inductor transformer. A frog's nerve muscle preparation worked as an actuator part drawing a line on a smoked drum. The first practical phonocardiographic device was introduced by Einthoven in 1894. By his invention of string galvanometer in 1901, this new apparatus became the basis for the electro-phonocardiographic devices for several decades and phonocardiographic studies became favored over the use of stethoscope in documentation of cardiovascular sounds.

Several improvements to the galvanometric recorder and other means to record heart sounds were made (Rappaport and Sprague 1941). Otto Frank, in 1904, recorded phonocardiograms directly using a special optical amplification, and Carl J. Wiggers modified and improved the device later on. Another popular method was to connect acoustical vibrations directly to a membrane that moved an optical device and the trace of vibrations was filmed as in the galvanometric devices. In 1921 H.B. Williams amplified heart sounds by means of four-stage audion tube amplifier and used an electromagnetic telephone receiver as a loudspeaker. The Western Electric

Stethophone, one of the very first commercial electrical stethoscopes, worked in similar manner.

Table 3.1. Landmarks in the history of phonocardiography

Year	Landmark/Innovation	Reference author(s)
1876	Telephone	Bell
1878	Carbon microphone	Richardson and Hughes
1893	Graphical recordings of heart sounds	Huertle
1901	String galvanometer	Einthoven
1921	Use of electronic amplifier	Williams
1941	Principles of amplifying stethoscope	Spraque and Rappaport
1949	High definition phonocardiography	Leatham et al.
1954	Spectral phonocardiography	McKusick et al.
1955	Standarisation of PCG	Manneheimer et al.
1957	Echocardiography	Edler and Gustafsson
1965	Fast Fourier Transformation (FFT)	Cooley and Tukey
1968	Echo and PCG correlations	Zaky et al.
1976	FFT analysis in PCG	Yoganathan et. al
1979	Microcomputer based PCG analysis	Durand et al.
1982	Digital signal processing in PCG	Durand et al.
1994	Modern handheld devices	Tavel
2001	New interpretation algorithms	Thompson et al.
2008	Computer assisted auscultation	Watrous et al.

Rappaport and Sprague, in 1941, summarised the characteristics of human ear in auscultation. Based on a long series of experiments they described the scientific principles of operation of acoustic stethoscope. That laid down a firm ground for the modern acoustical stethoscopes and ended a period of variations. In addition, they specified the general requirements that should be taken into consideration when designing amplifying stethoscopes and heart sound recording mechanisms, still valid nowadays.

Leatham et al. in 1949, constructed a high definition phonocardiographic recorder consisting of two Cambridge strings and two mirror galvanometer capable of recording several channels simultaneously (Leatham 1949). This apparatus was used for two decades to study and explain timings and mechanisms of the heart sound and murmur production (Leatham 1970).

In 1955 McKusik et al. applied the sound spectrography, originally introduced by the Bell Laboratories, to phonocardiography. The sound was first recorded on a magnetic tape. A segment of sound was selected, replayed and recorded to a magnetic disk and then replayed repeatedly through a tunable narrow bandpass filter. The intensity of band-passed signal was plotted on a paper which was rolled over a revolving drum connected to the magnetic disk. As the disk and the drum rolled the tunable mechanism scanned over a selected frequency range and as a result three parameters of sound - the timing, intensity and frequency spectrum - were presented in relation to each other. The quality (pitch, timbre, frequency content) of sounds and murmurs could be first time studied in detail.

In 1940's and 1950's a wide variety of phonocardiographic instruments were introduced (Mannheimer 1941; Sprague and Rappaport 1941; Leatham et al. 1949; Maass and Weber 1952; Luisada and Zalter 1959) and the dependence of results on instruments was recognised. Committees for standardisation of the microphones, filters, calibration and nomenclature were founded and the activity continued until the 1970's (Kleyn et al. 1955; Mannheimer 1957; Bekkering and Weber 1957; Groom 1970).

Although the first echocardiographic device was introduced as early as 1957 by Edler and Hertz, it's wider use for cardiac research started in late 1960's (Zaky et al. 1968). Echocardiography was first used in parallel with other examination methods, like to study the correlation of heart sound components with the closure of heart valves (Craige 1976), but soon it became the major method for cardiac examination.

The rapid development of microelectronics in 1970's opened up a new digital world. The early pioneers adapted digital computers for phonocardiographic analysis (Frome and Frederickson 1974; Litwin and Begon 1974). Fast Fourier Transformation (FFT) was used to analyse the spectral properties of the first and the second heart sound (Yoganathan et al. 1976). Digital signal processing techniques and intracardiac phonocardiography were applied for studying the acoustic transmission properties of human heart-thorax system (Durand and Pibarot 1995). A microcomputer based system for the segmentation and characterisation of phonocardiograms was developed (Lehner and Rangayyan 1987).

A new wave of electronic devices appeared in the cardiac auscultation field 1990s. Low-cost microelectronics and display components inspired

clinical and biomedical researchers and engineers to develop small hand-held devices (Bredesen and Schmerler 1991; Tavel, Brown and Schandler 1994).

2000's has been the renaissance of phonocardiography. New digital signal processing techniques were applied for developing cardiac auscultation and interpretation algorithms (Thompson et al. 2001; DeGroff et al. 2001; Kim and Tavel 2003; Voss, Mix and Hubner 2005). Increasing pressure for cost-effective patient evaluation and diagnostic decision making in the health care has opened a need for computer assisted auscultation (Watrous 2006). The better sound quality, recording and play back capabilities, visual display, and full analysis features can be implemented portably and inexpensively (Tavel 2006). As Watrous al. (2008) concluded the computer assisted auscultation together with graphical representation, quantification and archiving of auscultation findings provides increased objectivity; could increase the sensitivity and specificity; and reduce uncertainty in the screening and care of patients with heart murmurs.

3.2 Heart sound transducers

Several types of sound, pressure and vibration transducers have been employed for phonocardiographic studies. The microphone was introduced with the earliest telephone systems in the 1870s (Eargle 2006). The earliest systems did not employ electrical amplification and thus the design criteria for the microphone was produce maximum power output. Two such older microphone designs were the carbon and crystal microphone. Both were relatively simple and robust and could produce high electrical output to drive directly the galvanometer, but had very poor sensitivity and sound quality.

Piezoelectric crystal microphones replaced the other types of microphones. Regardless of the notable improvements in sound detection, reproduction, and amplifying techniques the sound quality of electrical auscultation devices was poor and the ordinary acoustical stethoscopes were favored for auscultation purposes. When electrical amplification became an integral part of audio signal transmission, the microphones could be engineered for higher quality rather than for a maximum power

output (Eargle 2006). The microphone design shifted to capacitor (condenser) and dynamic types providing wider frequency bandwidth and lower self-noise level. A typical high quality condenser microphone design, developed first in 1950s, consisted of a metal housing inside which an electrical insulator with a back-plate is mounted behind a delicate and highly tensioned diaphragm (Microphone handbook, Bruel&Kjaer, 1996). The condenser type microphone required constant charge between the diaphragm and the backplate. Typically the constant charge was applied from an external voltage source or may be applied from permanently charged polymer known as electret. This newer pre-polarisation principle became widely used, specially in microphones used with battery operated hand-held instruments, due to its small size and lower voltage requirements.

Korhonen developed a sound transducer for an electronic stethoscope (Korhonen 1996). Based on the stethoscope studies an air-coupled sound transducer with an electret microphone was selected for further development. For damping the external noises the transducer's cup was made from heavy brass material. A silicon rubber ring was placed between the cup and skin. He concluded that electret microphone, although not optimal in self-noise level, have advantages in small size, good sensitivity and low operational voltage. He continued that the microphone should be placed inside or very close to the chest-piece in order to achieve flat frequency response. The use of tubes should be avoided due to acoustical resonances. Some degree improvement in environmental and handling noise cancellation was achieved by proper material selection of the stethoscope structures.

Another approach was to use contact microphones where the mechanical vibrations of the chest wall were directly sensed either with piezoelectric materials, capacitively or electromagnetically. Blashkin and Yakolev (1975) introduced transducer where a plug touching the skin was rigidly coupled to an elastic membrane and coil, and the movement of the coil produced an electromotive force proportional to the speed of movement. Van Vollenhoven et al. (1968) studied both heavy weight (about 1 kg) seismic type and low weight (40 g) accelerometric type piezoelectric contact microphones. Contact microphones having a large mechanical impedance (high weight) made them relatively insensitive to sound borne noise,

whereas microphones with small mechanical impedance were more sensitive to ambient noise and will therefore require greater precautions for obtaining good phonocardiograms. Van Vollehoven and Wallenburg (1970) measured and modeled the mechanical impedance of chest wall and compared several methods to calibrate air and contact microphones. They described an easy and clinically useful method for checking contact microphones. The frequency response of all types of contact microphones could be compared (van Vollenhoven 1971). Ikegaya, Suzumura and Funada (1971) suggested that similar calibration methods than for ordinary sound pressure microphones should be used for calibration of contact type phonocardiographic microphones. Pasterkamp et al. (1993) evaluated the relative performance of commonly used air-coupled electret microphones and contact type accelerometers for measurements of respiratory sounds in situ. Cozic, Durand and Guardo (1998) developed a 22-channel cardiac acoustic mapping system based on air-coupled microphones and demonstrated how the heart sounds spread and radiate over the thorax.

The most recent electronic stethoscopes have sensors specially designed for sensing the body (Ahlstrom 2006). Smith introduced a capacitive sensor (Smith 2002), whereby a stethoscope diaphragm forms one plate of the capacitor. The capacitive sensor has been employed in a commercially available digital electronic stethoscope (ds32a digital electronic stethoscope, Thinklabs Medical LLC, Centennial, CO, US, 2011). Orten invented a sensor where piezoelectric foils were able to deliver electrical signals due to deformations and movements of the foils (Orten 2003). Orten's invention has been applied in Welch-Allyn's Elite electronic stethoscopes (Skaneateles Falls, NY, U.S, 2011). On contrary, 3M relies on more conventional technique using miniaturised microphone disclosed in a stethoscope chestpiece (Dieken 1999; 3M Littmann Electronic Stethoscope Model 3100, St. Paul, Minnesota, U.S., 2011).

3.3 Stethoscope properties

As early as in 1924, Frederik and Dodge recognised the peculiar behaviour of acoustic stethoscope and recommended to place the microphone in direct contact with the patient avoid the resonant peaks of the tubes. First

considerations to specify the amplifying stethoscope were made by Rappaport and Sprague in 1941. In their extensive work they summarised the properties of acoustic stethoscope and listed the generic characteristics that any amplifying stethoscope or phonocardiographic device should have. Their considerations are still valid and should be the basis for further improvements of cardiac auscultation devices.

Dunn and Rahm, in 1953, discussed the problems of calibration in heart sound recordings and the difficulties that have delayed the development of the heart sound recording field. Contrast to electrocardiogram, the phonocardiography was not widely accepted and there was no calibrated physical units nor standardised instrumentation. The variations in stethoscope properties, like the length, material or inner diameter of the tubes; the diameter of the chestpiece; the material of the diaphragm; and the size and number of additional vents, made the situation even worse.
Aim for standardisation of the phonocardiographic device was urgent in 1950's. The frequency spectrum sensitivity, the slope of the filtering systems and characteristics were tried to specified (Mannheimer 1957). The frequency range from 15 to 800 Hz was mentioned and specially the lower frequencies below 15 Hz should be eliminated. The necessity to amplify and filter the phonocardiographic signal before recording was considered. The speed of film was standardised to 5 or 10 cm/s. The possibility of recording several tracings was considered.

Abella, Formolo and Penney, in 1992, studied six popular stethoscope and compared their acoustic properties. They summarised that bells and diaphragms had different transmission characteristics at the low frequencies (below 120 Hz). The bells typically amplified the sounds as the diaphragms attenuated at the low-frequencies. There were no remarkable differences between the stethoscopes.

Korhonen et al. (1996) studied the frequency responses of commercially available acoustical stethoscopes. They concluded that the tubing affected most significantly to the frequency response. An acoustically poor stethoscope's diaphragm attenuated the sounds in all frequencies whereas a good diaphragm attenuated only the low frequencies. In his Master Thesis on the design of a sound transducer for an electronic stethoscope Korhonen (1996) continued that the response of the diaphragm correlated best with the suspected quality of the acoustic stethoscope. The responses

of the cup sides of the chest-pieces were almost identical among stethoscopes differing lightly in resonance peaks due to different shape and total volume of the air tubes.

Grenier et al. compared three acoustical and three electronic stethoscopes clinically (Grenier 1998). They considered that a new electronic stethoscope taking advantage both acoustical and electronics stethoscopes could be designed.

3.4 Electronic stethoscopes

The first electroacoustic devices for improving auscultation were introduced at the beginning of the 20th century (Rappaport and Sprague 1941). Although the sound was amplified, the poor and altered sound quality made these instruments useless. The main working principle was similar to those days telephone systems consisting of a carbon-granule microphone and a telephone receiver coupled with a simple electronic circuit. Rappaport and Sprague (1941) improved the apparatus by applying a more sensitive crystal microphone for receiving the sound signals, replacing the ordinary telephone receiver with an audiophone - binaurals of ordinary stethoscope assembled with a case and an electromagnetic phone - and using a high-quality two channel amplifier for combined phonocardiographic and electrocardiographic recordings. The whole system was still expensive, fragile, and cumbersome to use. However, despite the limitations, the authors made an important conclusion on the use of the amplifying stethoscope:

"The major advantage of the amplifying stethoscope over the acoustic one is that the intensity can be adjusted as desired, and thus a number of modifying characteristics which cannot be overcome with the acoustic stethoscope are eliminated."

Various portable electrical amplifying stethoscopes were introduced when the semiconductors and the silicon transistors came to mass production in 1950's (Rogers 1964; Chelikowksi 2004). In general, these were still not satisfactory in practice because the cost was high and the electrical components produced distortion in sound quality. An examples of early electrical stethoscope was the Maico Stethetron that included a battery and

an electronic amplifier. It weighted only 170 grams. Another example was a teaching and consultation portable electronic stethoscope manufactured by Amplivox, Ltd, England. It enabled several listeners to monitor a patient's heart beat at same time (Rogers 1964).

Abelson in 1971 wondered while the electronic stethoscopes still had a distortion and high background noise, the heart sound amplifiers incorporated in laboratory instruments generally had excellent characteristics and contained elaborate filter systems. He removed one of these amplifiers from a multichannel recorder and adapted it for bedside and office use. Philip and Raemer (1986) constructed a prototype of an electronic monitoring stethoscope from readily available, high-quality components. Twenty-one anesthesia clinicians evaluated the stethoscope and judged it to perform better than the conventional stethoscope. The electronic device was perceived to be louder, clearer in sound reproduction, more efficacious for monitoring, and easier to use continuously, and its head-phones were considered more comfortable than the conventional earpieces.

One branch of development, which didn't evolved further, was the combined acoustic-electronic stethoscope. Pfeiffer (1978) patented a combination of acoustic and electronic stethoscope which resembled a normal stethoscope and could be operated with one hand. Similarly, Phillips, Epstein and Tweed (1991) disclosed in their patent application a stethoscope, operable both in an acoustic or electronic mode.

A new wave of electronic stethoscopes appeared in the market in 1990s. The low-cost microelectronics and display components inspired the clinical and biomedical researchers and engineers to develop small hand-held devices. Tavel, Brown and Shander (1994) provided a new portable system having a small display for graphic presentations and printing of heart sounds. Bredesen and Schmerler (1991) patented an intelligent stethoscope for automatic diagnosing abnormalities by comparing sound signals to reference templates. Granzotto and Voegeli (2004) included a display and electrocardiographic sensors into the stethoscope chestpiece.

Belmont and Mattioli (2003) studied how a narrow-band analog signal telephonic line could be used to transmit the heart sounds remotely and how accurately the remote listener could detect heart disease. Their system consisted of an adult-size chest-piece of an acoustic stethoscope with tubing

terminating to microphone and a transmitter/receiver box. The analog signal was modulated and carried through an ordinary telephone line and demodulated in the receiver end. Even in this case the remote screening was accurate enough. Woywodt et al. (2004) linked an electronic stethoscope to a laptop computer and created a software to visualise the auscultatory findings. Hoyte, Jensen and Gjesdal (2005) studied how the electronic stethoscope compared to traditional acoustic stethoscope affected the cardiac auscultation skills of undergraduate medical students. They concluded that the electronic stethoscope alone didn't improve the performance.

Tavel (2006) listed 5 electronic stethoscopes where the limitations of the precessors were overcame. He listed the five main features that should be incorporated into the electronic auscultation devices:

1) The sound quality should be at least as good as in acoustical stethoscopes;
2) The visual display should include cursors synchronised with playback. The spectrogram would provide optional information for complementing echocardiographic examinations;
3) Playback with full or half speed would provide more detailed information when the heart rate is high;
4) Database for reference; and
5) Storage and transmission to distant sites may avoid traveling expenses and further consultations and provide accurate screening faster.

Lastly he concluded that these means should be taken into teaching of the cardiac auscultation - that still, in his opinion, remains an important role in clinical medicine. Soltani (2009 modified a personal digital assistant (PDA) into a versatile electronic stethoscope for fetal monitoring.

The most recent electronic stethoscopes apply sensors specially designed to suit cardiac sounds (Smith 2002) (Orten 2003) whereas some still relies on more conventional technique using miniaturised air-coupled microphone disclosed in a stethoscope chestpiece (Dieken 1999). In addition, they can make the heart and lung sounds more clearly audible using different filters and amplifiers (Dieken, Dufresne, and Hulse 2000) or reduce the ambient noise level. The latest innovations also allow storage and the possibility to connect the stethoscope to a computer for further

analysis of the recorded sounds (Lukkarinen 1996; Ahlstrom 2006; 3M Littmann Electronic Stethoscope Model 3100, St. Paul, MN, U.S. 2011; ds32a Digital Electronic Stethoscope, Thinklabs medical LCC, Centennial, CO, U.S., 2011; Elite Electronic Stethoscope, Welch Allyn Inc, Skaneateles Falls, NY, U.S, 2011).

3.5 Phonocardiographic signal analysis

The earliest phonocardiographic systems recorded the heart sounds graphically on photographic paper or film. The same electrical pulsations which passed to the audiophone were applied to the moving-coil galvanometer and recorded photographically (Rappaport and Sprague 1941). Acoustic and electric filters were studied and used to in order to capture the wide range of frequencies and loudness and resemble the audible response of ordinary stethoscope (Leatham 1949). Rappaport and Sprague (1941) suggested three different filtering type - linear, stethoscopic, and logarithmic - with gradually increasing slope in attenuation for low frequencies. In linear phonocardiography the visual record of the heart sound vibrations were recorded without any modification, as they occured on the chest wall. As the heart sound vibrations consist mostly of the intense low frequency components, the linear phonocardiograph resembled a jugular venous pulse recordings. The stethoscopic phonocardiogram modified the sound as an average stethoscope would do as it is reached to human ear. These records showed the whole range of murmurs and heart sounds and was most useful for clinical purposes. The logarithmic phonocardiogram summed the additional modification of the average human ear. The amplitude corresponded to the loudness heard by the clinician and the low frequencies were extremely attenuated.

Mannheimer (1940) splitted the frequency range into many channels and took a record with suitable amplification for each. This was, however, considered too complicated for routine use (Leatham 1949). Cowen and Parnum (1949) replaced the acousto-mechanical filters used by Rappaport and Sprague with electrical ones. With combined electrocardiogram the timings of the events, like onset of the systolic murmurs could be analysed. Leatham (1949) used similar filters to Rappaport and Sprague but

explained the filtering properties in more technical terms (low, mid, and high frequency). Both systems - linear, stethoscopic, logarithmic vs. low, mid, high frequency - were commonly used.

The first spectrograms of the heart sounds were produced by McKusik et al (1955). They used a modified Bell Telephone laboratories' sound spectrography, where the sounds were first recorded on the magnetic tape and then the tape was repeatedly analysed with narrow band filter and the intensities plotted either on electrosensitive or photographic paper. They observed the correlation between the intensity and the frequencies of the sound events. They could also demonstrate how the spectral phonocardiogram displayed the quality of the sound and the higher frequency contents of murmurs more precisely than traditional phonocardiogram.

Rangayyan and Lehner (1988) reviewed the techniques used for the phonocardiogram signal analysis. They divided the main techniques into frequency domain analysis, time domain analysis and parametric modeling. They described that before the FFT based techniques the frequency contents was detected by bandbass filter banks, analog-digital circuitry and zero-crossing analysis.

The earliest trials of using artificial neural networks (ANN) in heart murmur classification was made by Barschdorff, Bothe, and Renghausen (1989). They compared classical pattern recognition to neural networks. Using 8 frequency related and 128 envelope intensity related features the neural network was capable to classify 90% of the cases. Guo et al. (1994) used ANN to classify bioprosthetic valvular sounds. DeGroff et al. (2001) demonstrated the applicability of the ANNs for screening heart murmurs in children and later applied the ANN-based classifier for larger data set of 241 recordings (Bhatikar, DeGroff and Mahajan 2005). They were able to achieve sensitivity of 83 % and specificity of 90 % in decision between innocent and pathological cases.

Durand and Pibarot (1995) in their review summarised most recent achievements in instrumentation and signal processing techniques of phonocardiography between the years 1984 and 1995. Applications of digital signal and spectral analysis techniques, like the fast Fourier transformation, short time Fourier transformation, parametric spectral analysis, time-frequency representations, spectrograms and acoustic

mapping gained more popularity with the march of personal computers and sophisticated algorithms and softwares. These techniques were applied in studies of genesis of heart sounds and murmurs, transmission characteristics of the heart-thorax system, to describe the time-frequency distributions of the components of the heart sounds, and spatial distribution and propagation of heart sounds and murmurs on the surface of the thorax.

Ritola and Lukkarinen (1996) compared time-frequency distributions in the heart sound analysis. They concluded that the reduced interference distributions (Choi-Williams Distribution (CWD) and Binomial Distribution (BD)) may provide more detailed view to study heart sounds than traditional Short-time Fourier Transform (STFT). The drawback is that they required extensively more calculations than STFT. The resolution of WD is most detailed but the additional cross-terms may cause problems in interpretation.

Sikiö (1999) developed a biosignal monitoring and analysis software. It was capable for both real-time monitoring and graphical analysis of heart sound signals. Kim and Tavel (2003) used and electronic stethoscope connected to a portable computer to analyse the time-frequency contents of the murmurs caused by aortic stenosis. The doppler echocardiographic peak pressure gradient correlated well with the duration of the murmur in a specific frequency level. Ahlström (2008) studied nonlinear and higher order statistical signal analysis tools suitable for phonocardiographic detection, prediction and extraction in order to improve the the diagnostic value of the phonocardiography.

Liang, Lukkarinen and Hartimo (1997, 1998) developed a heart sound segmentation algorithm that used only the heart sounds without any additional signals like ECG or respiratory phase signal. The segmentation was based on the envelogram calculated using averaged Shannon energy of the normalised signal (Liang 1999). Both physiological (normal) and pathological heart sounds recordings were investigated. The automatic identification algorithm found the S1 and S2 correctly in 93% of the cycles. The misinterpretations (missing 6% and incorrect 1%) were mostly caused by the large background noise, artefacts and high intensity murmurs. The segments of the heart sound (S1, systole, S2, diastole) can be relatively reliably detected without the use of any other triggering signal, like

electrocardiogram or phletysmogram. Specially in the diagnostically problematic cases, like innocent vibratory murmurs vs. mild pathological case, when the murmur is low in intensity and S1 and S2 clearly detectable, this segmentation algorithm might be a valuable tool for automatic or semi-automatic analysis of the heart sounds and murmurs in children. The segmentation algorithm is rather robust and implementable with small effort to run in normal personal or handheld computers. More accurate boundaries of the sound segments can be achieved using spectrographic analysis parallel with the traditional phonocardiographic signal analysis.

El-Segaier et al. (2005) developed a computational algorithm for detection and analysis of the heart sounds signals. 300 children with cardiac murmurs were recorded using a digital phonocardiographic system. The ECG signal intervals were used as reference for the heart sound detection. The maximum intensity, its average frequency, mean spectral power, the timing and the frequency of the maximum intensity peak, the highest frequency, and the frequency range were measured from the selected systolic period. They concluded that the detection of S1 and S2 based on ECG signal timing is possible with high success rate. The heart rate variations should be accounted specially in detection of S2. The heart rate has minimal effect on the timing of S1 relative to the R-signal of ECG.

3.6 Screening heart murmurs in children

Henikoff, Stevens and Perry (1968) reviewed activities in detection of heart disease in children in United States. Before the 1950's the screening was almost exclusively made by direct examination by physicians. The lack of experienced physicians initiated search for more efficient technique. ECG and X-ray were evaluated but they were found to be too insensitive for screening purposes. In mid 1950's a specialised tape-recording equipment was developed. The heart sounds and murmurs of almost 190,000 children were recorded by a technician and later interpreted by physicians. The low agreement between the physicians, fatique of the listener during evaluation, frequent equipment failures, variations in the quality of the recordings, logistical problems in re-evaluation of the patients, and high costs of the program reduced the efficiency of this technique. In mid 1960's a portable

analog-digital computer was applied for screening purposes. 23,000 children were scanned (Henikoff, Stevens and Perry 1968). The conclusion of all of these studies was that:

"for the purpose of obtaining a maximum yield of previously unknown heart disease with a minimum expenditure of physician time and public health care dollars, the analog-digital device screening technique is the best technique currently available."

With simple duration and amplitude based criterias Ninova, Dascalov, and Dimitrova (1978) could achieve sensitivity of 96.5% and specificity of 92.4% in mass screening heart disease in children. They tested their method in 2,583 children of which 345 were pathological. Newburger et al. (1983) prospectively examined the usefullness of the noninvasive tests in the initial evaluation of heart murmurs in children. They concluded that a qualified paediatric cardiologist can reliably evaluate heart murmurs without any diagnostic tests like electrocardiography, chest radiography, and M-mode echocardiography. Smythe et al. (1990) studied the necessity of the laboratory tests for initial evaluation of heart murmurs in children. They concluded that the echocardiography is unnecessary if an experienced paediatric cardiologist has made the clinical examination. The found a sensitivity and specifity for the clinical examination of 96% and 95 %.

McCrindle et al. (1996) determined the diagnostic accuracy of academic paediatric cardiologists to differentiate the pathological murmurs from normal. The clinical findings and diagnostic impressions were recorded before and after electrocardiogram and echocardiogram. The sensitivity and specificity of clinical evaluation was 92% and 94%. Only trivial or minor lesions were missed. Danford and McNamara (1995) reviewed the records of paediatric patients evaluated for heart murmurs. They concluded that it is more cost-effective to let the cardiologist evaluate the asymptomatic child with a heart murmur first than start with the echocardiographic study. In another study Danford et al. (2000) compared the accuracy of the expert clinical examination with and without electrocardiography and chest X-ray. They found out that the electrocardiography aids in detection of ASD and maybe helpful in diagnosing PS. The X-ray helps in detection of intermediate to large VSD. Otherwise electrocardiography and X-ray are of limited use for defect-specific diagnosis of cardiac murmurs in children. In addition, in more doubtful innocent murmurs ECG or X-ray did not

enhance diagnostic accuracy. In a prospective study of 903 outpatients Danford et al. (2002) they concluded that the paediatric cardiologists should have very low threshold for echocardiography when evaluating the heart murmurs.

Geggel (2004) determined the conditions leading to paediatric cardiology consultation. Totally 2071 consultations were performed in academic hospital during a year. Murmurs were the most included clinical concern (18.5%) of which most common were: a) patent ductus arteriosus - 68% of the cases in the neonatal intensive care unit, b) ventricular septal defect - 64% in the well-child nursery and c) innocent murmur 62% on medical ward.

Dahl et al. (2002) recorded heart murmurs in 400 children by a sensor based electronic stethoscope and studied how a remote cardiological assessment could screen the pathological cases. Four paediatric cardiologist studied the cases and categorised them in three classes: no murmur, innocent murmur, or pathological murmur. In average they used 2 minutes for each case with the sensitivity of 89.7% and specificity of 98.2%. They concluded that telemedical referral of patients with heart murmurs by cardiologist is safe screening method and saves time .

Finley et al. (2006) recorded 55 children emailed them to a computer for later assessment. Three cardiologists reviewed the recordings to assess the splitting of the second heart sound and whether the murmur was innocent or not. They concluded that digital heart murmur recordings examined remotely by cardiologist could avoid the expenses and stress of travel for some cases. This could be particularly useful for rural patients .

Germanakis et al. (2008) evaluated the performance of the paediatric cardiologist to blindly evaluate the digital phonocardiographic findings to identify heart disease and normal murmurs. 96% of moderate to severe heart diseases, 66% of trivial to mild heart disease, and 94% of normal cases were correctly identified.

The American College of Cardiology (ACC) and the American Heart Association (AHA) in their jointly produced guideline for the management of patients with valvular heart disease has summarised the recommendations for use of echocardiography (Bonow et al. 2006). It's use is recommended for asymptomatic patients with a) diastolic murmurs, b) continuous murmurs, c) holosystolic murmurs, d) late systolic murmurs, e)

murmurs associated with ejection clicks, f) murmurs radiating to the neck or back, g) or midpeaking systolic murmurs grading 3 or louder. In addition, echocardiography is recommended for patients having murmur if any other clinical evidence of structural heart disease points to that. However, echocardiography is not recommended for patients having a soft (grade 2 or less) midsystolic murmur which experienced observer has identified as innocent or functional.

3.7 Summary

Cardiac auscultation and phonocardiographic analysis have a long and rich history. Phonocardiographic devices have evolved hand in hand with the development of general technology. The technological obstacles to the detection, amplification, processing, storing and visualisation of heart sounds have been solved one by one. As Morton E. Tavel, clinician, researcher, author and teacher of internal medicine, has concluded (2006):

"The time has arrived for the medical profession to keep pace with the technological methods now available and to employ them in the practice and teaching of cardiac auscultation."

4 The phonocardiographic system

4.1 Introduction

The phonocardiographic system was developed between 1995 and 2000 in the Helsinki University of Technology (now Aalto University School of Science and Technology). The aim was to build a prototype of a system that could be used for heart sound database collection, clinical evaluation, and further technical system development.

4.2 Hardware

The basic system, which was used in clinical studies at the rural hospitals of Helsinki University, consisted of an electronic stethoscope connected to a personal computer (Figure 4.1; Publications II and III). The sound signals were digitised using a sound card integrated into the personal computer. The signals were monitored, recorded and analysed with software designed and customised for that purpose (Figure 4.2). The electronic stethoscope and sound card were replaced with a multichannel amplifier and a data acquisition card for the clinical research conducted in Lund University Hospital and the software was modified accordingly (Publication VII).

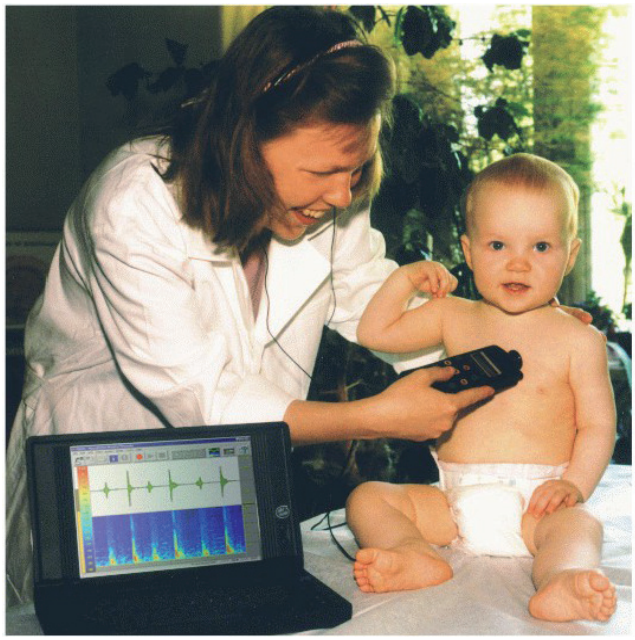

Figure 4.1. *The phonocardiographic system developed consisting of the electronic stethoscope with headphones connected to a multimedia laptop computer*

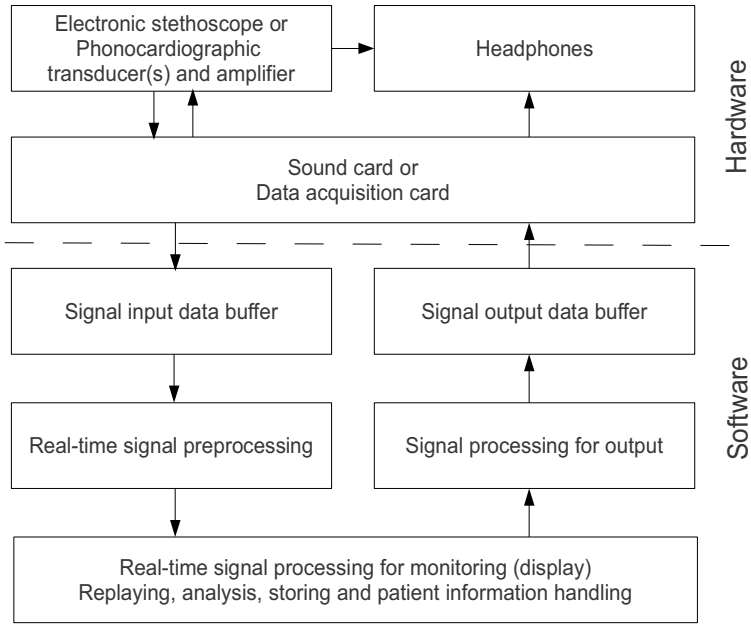

Figure 4.2. *Block diagram of the heart sound signal processing flow in the phonocardiograpic system showing the hardware/software interface (Adapted from Sikiö 1999).*

Based on the preliminary studies, an electret -type microphone enclosed in a bell-type chest piece was selected for the detection of the heart sounds (Figure 4.3; Korhonen 1996). Two bell-type chest pieces with different inner diameters were used. A chest piece with a diameter of 10 mm was used in Lund University Hospital (Publication VII)) and the one with a larger diameter of 21 mm was used in the Helsinki rural area (Publication VIII). The inner depth of both designs was 7 mm. The chest pieces together with the microphone capsule had a flat frequency response over the whole heart sound frequency range of interest: from 20 to 1,500 Hz. The selected microphone capsule had a sensitivity of 6 mV/Pa and a self-noise level of -58 dB (Publication II).

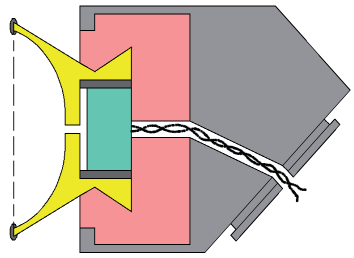

Figure 4.3. *Cross-sectional drawing of the chest piece used for heart sound detection in the electronic stethoscope design. A parabolic-shaped cup made of brass (yellow), inner diameter of 21 mm and inner depth of 7 mm is surrounded by soft elastic polyuretane foam (red). The electret microphone (green) is attached to the cup with silicon (dark grey). A small hole with a diameter of 2 mm conducts the sounds from the inner chamber of the cup to the microphone. The whole structure is covered in a hard plastic enclosure (grey). A narrow silicon ring (dark grey) on the edge of the cup seals contact with the skin (Adapted from Korhonen 1996).*

The detected sound signal was conducted to a pre-amplifier. In the electronic stethoscope using the chest piece with a larger diameter, a 20 dB pre-amplification was needed, whereas with the smaller chest-piece the gain was adjusted to 40 dB, due to its lower level of sensitivity (Publications II and VII). The pre-amplifier circuit contained first order RC-filters which decreased the frequency response to 6 dB/octave. The 3 dB corner frequencies were originally designed for a wider frequency range of 35 to 3,500 Hz but later restricted to a band from 40-75 to 1,500 Hz (Publications II, VII, VIII). Low voltage and low noise audio operational amplifiers were used for the electronic amplifier design (SSM2135, Analog Devices Inc., Norwood, MA, USA)(Publication III).

The standard sound card included in a multimedia personal laptop was used for the sampling and data acquisition (II). Typically the frequency response was flat from 20 to 20,000 Hz, the signal-to-noise ratio was 80 dB, the sampling resolution 16-bit, and the sampling range selectable from 5 to 44.1 kHz. For the multichannel recordings in Lund Hospital University, a multichannel data acquisition card was used (AT-MIO-16XE-10, National Instruments Corp., Austin, TX, USA, see Publication VII). The 16-bit sampling resolution and 11,025 Hz frequency were selected for all clinical recordings.

4.3 Software

Custom software was developed for monitoring, recording and analysing the phonocardiographic signals (Publications III and IV). The software was capable of several functions. Its major features were related to informative and fast visualisation during recording and post-recoding analysis of the heart sound signals. The software is documented in more detail in a related master's thesis (Sikiö 1999).

The main user interface was designed to support two basic operations: monitoring/recording and analysis. All signals were visually monitored on the display during simultaneous recording of and listening to the heart sounds. Similarly, during the analysis phase, a moving marker tracked the position in the replayed signal over the graphs. In analysis mode, the duration, timing, relative amplitude, and frequency of the sounds were manually measurable from the graphs and the user could add comments on specific time locations to highlight and mark findings of interest (Figure 4.4).

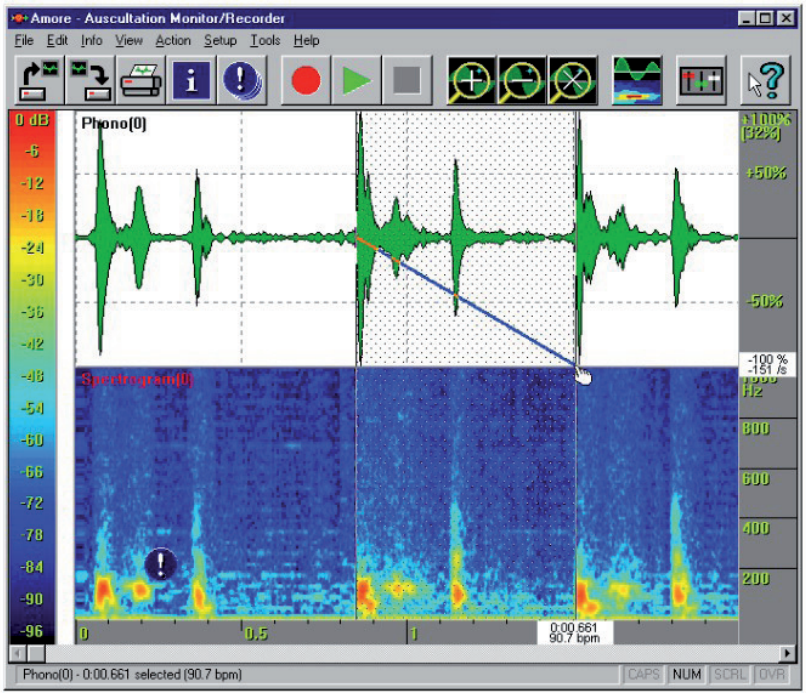

Figure 4.4. *User interface of the phonocardiographic monitoring/recording and analysis software. The upper frame shows the envelope of the amplitude of the sound signal and the lower frame the spectrographic view. The time scale is shown on the bottom and the relative intensity and frequency scales on the right. The colour bar on the left marks the intensities of the spectrogram in decibels. The mouse (finger symbol) is used to select an area (dotted) and measure either the intensity or frequency and the timing of sound events of interest (shown with white legends over the time and intensity/frequency scales). Comments on specific timings can be added to the recording (exclamation symbol on lower left corner of the spectrogram) (Sikiö 1999).*

All views could be altered for research purposes. The number of signals shown in multichannel analysis could be selected. The signal could be shown either as a standard amplitude presentation or as an envelope. A spectrographic view could be shown simultaneously with the amplitude presentation. For clinical use, a combined phono-spectrographic view was selected (Publications VII and VIII). The signals were digitally filtered using pass-band filtering in a frequency range from 75 to 1,000 Hz applying the 3rd order Butterworth -type high-pass and low-pass filters. The signals were automatically normalised. Short time Fast Fourier Transform (STFT) with Hanning windowing, 512 data samples (46 ms time resolution) and a

total of 1024 FFT points (10.7 Hz frequency resolution) were used for calculating the spectrogram.

In addition to the recorded signals, the document file contained the patient history and diagnostic information; comments; display settings; pre- and post-processing settings; filtering settings; and preferences. The document files created with the software could be opened with any application complying with the RIFF-standard (Kaball 2011). However, typically only the signal data block (WAV or WAVE-file) was supported by other software applications.

The documents were saved as separate document files and they could be organised in groups using ordinary document folders in the computer's hard disk. A simple database of the contents of each folder was maintained. Using the database dialog the old documents could be arranged, searched and reopened for reviewing and post analysis purposes.

The software was capable of filtering the signals with user-defined filters in real time during both monitoring and replaying of the sounds, within the limits of the computer's capabilities. Algorithms to design low-pass, high-pass, band-pass, and band-stop filters were implemented. In addition, the user had the possibility to provide custom filters by entering the filter coefficients manually (Sikiö 1999).

5 Setup and methods for clinical experiments

5.1 Introduction

Two independent heart sound databases were collected using the system developed. Between the years 1995 and 1999 an electronic stethoscope connected to a multimedia laptop computer was used to record heart sounds and murmurs from patients at outpatient paediatric cardiology clinics of the rural hospitals in the vicinity of Helsinki (Publications VI, VIII). Part of this first database was collected during a pilot study on videoconferencing (Publication V).

The second database consisted of 257 recordings from patients with a cardiac murmur referred to the outpatient paediatric cardiology clinic at Lund University Hospital. This database was collected between 1998 and 2001 (Publication VII).

5.2 Arrangement for videoconference experiment

In a pilot study on videoconferencing, physicians carried out remote consultations for 27 children and 3 adults who had a heart murmur (Publication V). The patients were selected and examined by a healthcare centre physician. A specialist in paediatric cardiology or internal medicine followed the examination in real time by videoconference. The electronic stethoscope developed for this study was used to detect the heart sounds

(Publication III). The stethoscope was connected to the videoconferencing system (Videra VCS roll-about, Videra Oy, Oulu, Finland) and the sound signals were coded and transmitted to the specialists using G.711, G.728 or G.722 voice over IP standard. The specialist listened, recorded and analysed the transmitted sounds using a multimedia laptop computer and the specifically developed monitoring and recording software (Publication IV).

The control patients were asked to visit an outpatient clinic where they were examined, their heart sounds were recorded for a second time, and the diagnosis was verified with ultrasonic examination by a paediatric cardiologist. The quality of the transmitted sound was subjectively estimated by comparing the recording of the transmitted sound to the bedside recording on each control case.

5.3 Experiment setup and methods for database 1

Auscultation findings from 807 children were digitally recorded by an experienced paediatric cardiologist in outpatient clinics of the Helsinki region rural hospitals using the phonocardiographic system developed (Publication VI and VIII). The paediatric cardiologist confirmed the diagnosis using echocardiography when necessary.

Table 5.1 summarises the diagnostic findings of this database. The database comprised 807 subjects, whose ages varied from newborn to 16 years. The recordings and diagnoses were made by an experienced paediatric cardiologist and confirmed with echocardiography when necessary.

Table 5.1. Heart sound recordings collected with the electronic stethoscope and multimedia laptop at outpatient paediatric cardiology clinics of the Helsinki region (Publication VIII)

Diagnosis	**Cases**	**%**
Vibratory murmur	310	38.4
Ejection murmur	107	13.3
Venous hum	26	3.2
Other innocent murmur	4	0.5
Ventricular septal defect (VSD)	87	10.8
Pulmonary stenosis (PS)	47	5.8
Aortic stenosis (AS) or coartation of aorta (CoA)	43	5.3
Mitral valve defect with (MI) or without leakage	29	3.6
Patent ductus arteriosus (PDA)	19	2.4
Atrial septal defect (ASD)	17	2.1
Other	30	3.7
No murmur (control)	88	10.9
Total	**807**	**100**

The timing, duration and frequency contents of each murmur were manually quantified from the phono-spectrograms. The characteristic phono-spectrographic features of the vibratory murmur were graphically compared to the murmurs of: mitral valve prolapse, small muscular and perimembranotic VSDs, right ventricular muscular band, aortic stenosis, and cardiorespiratory murmur.

The heart sound database collected at the outpatient paediatric cardiology clinics of the rural hospitals in the vicinity of Helsinki was examined in more detail (Publication VIII). Illustrative examples of the most common heart murmurs were selected to demonstrate their typical features and characteristic phono-spectrographic representations. A smaller set of 50 cases of innocent vibratory heart murmurs, 25 innocent ejection murmurs, and 50 mildly pathological systolic murmurs were selected for further analysis. The timing, duration and frequency features of the sound components for each of the three selected cardiac cycles were manually extracted from the graphical representation. Statistical analysis was used to find the most effective differentiators between the groups.

Recorded sounds were replayed and graphical presentations were simultaneously studied. Sounds were digitally filtered using band-bass filtering from 75 to 1,500 Hz. The digital filter was a combination of the 3rd order butterworth type high- and low-pass filters. phono-spectrographic presentation was showed (Figure 4.4). The upper part of the presentation showed the traditional phonocardiogram and the lower part the spectrogram. The amplitude scale was normalised to the maximum amplitude of the selected period. The spectrogram was calculated using STFT with Hanning window of 512 data samples (46 ms time resolution) and a total of 1024 of FFT points (10.7 Hz resolution).

The whole recording was first listened to carefully and a shorter period of three whole heart cycles was selected. The locations of S1 and S2 were identified from the graphical presentation. The time locations as well as the intensities of S1 and S2 were manually read from the scales. The intensity of the murmur was noted and compared to the average of the intensities of S1 and S2. The frequencies were read from the spectrogram.

The mean and standard deviation of the duration of the S1, S2, and systolic murmur, and the relative amplitude, as well as the low and high frequency limits were calculated for each of the smaller selected groups. Two-tailed heteroscedasticity t-tests for independent samples were used to find the most significant differences between the groups.

Based on the statistical analysis, the relative duration of the systolic murmur (SM%) and the occurrence of intensive high-frequency components on the murmur were used as criteria for testing the pathology of the murmur. The ROC curve was obtained by calculating the sensitivity and specificity for varying the selected criteria. The area under the curve was calculated for the ROC curves.

5.4 Experiment setup and methods for database 2

Cardiac sound signals from 257 children were recorded simultaneously with ECG and respiration phase signal in the outpatient paediatric cardiology clinic at Lund University Hospital between 1998 and 2001 (Table 5,2 Publication VII). The database consisted of recordings from patients with a cardiac murmur referred to the outpatient paediatric cardiology clinic at

Lund University Hospital. 69 (26.9%) of the cases were physiological murmurs and 188 (73.1%) with non-cyanotic cardiac pathologies. The age of the subjects varied from 1 month to 17 years, with a median age of 5.5 years.

The electrocardiogram (ECG) and respiration phase were recorded simultaneously with the phonocardiographic signal. In all cases the diagnosis was confirmed through echocardiography by an experienced paediatric cardiologist. The paediatric cardiologist examined the children and confirmed the diagnosis using echocardiography. Clinical data on the sex, weight, height and body mass index of the patient were collected and their heart volume was calculated from chest X-rays and adjusted to body surface area. The test population was divided into three groups – the group with significant cardiac pathologies, the group with mild cardiac pathologies, and children with a physiological murmur – according to the severity of the disease.

Table 5.2. Number of patients grouped according to diagnosis and the severity of cardiac pathology recorded at the outpatient paediatric cardiology clinic of Lund University Hospital (Publication VII)

Diagnosis	**Degree of severity**			
	Significant	**Mild**	**Total**	**%**
Physiological murmur	-	-	60	25.8
Semilunar valve stenosis				
AS	28	12	40	17.2
PS	8	3	11	4.7
Shunt lesions				
VSD	30	15	45	19.3
ASD	34	19	53	22.7
PDA	17	2	19	8.2
MI	5	-	5	2.1
Total	**122**	**51**	**233**	**100**

The heart sound signal was first band-pass filtered on a range of 40 to 1,500 Hz by an analog electric filter (a first order high-pass filter with cut-off frequency at 40 Hz, 6 db/octave and a second-order low-pass filter with cut-off frequency at 1,500 Hz, 12 dB/octave) and later by a digital fourth-

order Butterworth filter with cut-off frequencies at 40 Hz and 1,100 Hz for spectral analysis.

The timings of the S1 and S2 were visually determined from the simultaneous graphical presentation of the phonocardiographic and ECG signals. The time interval measurements were manually extracted from the graphical display (Figure 5.1). The interval from the ending of the S1 to the beginning of the systolic murmur (S1SM) and the splitting of S2 – the interval between the aortic and pulmonary valve closing sounds in S2 were measured over five cardiac cycles at the maximum of inspiration and expiration phases (Table 5.3). The difference between the longest splitting of S2 during inspiration and the shortest splitting of S2 during expiration was chosen for calculation of respiratory variation of the splitting of S2 (ΔS2).

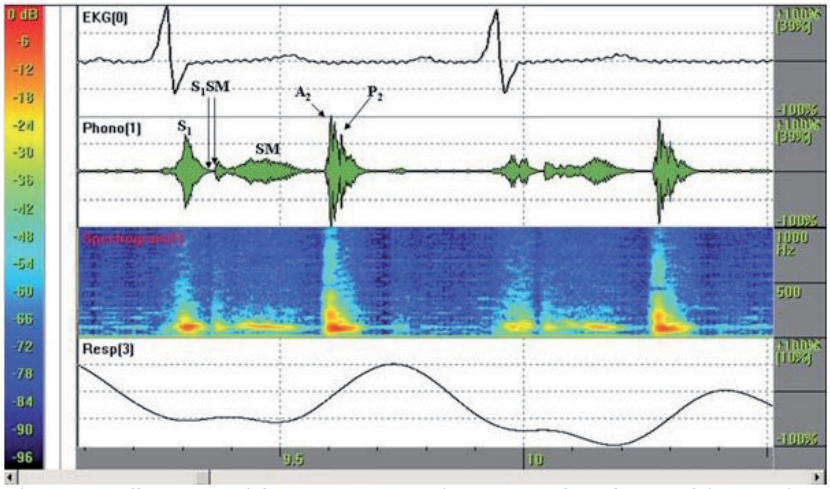

Figure 5.1. *Illustration of the measurements of time intervals and spectral features from the phonocardiographic signal. The upper pane shows the ECG, the second the PCG, the third the spectrogram of the PCG and the bottom pane the respiratory phase. The intensities, timings and the frequencies are manually read from the scales: left colour scale = the relative intensity of the spectrogram, right scale(s) = the relative amplitude (ECG, PCG and respiration) or the frequency scale (spectrogram) (VII).*

Table 5.3. The extracted time interval and spectral variables, their abbreviations and units (Publication VII)

Variable	**Abbreviation (units)**
The time interval between the end of S1 and the beginning of the SM	S1SM (ms)
The respiratory variation of the splitting of S2	ΔS2
Combination of S1SM and DS2 - If S1SM = 0 (ms) then Designed variable = 0 - Otherwise Designed variable = ΔS2	Designed variable
Mean spectral power of the SM	Sp (dB)
Mean frequency	Fm (Hz)
The time interval from the end of S1 to the maximum intensity of the SM	Timax (ms)
The frequency at the maximum intensity of the SM	Fimax (Hz)
The maximum intensity of the SM	Imax (dB)
SM intensity in frequencies > 250 Hz relative to S1 intensity	Imax/S1 intensity
Highest intensity point, punctum maximum	PM
Standard deviation of Timax registered in 4 auscultation point	SDTimax

Software developed at Lund University was used to calculate spectral features of the systolic murmur (Publication VII). S1 and S2 and timing of the systolic period were automatically detected using the ECG and PCG signals (Publication VII). The maximum intensity (Imax), the timing of the maximum intensity (Timax), the frequency at the maximum intensity (Fimax), the mean frequency (Fm), and the mean spectral power (MSp in dB) of the murmur were extracted and the mean and standard deviation of the features were calculated (El-Segaier 2005).

The most significant features for classification between pathological and physiological cases was determined using stepwise logistic regression analysis. The extracted time intervals, spectral features and clinical data were included in the analysis. The S1SM and ΔS2 were combined into one independent variable (Publication VII).

6 Results of clinical experiments

6.1 Introduction

The purpose of the clinical experiments was to clinically evaluate the phonocardiographic system developed. The first findings of the clinical test cases were reported in an early technical publication (I). The usability and reliability of the system was tested in a smaller scale teleconsultation study, where a videoconference system was used to transmit the sounds between the health centre and the outpatient paediatric clinic (Publication V). The characteristics of the innocent vibratory murmur were identified and their differences to pathological systolic murmurs were described in Publication VI. Finally, an objective diagnostic method for the detection of non-cyanotic congenital heart diseases was developed (Publication VII) and the value of the system in determining the characteristic features of heart murmurs in children and distinguishing innocent systolic murmurs from pathological was evaluated (Publication VIII).

6.2 Early clinical tests

The envelope and spectrographic presentation of the early clinical cases of a small ventricular septal defect, an innocent vibratory murmur, systolic murmur of a mild pulmonary stenosis and an innocent ejection murmur clearly showed the first and the second heart sound components and timing and frequency contents of the murmurs (Publication I).

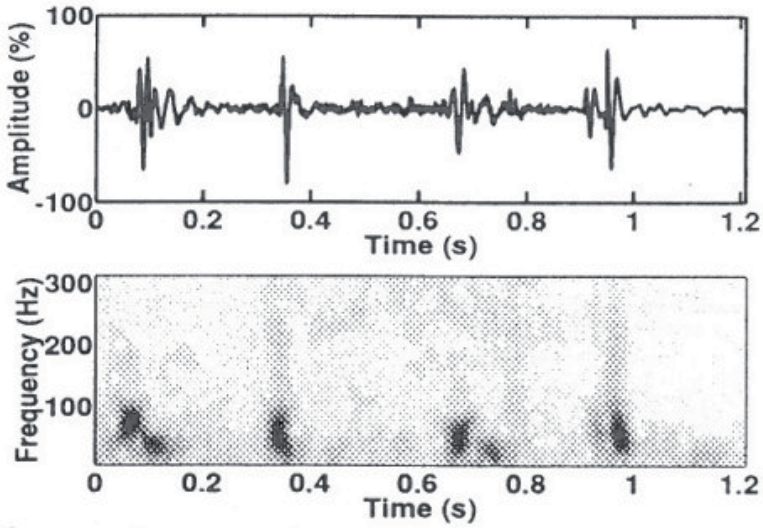

Figure 6.1. *Phono-spectrographic presentation of two cycles of innocent vibratory murmur. For visual analysis the original signal was down-sampled from 11,025 Hz to 2,205 Hz and pass-band filtered from 50 to 300 Hz. The spectrogram is calculated using 128-point FFT and 75 % overlapping between the segments (Publication I).*

6.3 Experiences with videoconferencing

Due to additional analog and digital transmission layers in videoconferencing, the recorded sounds had a higher level of background noise in video consultation than on the spot (Publication V). However, the quality of the sound was comparable to bedside recordings. The typical features of the innocent and mild pathological murmurs were recognisable, also when analysed remotely. In one case, the examination by teleconsultation, combined with clinical findings, gave reason to suspect aortic coarctation, and the patient was advised to visit the paediatric cardiologist immediately. The diagnosis was confirmed in further examinations. In 3 adult test cases, the specialist, based on the video consultation, evaluated the murmurs as innocent and decided that no further examinations were needed.

6.4 Recognising the innocent vibratory murmur

An early or mid-systolic, narrow-band, well-localised spot, typically around 120 Hz, was identified in phono-spectrograms for the innocent vibratory murmur (Publication VI). In children under 2 years of age the major frequency of the innocent vibratory murmur may be higher, but seldom over 200 Hz. The innocent vibratory murmurs seemed to contain slightly higher frequencies than innocent ejection murmurs. The murmurs of the aortic stenosis and ventricular septal defect differed from the innocent murmurs by containing wider frequency spectrum. The musical murmurs recorded in some pathological cases, like in mitral valve prolapse, small muscular VSD or right ventricular muscular band, typically had higher frequencies than the innocent vibratory murmur.

6.5 Detecting cardiac pathology

All significant cardiac defects were correctly classified as pathological using the stepwise logistic regression analysis model (Publication VII). The most significant distinguishing variables for classification were: S1SM, ΔS2, the standard deviation of the Timax and the standard deviation of SDTmax. With the selected probability cut-off point, the model gave a sensitivity level of 95% and a specificity of 72% in the detection of cardiac pathology (Figure 6.2). The area under the ROC-curve was 0.95.

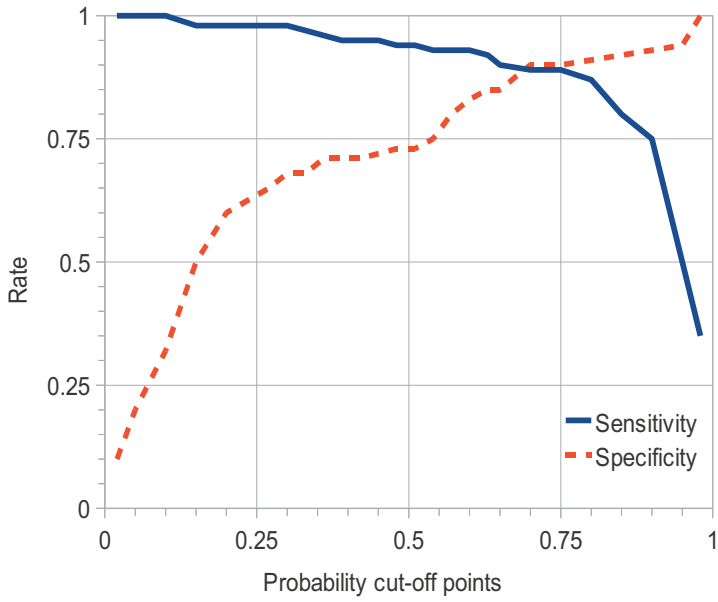

Figure 6.2. *The sensitivity and specificity of the stepwise logistic regression model at different cut-off points in detection cardiac disease in children (Publication VII).*

6.6 Screening heart murmurs in children

The system was able to display and reproduce the cardiovascular sound events. The musical murmur caused by the vibratory innocent murmur was usually visualised as a well-defined spot in spectrogram (Figure 6.3). The most typical murmurs in children were illustrated with phono-spectrograms (Publication VIII). The continuous murmurs were clearly visualised in the phono-spectrogram. The widely and constantly splitted S2, typical for atrial septal defect, is seen both in phono- and spectrogram. The innocent murmurs appeared to have lower frequencies and shorter duration than pathological murmurs (Figure 6.4).

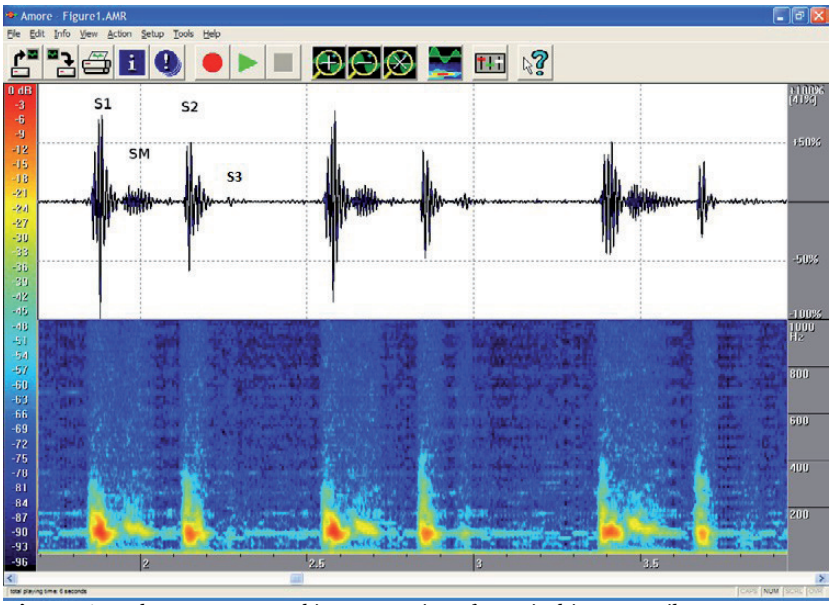

Figure 6.3. *phono-spectrographic presentation of a typical innocent vibratory murmur (VIII).*

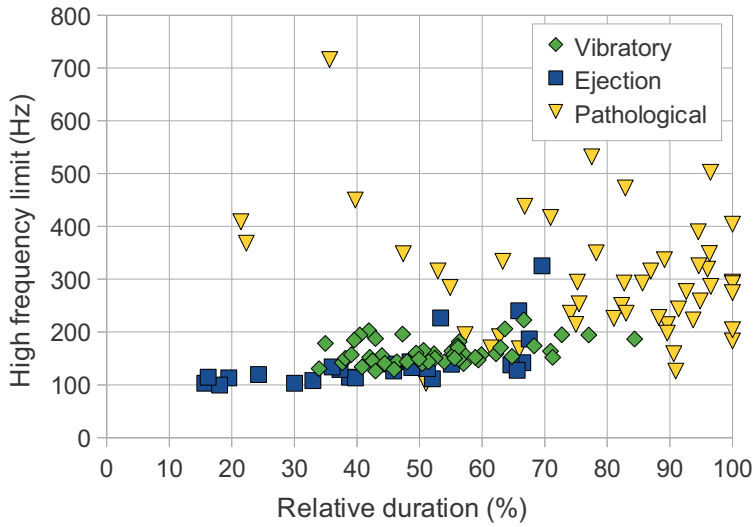

Figure 6.4. *Distribution of the relative duration and high frequency limit among the vibratory, ejection and mild pathological murmur cases.*

The patients with innocent vibratory murmurs were referred for examination at a younger age than those with an ejection murmur or mild pathological cases (Figure 6.5). There were no significant differences in the duration of S1 and S2 between the mild pathological and physiological systolic murmurs (Table 6.1). Although S2 was constantly split in ASDs, the duration of S2 in these cases did not differ from the average in the series. The pathological murmurs were significantly longer than the physiological murmurs. The pathological murmurs also contained higher and lower frequencies than physiological ones (Table 6.2).

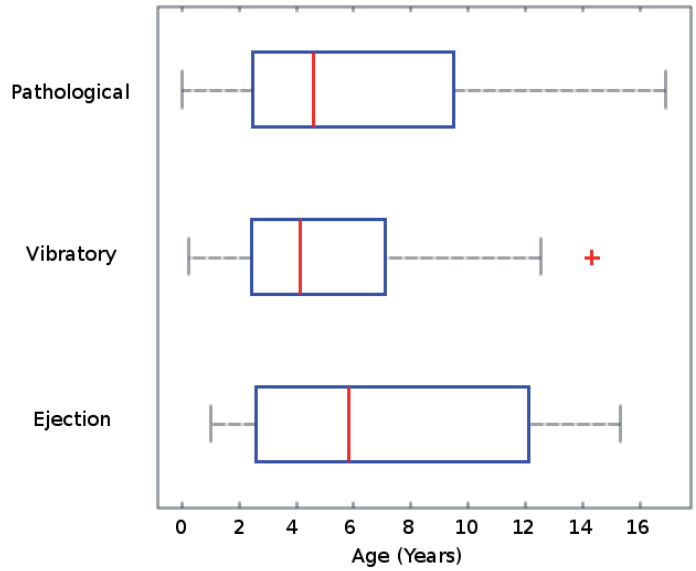

Figure 6.5. *Distribution of the patient's ages in the three groups. Mid (red) bar = median, blue box = 25th and 75th percentiles, whiskers = the extreme data points, (red) cross = statistical outlier.*

Table 6.1. Duration of S1, S2 and SM and relative SM (%) between the three groups (VIII).

Group	**Duration**			
	S1 (ms)	**S2 (ms)**	**SM (ms)**	**SM (%)**
Vibratory	81 ± 15	69 ± 12	100 ± 12	53 ± 12
Ejection	92 ± 16	75 ± 14	84 ± 36	44 ± 17
Pathological	87 ± 19	77 ± 17	147 ± 49	78 ± 21
P-value	**0.47**	**0.029**	**<0.001**	**<0.001**

Table 6.2. Relative amplitude and low and high frequency limits of the SM (VIII).

Group	Amplitude (%)	Low frequency limit (Hz)	High frequency limit (Hz)
Vibratory	23 ± 9	72 ± 15	161 ± 22
Ejection	20 ± 9	60 ± 9	142 ± 51
Pathological	30 ± 20	52 ± 19	299 ± 133
P-value	**0.013**	**<0.001**	**<0.001**

Based on the statistical analysis, the relative duration of the systolic murmur and the occurrence of intensive high-frequency components were selected as criteria for testing the pathology of the murmur. Sensitivity and specificity increased and the number of false negatives (missed pathologies) and false positives (misclassified physiological) decreased when changing the criteria, as summarised in figures 6.6 and 6.7. The limits of 80% for the relative duration and 200 Hz for the high frequencies gave optimal results for the combined criteria. Of the 5 missed pathological cases one was a clinically insignificant tricuspid valve leakage, one a very mild mitral valve leakage, one a bicuspid aortic valve without stenosis and one a hypertrophic cardiomyopathy.

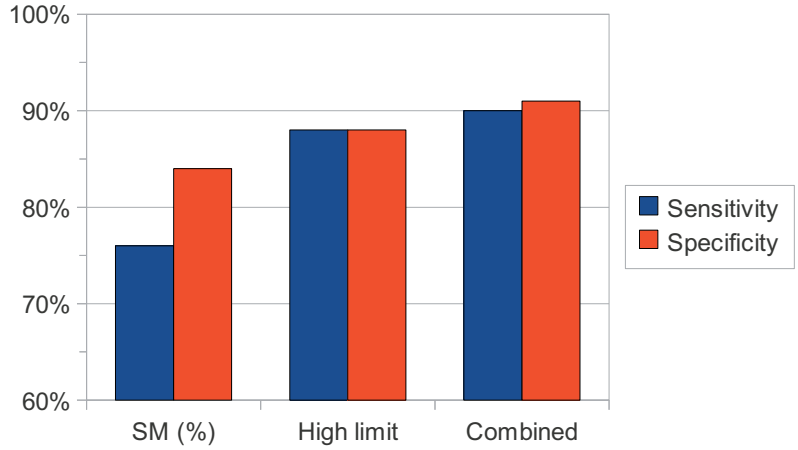

Figure 6.6. *Increase in sensitivity and specificity when changing the decision criterion from relative duration of systolic murmur (SM (%)) to high frequency limit and combined criteria (SM(%) >= 80 % OR High_limit >= 200 Hz).*

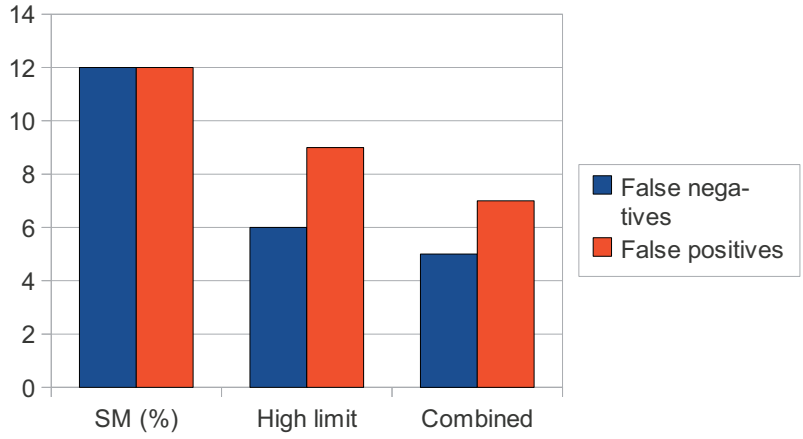

Figure 6.7. *Decrease in number of false negative and false positive cases using relative duration of systolic murmur, high frequency limit or combined criteria for selection criteria. Total number of pathological cases was 50 and total number of physiological cases was 75.*

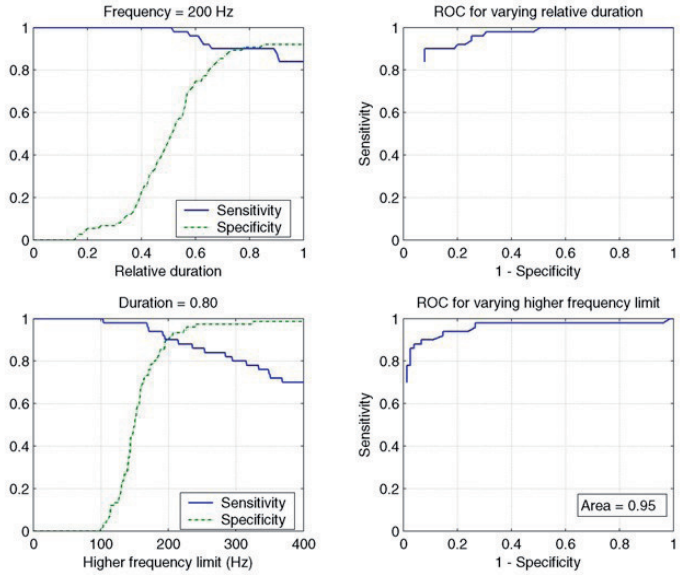

Figure 6.8. *Sensitivity and specificity for the combined criteria around the optimal point (closest to 100 % sensitivity and specificity) to differentiate between the pathological and physiological murmurs (top left). The highest frequency limit is fixed to 200 Hz and the relative duration is varied (top right). The ROC vs. the relative duration around the optimal point. The relative duration is fixed to 0.80 and the high frequency limit is varied (bottom left). ROC vs. the highest frequency limit. Area under the curve is 0.95 (bottom right).*

7 Discussion

The rapid development of microelectronics and computer systems – witnessed as high quality, complex, ergonomically designed and economically achievable electronic devices – has also opened up the market for electronic stethoscopes. The costs of electronic stethoscopes are diminishing and their quality has overcome the properties of their acoustical counterparts. A quality electronic stethoscope or phonocardiographic amplifier can be constructed from ordinary electronic components relatively easily as demonstrated in this thesis.

Personal computers, tablets and mobile devices can be used for heart sound recording and analysis. A visual presentation allows for a more accurate analysis of heart sound events than auscultation alone. The characteristic diagnostic features, such as timing, intensity, shape and quality of normal and pathological murmurs can be identified. The phonocardiographic system developed in this thesis utilised personal computers and demonstrated their potential. The custom software in turn allowed accurate analysis of the heart sound events.

Compared to traditional phonocardiographic devices, personal computers offer several advantages. The recorded sound signals can be replayed, the signals can be digitally filtered and special events can be visually highlighted by zooming in on the section of the recording that is of interest. In addition, the recorded signals can be digitally stored as a part of patient documentation and re-evaluated later if necessary. All these features were implemented in the system developed.

The overall solution for screening for heart murmurs in children should be reliable and robust. It should not burden the healthcare system but accelerate and improve the efficiency of the screening process. In its simplest form it could be a described clinical procedure and if any additional tests and devices are needed, they should be simple to use and easily available. The personal computer -based phonocardiographic system can fulfill these requirements.

The phonocardiographic device developed in this study may also be useful for educational purposes. The sounds are heard and seen simultaneously which could assist learning. The device is more accurate and easier to use than the traditional phonocardiogram in ECG-machines. It can also be used in developing personal auscultation skills.

Paediatric telecardiology has developed rapidly in the past years. In Canada telemedicine is now an integral part of regular clinical and educational activities in paediatric cardiology (Finley 2006, 2009). Trial studies in several countries have confirmed the feasibility of remote auscultation in the screening of children with murmurs (Finley 2006; Belmont 2003; Dahl et al. 2002). Teleconsultation can eliminate the need for in-person consultation and shorten the waiting time significantly (Sable et al. 2002). Telemetric monitoring is effective. Teleconsultation gives the specialist the possibility of becoming acquainted with the patient in advance and deciding what additional examinations are needed. The paediatric cardiologist in our study group, for example, had over 1000 paediatric consultations per year. Of these cases approximately 50 % are normal controls having an audible asymptomatic normal murmur. Using the information provided in the teleconsultation, the specialist could identify the patients who needed to be examined more carefully and who required special treatment.

The most important aspect of cardiac auscultation in children is understanding what is a normal heart sound. An asymptomatic, soft, early-to-mid systolic, and low-pitched musical or slightly harsh murmur is a normal finding in children. A healthy child with a normal innocent murmur does not need further examinations. The ECG or thorax X-ray is unlikely to help the diagnosis of quiet asymptomatic murmurs (Rushforth and Wilson 1992) and even echocardiography may be misleading (Walsh et al. 2011). The combined phono-spectrographic analysis may provide necessary

additional confidence for the non-cardiologist in order to make a decision regarding the normality of the sound. If it is necessary to confirm the diagnosis, then a consultation with a specialist is the most efficient and economical way to proceed.

8 Conclusions

In this thesis a prototype of a phonocardiographic system for non-cardiologist use was developed and its applicability to screening for heart murmurs in children was evaluated. The prototype was used for research and development purposes. A heart sound database of the most common heart sounds and murmurs in children was collected. The heart sounds and murmurs were analysed in more detail and the characteristic features of the innocent and pathological murmurs were explored. The applicability of the system to screening for heart murmurs in children was demonstrated. Based on the results the following conclusions are drawn:

1. The digital phonocardiographic system for screening for heart murmurs in children can be implemented using the electronic stethoscope and personal computer.
2. Enhanced phonocardiography, including both timing and spectral analysis features, provides more information than traditional phonocardiography or auscultation alone.
3. Features extracted from the phono-spectrogram may significantly improve the diagnostic quality of primary healthcare in screening for systolic heart murmurs in children.
4. Applying enhanced phonocardiography for screening heart sounds in children could lead to more efficient use of personnel and technical resources in the whole healthcare system. The burden of consulting specialists and the use for costly tests and examinations could be lowered if decisions could be made earlier in healthcare provision.

In order to achieve broader acceptance in healthcare, the phonocardiographic system for screening heart murmurs in children in non-cardiologist use should be technically robust and simple to use. The analysis should preferably be automatic. If it is manual, the instructions for feature extraction and interpretation guidelines should be such that even a non-specialist could carry out the test. The development of such a system, which this thesis has clearly demonstrated to be both technically and clinically achievable, will allow phonocardiographic devices and analysis to claim their place in healthcare for young adults and children.

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In this thesis a prototype of a phonocardiographic system for non-cardiologist use was developed and its applicability to screening heart murmurs in children was evaluated. The system was used to collect two independent heart sound databases in co-operation with Helsinki University Hospital and Lund University Hospital. The digital phonocardiographic system and the enhanced phono-spectrographic presentation of the heart sounds and murmurs provides more information than the traditional auscultation or phonocardiography alone. Features extracted from the phonospectrogram may significantly improve the diagnostic quality of the primary health care in screening heart murmurs in children and thus lead to more efficient use of personnel and technical resources in the whole health care system.

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