國立臺灣大學獸醫專業學院臨床動物醫學研究所

碩士論文

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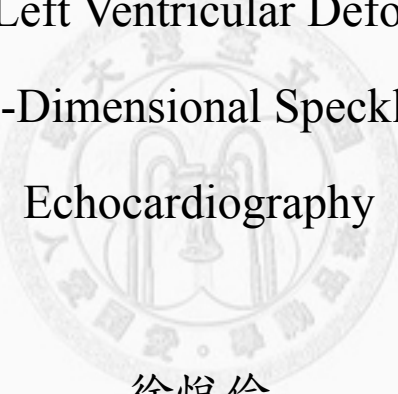
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National Taiwan University

Master Thesis

以二維斑點追蹤心臟超音波評估貓之左心室運動

Assessment of Left Ventricular Deformation in Cats

Using Two-Dimensional Speckle Tracking

Echocardiography

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本論文係徐悅倫君（R98643005）在國立臺灣大學獸醫學系、所完成之碩士學位論文，於民國 101 年 07 月 18 日承下列考試委員審查通過及口試及格，特此證明

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Abstract

Two-dimensional speckle tracking echocardiography (2D-STE) applies the special corrugated of constructive interference and destructive interference when ultrasound passes through myocardial tissue to locate myocytes. This modality is able to calculate myocardial deformation, strain and strain rate (SR), synchrony and heterogeneity.

This thesis contains two studies. The first study established 2D-STE of strain, SR, synchrony and heterogeneity of clinically normal cats, physiological characteristics might affect the indices derived from 2D-STE were analyzed, and the correlation between 2D-STE and conventional echocardiography were also evaluated. In the second study left ventricular function of clinically normal cats and cats with lower respiratory tract diseases was assessed using 2D-STE.

In general, strain, SR, synchrony and heterogeneity derived by 2D-STE were almost not influenced by age, body weight, heart rate and blood pressure, but affected by gender. In clinically healthy cats, segmental and transmural heterogeneity were evidenced in myocardial deformation. The correlation between 2D-STE indices and conventional echocardiography were weak. It is implied that 2D-STE was more sensitive in detection of left ventricular dysfunction. In terms of decreased myocardial strain and SR, mild systolic and diastolic dysfunction was found in cats with lower respiratory tract diseases, and it might be caused by the mechanism other than ventricular interdependence.

摘要

二維斑點追蹤心臟超音波利用超音波在心肌細胞內產生的建設性干涉和破壞性干涉的特殊波紋，對心肌進行定位，進一步計算位移和形變量、形變率，比起傳統超音波利用整體容積形變或壓力差為基礎，測量估計心臟整體收縮力，斑點追蹤心臟超音波可以達到局部心臟收縮力的評估。局部心臟收縮力的表現包括形變量和形變率，綜合各個局部心臟收縮力的表現可進一步評估收縮的同步性和異質性。

本篇論文有兩個章節，第一章節以建立二維斑點追蹤超音波應用於臨床上健康貓計算左心運動形變量、形變率、同步性和異質性的範圍為目的，了解生理因子是對於這些數值的影響，以及二維斑點追蹤超音波計算出的局部收縮力和傳統超音波計算出的整體收縮功能的關聯。第二章節應用二維斑點追蹤心臟超音波比較下呼吸道疾病貓和臨床健康貓隻的左心功能改變。

總體來說，二維斑點追蹤心臟超音波計算出的形變指數，同步性和異質性不受到年齡、體重、心跳、血壓影響，但存在性別差異；並且證實臨床健康貓的心肌運動具有跨壁和節段形變量的異質性；二維斑點超音波的形變指數和傳統超音波的功能指數關連性低，顯示心肌局部功能的改變可能受到其他區域的心肌運動代償，因而傳統超音波的整體功能測量敏感性較低。下呼吸道疾病貓隻的左心形變量偏低，顯示左心收縮、舒張功能受到影響，應該是藉由心室間關聯性以外的機制造成。

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Chapter I
General introduction

Key to abbreviations

LV	Left ventricular
STE	Speckle tracking echocardiography
TDI	Tissue Doppler imaging
ε	Lagrangian strain
ε_N	Eulerian strain

Introduction

Echocardiographic imaging is ideally suited for the evaluation of cardiac mechanics because for its intrinsically dynamic nature. Speckle tracking echocardiography (STE) is a technology development in the decade. In contrast to tissue Doppler imaging, there is no dependency of the measurements on the insonation angle between the ultrasound beam and the direction of motion. Speckle tracking echocardiography is also a non-invasive and less cost examination compare to tagged magnetic resonance imaging or sonomicrometry.

Continuum mechanics－Context of cardiac mechanics

Langrangian description & Eulerian description －Speckle tracking echocardiography & tissue Doppler imaging

The continuum mechanical description of material relies on the characterization of material motion through space and time. The variation in observed motion within a material depends strongly a reference frame. There are two methods for description deformation on a continuum [1-3].

One description is made in terms of the material description. This is called "material description" or "Lagrangian description", which defines motion around a given point in tissue as it traverses through space and time. Speckle-tracking echocardiography analyzes Lagrangian strain, in which the end-diastolic tissue dimension represents the unstressed, initial material length as a fixed reference throughout the cardiac cycle [1-3].

Another description is made in the terms of the spatial coordinates. This is also called the "spatial description" or "Eulerian description". It describes deformation by considering the relative velocity of motion at a particular location in space as despite

time goes by. Tissue Doppler imaging (TDI) analyzes Eulerian strain (Fig. 1) [1-3].

Definitions of strain and strain rate

Strain－Langarian strain & Eulerian strain

Langarian strain (ε) is mathematically defined as the change of myocardial fiber length during stress at end-systole L(t) compare to its original length in a relaxed state at end-diastole, $L(t_0)$. In one-dimensional object, the only possible deformation of the object is lengthening or shortening.

$$\varepsilon(t) = \frac{L(t) - L(t_0)}{L(t_0)}$$

Strain is usually expressed in percent (%).

Eulerian strain (ε_N) is described expressed relative to the length at a previous time instance:

$$d\varepsilon_N(t) = \frac{L(t+dt) - L(t)}{L(t)}$$

$$\varepsilon_N(t) = \int_{t_0}^{t} d\varepsilon_N(t)$$

The reference value is not constant over time bit changes during the deformation process. The Lagrangian strain ε and the Eulerian strain ε_N have a fixed, but non-linear, relationship which is given by $\varepsilon_N(t) = \ln(1+\varepsilon(t))$.

If strains are small (of the order 5-10%) Lagrangian and Eulerian strain values are approximately equal. However, for the large deformations which can occur during cardiac ejection and rapid filling, the differences become significant [1, 3-5].

Strain－Normal strain & shear strain

As with stresses, strains may also be classified as 'normal strain' and 'shear strain'. In other words, normal strain is the deformation acting along the direction of stress and shear strain is the deformation acting perpendicular to the direction of stress (Fig.

2) [3, 4, 6].

Strain rate

The change of strain per unit of time is referred to as strain rate. As strain rate is the spatial derivative of tissue velocity (mm/s) in, and strain (%) is the temporal integral of strain rate, all of these three parameters are mathematically linked to each other by method of STE and TDI (Fig. 1) [3, 4, 7].

Regional myocardial coordinate system

To decompose the cubic regional myocardial deformation of 3 directions by using Cartesian coordinates (Fig.3), including three direction of normal strain (ε_x, ε_y and ε_z) and 6 direction of shear strain (ε_{xy}, ε_{xz}, ε_{yz}, ε_{yx}, ε_{zx}, ε_{zy}).

The 3 normal strains (ε_x, ε_y and ε_z) named as circumferential, radial and longitudinal strain. Myocardial shear in the circumferential-longitudinal plane results in twist or torsion [2, 3].
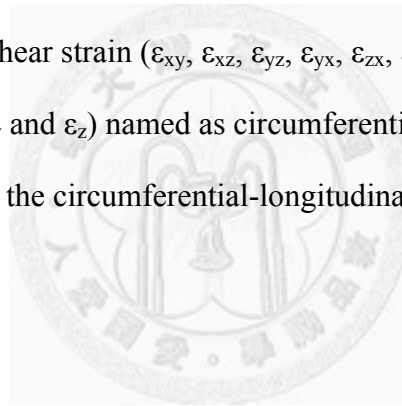
Structural mechanics

"We cannot claim to have mastered the mechanism of the human heart until we have a fundamental explanation of its architecture."－stated by Keith in1918.

Studies have pointed out that heart is a band of muscle, which consist of 4 segments, circumferential fiber right/left segments, descending segments(right-handed helix), ascending(left-handed helix)-Torrent-Guasp's model [8]. The band of muscle twines like a figure-of-eight-knot. Therefore, LV free wall is compatible with overlapping myocardial segments that are discontinuous or separated by a narrow zone in which fiber angles change markedly over very short distance.

In contrast to Streeter model of heart, cardiac wall is a continuum of fiber angles

across the wall, the fiber located at subendocardial region shows right-handed helical myofiber geometry, which changes gradually into a left-handed helical geometry in the subepicardium. Thus, the subendocardium, the fibers are roughly longitudinally oriented with an angle of about 80° with respect to the circumferential direction. The angle decreases toward the midwall, where the fibers are oriented in the circumferential direction (0°), and decreases further to an oblique of about -60° in the subepicardium [7-9].

The common feature of a circumferential muscle mass with predominantly transverse fibers and the oblique helical fiber arrangement of the inner and outer wall are documented by all anatomic descriptions and must be integrated by all functional models that can explain how the heart fills and empties [8].

Regional cardiac mechanics

The regional myocardial mechanics can simply by application the theory of physical tension to simulate myocardial forced status.

Regional myocardial stress state can be explained as the following formula [10, 11]:

Wall stress $_{passive}$ (t) – contractile force $_{active}$ (t) = elasticity x deformation (t)

There is a Heart filled with blood (Fig. 4) and we analyzed a small area A at the cardiac surface of force status. Therefore, the main factors influencing regional myocardial deformation are:

1. Cardiac wall stress from intracardiac blood pressure (loading)

2. Intrinsic contractile force developed by myocardium

3. Interaction between area A with other neighboring area (tension)

4. Tissue properties (elasticity)

For example, the more loading of heart rely on the greater tension from

neighboring area interaction. Thence, myocardial deformation evaluated by STE cannot fully express the myocardial contractility, but it is the closest method to the assessment of contractile forces among current multiple fashion.

Aims

The aims of this study were application of speckle tracking echocardiography to assess left ventricular deformation in feline, establish of repeatability and reproducibility in speckle tracking echocardiography, outline the baseline range of normal strain(circumferential, radial and longitudinal) and heterogeneity/ synchrony, determine physiologic factor effects and understand the correlation with conventional echocardiography.

Further apply of STE to investigate the effect of lower respiratory tract disease on left ventricular systolic/diastolic function.
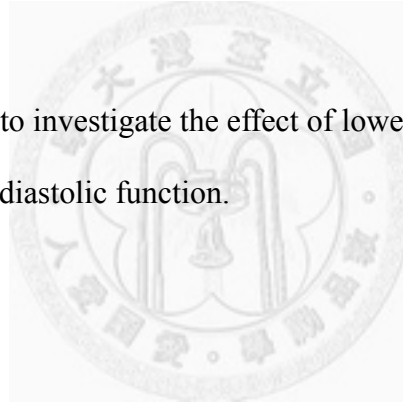
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Fig. 1 Mathematical relationship between different deformation parameters and mode of calculation for speckle tracking echocardiography (STE) and tissue Doppler imaging (TDI), STE primary asses myocardial displacement, whereas TDI primarily assesses tissue velocity.
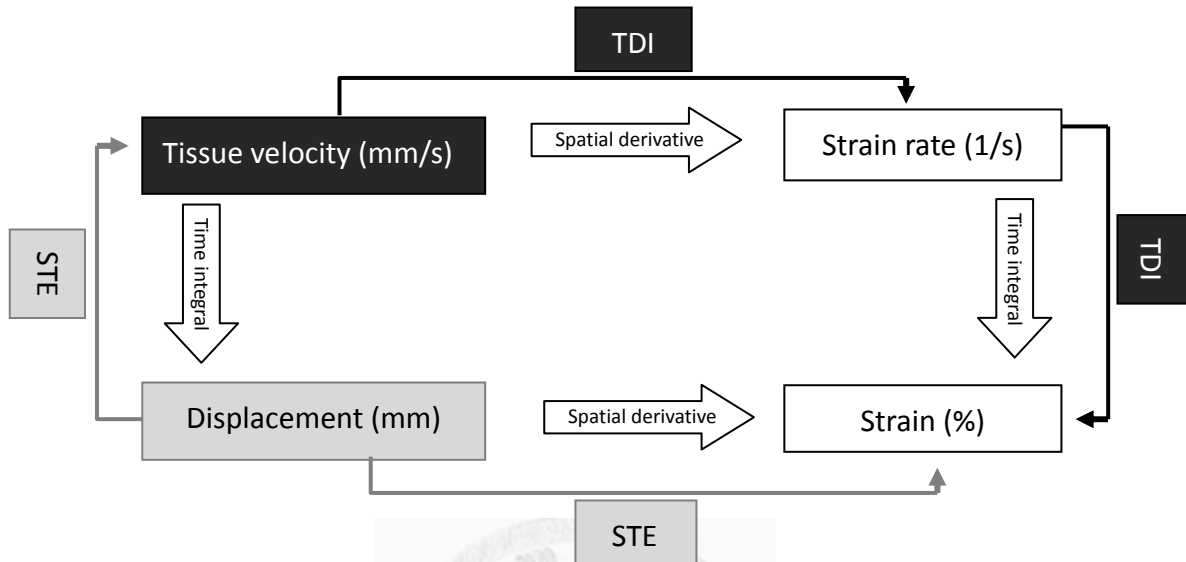
Adapted from" NON-invasive imaging: Two dimensional speckle tracking echocardiography: basic principles" by H. Blessberger and T. Binder, 2010, *Heart*, 96, p.716-722. Copyright 2000 by BMJ Publishing Group Ltd & British Cardiovascular Society.

Fig. 2 Definition of strain and shear strain.

Strain at one-dimension

Change of myocardial fiber length during stress at end-systole (L) compare to its original length in a relaxed state at end-diastole (L_0).
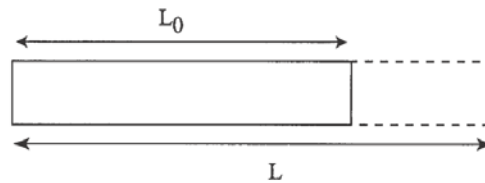
Normal strain at two-dimension

Deformation along the stress

$$\varepsilon_x = \frac{\Delta x}{x} \qquad \text{(left, stress direction, x)}$$

$$\varepsilon_y = \frac{\Delta y}{y} \qquad \text{(right, stress direction, y)}$$
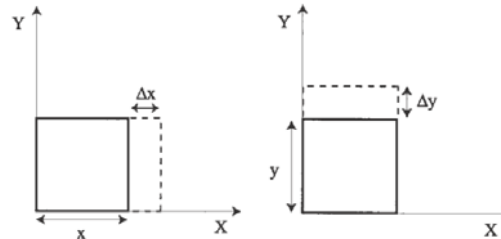
Shear strain at two-dimension

Deformation perpendicular the stress

$$\varepsilon_{xy} = \frac{\Delta x}{y} \qquad \text{(left, stress direction, y)}$$

$$\varepsilon_{yx} = \frac{\Delta y}{x} \qquad \text{(right, stress direction, x)}$$
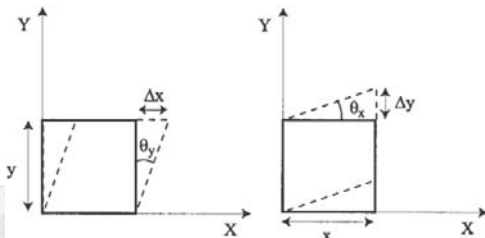
Normal strain at three-dimension

Deformation along the stress

$$\varepsilon_x = \frac{\Delta x}{x} \qquad \text{(stress on the yz plane)}$$
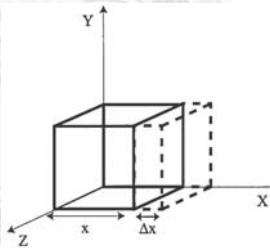
Shear strain at three-dimension

Deformation perpendicular the stress

$$\varepsilon_{yx} = \frac{\Delta y}{x} \qquad \text{(upper, stress on the yz plane)}$$

$$\varepsilon_{zx} = \frac{\Delta z}{x} \qquad \text{(lower, stress on the yz plane)}$$
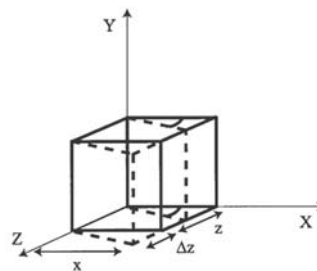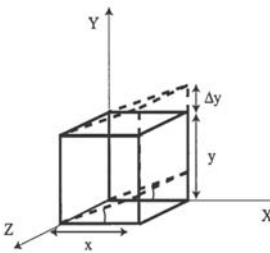
Adapted from" Regional strain and strain rate measurements by cardiac ultrasound: principles, implementation and limitations" by J. D'hooge and A. Heimdal, 2000, *Eur J Echocardiogr*, 1, p. 154-170. Copyright 2000 by the European Society of Cardiology.

Fig. 3 Local heart coordinate system: Sampling a cubic myocardium, and analysis the deformation in Cartesian coordinate system with circumferential, radial and longitudinal orientation.
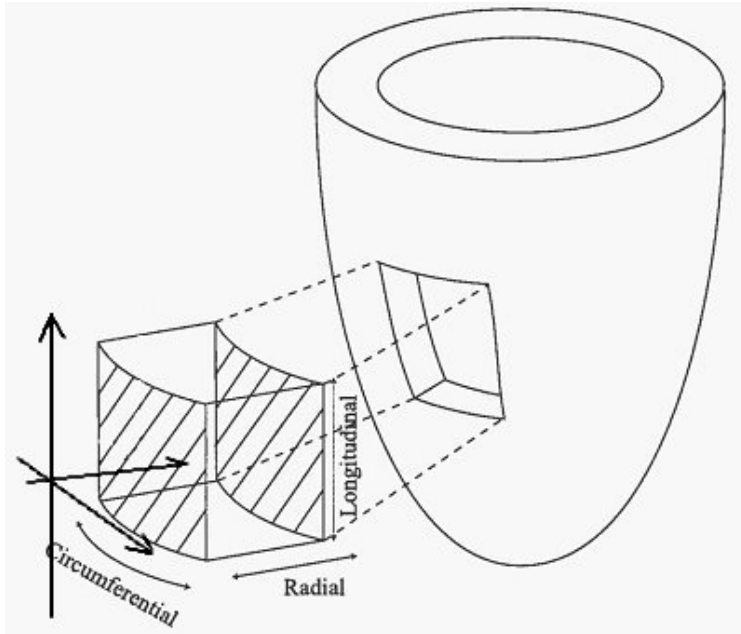
Adapted from" Regional strain and strain rate measurements by cardiac ultrasound: principles, implementation and limitations" by J. D'hooge and A. Heimdal, 2000, *Eur J Echocardiogr*, 1, p.154-170. Copyright 2000 by the European Society of Cardiology.

Fig. 4 Illustration of regional myocardium forced status.
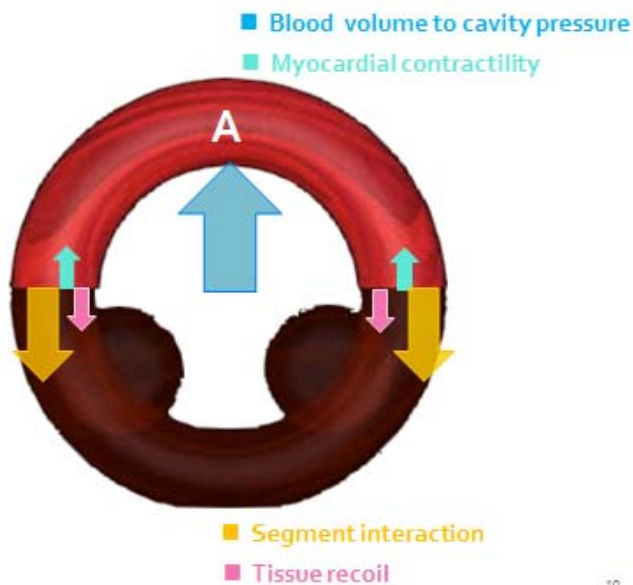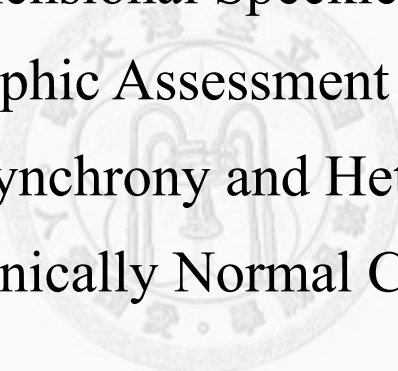
Segment A of myocardium maintain the balance of tension with blood pressure, intrinsic contractility, tissue recoil stress and segmental interaction. Adapted from" Velocity and deformation imaging for the assessment of myocardial dysfunction" by B.H. Bijnens and M. Cikes, 2009, *Eur J Echocardiogr*, 10, p.216-226. Copyright 2008 by the European Society of Cardiology.

Chapter II

Two-Dimensional Speckle Tracking Echocardiographic Assessment of Mechanical Ventricular Synchrony and Heterogeneity in Clinically Normal Cats

Key to abbreviations

2D-STE	Two-dimensional speckle tracking echocardiography
AAT	Aortic outflow acceleration time
AGp	Aortic outflow peak velocity pressure gradient
AVp	Aortic outflow peak velocity
BW	Body weight
CS	Peak circumferential strain
CSg	Global peak circumferential strain
CSR	Peak circumferential systolic strain rate
CSR$_{-A}$	Peak circumferential late diastolic strain rate
CSR$_{-Ag}$	Global peak circumferential late diastolic strain rate
CSR$_{-E}$	Peak circumferential early diastolic strain rate
CSR$_{-Eg}$	Global peak circumferential early diastolic strain rate
CSRg	Global peak circumferential systolic strain rate
EF$_M$	Ejection fraction derived from m-mode
EF$_{ste}$	Ejection fraction derived from speckle tracking echocardiography
EPSS	E point to septal separation
ESVI	End systolic volume index
FAC	Fractional area change
FS	Fractional shortening
HR	Heart rate
IVRT	Isovolumic relaxation time
IVS%	Percentage thickening of the interventricular septum
IVSd	Interventricular septal thickness in end diastole
LA/Ao	The ratio of left atrium and aortic diameter
LS	Peak longitudinal strain
LSg	Global peak longitudinal strain
LSR	Peak longitudinal systolic strain rate
LSR$_{-A}$	Peak longitudinal late diastolic strain rate
LSR$_{-Ag}$	Global peak longitudinal late diastolic strain rate
LSR$_{-E}$	Peak longitudinal early diastolic strain rate
LSR$_{-Eg}$	Global peak longitudinal early diastolic strain rate
LSRg	Global peak longitudinal systolic strain rate
LVDd	Left ventricular dimension in end-diastole
LVDs	Left ventricular dimension in end-systole
LVFW%	Percentage thickening of the left ventricular free wall
LVFWd	Left ventricular free wall thickness in end-diastole

LVFWs	Left ventricular free wall thickness in end-systole
LVMI	Left ventricular mass index
MAvp	Peak late mitral inflow velocity
$M_{E/A}$	Early and late mitral inflow ratio
MEVp	Peak early mitral inflow velocity
PEP:ET	Pre-ejection time period and ejection time ratio
PVp	Pulmonary outflow peak velocity
Q_{P-Ao}	Difference between pulmonary pre-ejection time and aortic pre-ejection time
RS	Peak radial strain
RSg	Global peak radial strain
RSR	Peak radial systolic strain rate
RSR_{-A}	Peak radial late diastolic strain rate
RSR_{-Ag}	Global peak radial late diastolic strain rate
RSR_{-E}	Peak radial early diastolic strain rate
RSR_{-Eg}	Global peak radial early diastolic strain rate
RSRg	Global peak radial systolic strain rate
RT-cε	Range of the 6 segment time to peak circumferential strain
RT-lε	Range of the 6 segment time to peak longitudinal strain
RT-rε	Range of the 6 segment time to peak radial strain
RT-ε	Range of the 6 segment time to peak strain
SDT-cε	Standard deviation of the 6 segment time to peak circumferential strain
SDT-lε	Standard deviation of the 6 segment time to peak longitudinal strain
SDT-rε	Standard deviation of the 6 segment time to peak radial strain
SDT-ε	Standard deviation of the 6 segment time to peak strain
Sg	Global peak strain
SH-cε	Circumferential segmental heterogeneity
SH-lε	Longitudinal segmental heterogeneity
SH-rε	Radial segmental heterogeneity
SH-ε	Segmental heterogeneity
SR	Peak systolic strain rate
SR_{-A}	Peak late diastolic strain rate
SR_{-Ag}	Global peak late diastolic strain rate
SR_{-E}	Peak early diastolic strain rate
SR_{-Eg}	Global peak early diastolic strain rate
SRg	Global peak strain rate
SV	Stroke volume

TAVp	Peak late tricuspid inflow velocity
$T_{E/A}$	Early and late tricuspid inflow ratio
Tei index	Myocardial performance index
TEVp	Peak early tricuspid inflow velocity
TH-ε	Transmural heterogeneity
Vcf	Velocity of circumferential fiber shortening
ε	Langarian strain

Two-Dimensional Speckle Tracking Echocardiographic Assessment of Mechanical Ventricular Synchrony and Heterogeneity in Clinically Normal Cats

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Abstract

Two-dimensional speckle tracking echocardiography (2D-STE) makes the regional cardiac deformation and function can be evaluated. Regional myocardial synchrony and heterogeneity in the human cardiac disease can be featured as pathogenesis or the consequence of specific diseases.

The aims of this study were firstly to assess the reproducibility and reproducibility of 2D-STE in clinical healthy feline, secondly to determine the influence of physical characteristic (age, body weight, heart rate, sex and blood pressure) in strain, strain rate (SR), synchrony/heterogeneity of left ventricle, and thirdly to compare the indices derived from 2D-STE with hemodynamic analysis obtained by conventional echocardiography.

Thirty-three clinical healthy cats were included. Both standard conventional echocardiography and 2D-STE were performed. Indices of circumferential, radial and longitudinal strain and SR, synchrony and heterogeneity were collected.

Indices of 2D-STE were almost free from the influence of physiological factors, but there were presence of gender differences. The deformations of left ventricle in clinically healthy cats possess heterogeneity, which the longitudinal strain/SR was lower in apex and circumferential strain was decreasing from subendocardium to subepicardium. Indices derived from 2D-STE were not correlated to M-mode indices of conventional echocardiography, and weakly correlated to pulse-wave Doppler indices. It is implied that regional deformation alteration may compensate by each other and makes 2D-STE more sensitive in detection of left ventricular dysfunction. Meanwhile, systolic strain or SR was correlated to diastolic indices in conventional echocardiography. It is indicated that the boundary of diastolic and systolic function in the regional deformation may not be aware. Need more diseases and health research or longitudinal study in order to further understand the significance of the deformation.

Key words: two-dimensional speckle tracking echocardiography, heterogeneity, synchrony, feline

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Introduction

Ventricular contraction normally occurs in a highly coordinated process. Diseased myocardium is usually resulted from impaired electrophysiological activity (electrical dyssynchrony), and induce electrical conduction delay [1, 2]. Non-uniform in timing of electromechanical activation in different areas of the myocardium can produce myocardial contraction dyssynchrony (mechanical dyssynchrony) [3, 4].

In recent years, ventricular dyssynchrony are found to be associated with causes and consequence both valvular insufficiency and myocardial disease in human patients [5-7]. Cardiac failure would amplify the regional stress disparities that result from discoordinate activation, and this may be an important interaction [8]. Dyssynchrony may induce asymmetric ventricular hypertrophy and alterations in regional myocardial blood flow [8, 9]. Mitral regurgitation, caused by delay in both the rise in left ventricular pressure and discoordinate papillary muscle contraction, can exacerbate this inefficiency further [8]. Presence of dyssnchronous ventricular contraction is an independent predictor of worsening heart failure [10, 11].

Quantification of ventricular synchrony and heterogeneity in clinical healthy cats is an essential first step in assessment of ventricular synchrony in cats. The aims of this study are to investigate left ventricular synchrony and heterogeneity in clinically healthy cats using two dimensional speckle tracking echocardiography (2D-STE).

Material and Method

Animals

Thirty three client-owned cats admitted to the National Taiwan University Veterinary Hospital during 2010-2012 were included for this perspective study. Without history of respiratory or cardiac disease, all cats were deemed to be clinically

healthy based on physical examination, blood pressure measurements, routine blood work (complete blood counts and biochemical profiles), chest radiographs and conventional echocardiography. The mean age was 3.11 ± 2.17 years (range 6 months to 8 years old) and a mean body weight was 4.32 ± 1.32 kg, 18 were males, and 16 were females. The represented breeds were 19 Domestic Short-hairs, 6 American Short-hairs, 7 Persians, 1 Bengal cat and 1 British Blue.

Measurement reliability

All echocardiographic studies were performed by 1 examiner (YLH), using an ultrasound unit equipped with a 5.5-7.5 MHz phased-array transducer (MyLab^{TM}50 XVision, Esaote, Genova, Italy).

STE examinations, including circumferential, radial and longitudinal orientation, of five clinical cats were acquired by one echocardiographer (YLH) thrice in one day to calculate intra-observer coefficient of variation. The resultant echocardiograms were analyzed by another investigator(BIY). Each variable was measured 3 times on 3 consecutive cardiac cycles using the same recorded loop. The intra-observer coefficient of variation (CV) was expressed as a percent value, calculated as CV=Standard deviation/ mean X 100% in order to assess the repeatability of the measurements used in this study.

Blood pressure

Systemic blood pressure was measured by Doppler flow detector and an inflatable cuff attached to a sphygmomanometer which position between the carpal and metacarpal pad. Record the average result of 5 consecutive measurements.

Conventional echocardiography

Ultrasound examinations were performed without sedation in gently restrained cats in lateral recumbency [12].

Indices of left ventricle was including left ventricular diastolic dimension (LVDd), left ventricular systolic dimension (LVDs), the ratio of Left atrium and aortic diameter (LA/Ao), interventricular septal thickness in diastole (IVSd), left ventricular free wall thickness in diastole (LVFWd), and left ventricular mass index (LVMI) were obtained from the standard views [13, 14].

Parameters of left ventricular systolic function were derived from M-mode, including end-posterior E point to septal separation (EPSS), percentage thickening of the interventricular septum (IVS%), percentage thickening of the left ventricular free wall(LVFW%), fractional shortening (FS), ejection fraction by M-mode (EF_M); parameters were derived from pulse-wave Doppler including velocity of circumferential fiber shortening (Vcf), the ratio of pre-ejection period an ejection time (PEP:ET), Aortic outflow acceleration time (AAT), including aortic outflow peak velocity (AVp), aortic outflow peak velocity pressure gradient (AGp), pulmonary outflow peak velocity (PVp), stroke volume (SV), and derived from B mode, including end systolic volume index (ESVI) were obtained from the standard views [14-23].

Parameters of left ventricular diastolic function were including mitral early and late diastolic inflow velocity (MEVp, MAVp), and tricuspid early and late diastolic inflow velocity (TEVp, TAVp), the ratio between MEVp and MAVp ($M_{E/A}$), the ratio between TEVp and TAVp ($T_{E/A}$), isovolumic relaxation time (IVRT), and myocardial performance index (Tei index) were obtained from the standard views [16, 24, 25].

Interventricular synchrony, the difference between pulmonary pre-ejection time and aortic pre-ejection time (Q_{P-Ao}) was obtained from standard views [26].

Two-dimensional speckle tracking echocardiography

Measurement regional strain and strain rate

Indices of left ventricular longitudinal and circumferential/radial/longitudinal strain and strain rates were obtained using right parasternal apical 4-chamber and short axis views, respectively. All images were acquired in cine loops of 3 cardiac cycles recorded at frame rate of 54-111 frames per seconds, saved in digital format, and analyzed by off-line software (XStrain^{TM} software for MyLabTM50 X Vision).

In quantification of circumferential and radial strain and strain, 6 segments (cranio-septum, cranial, lateral, caudal, ventral, and septal) of endocardium were semi-automatically selected by Aided Heart Segmentation (AHS) for analysis. In left ventricular longitudinal strain and strain rate, 6 segments (basal-septal, mid-septal, apical-septal, apical-lateral, mid-lateral, basal-lateral) of endocardium were semi-automatically automatically selected by the AHS tool for analysis. Left ventricular ejection volume (EF_{ste}) and fraction area change (FAC) were also calculated by modified Simpson's rule.

The 2D-STE indices included in this study were circumferential/radial/longitudinal peak systolic strain (CS/RS/LS), circumferential/radial/longitudinal peak systolic strain rate (CRS/RSR/LSR), circumferential/radial/longitudinal peak early diastolic strain rate ($CSR_{-E}/RSR_{-E}/LSR_{-E}$) and circumferential/radial/longitudinal peak late diastolic strain rate ($CSR_{-A}/RSR_{-A}/LSR_{-A}$). The 2D-STE off-line analysis was performed by 1 examiner (YLH).

The images without adequate visualization of one or more segments of the endocardium were excluded from this study.

Measurement of synchrony and heterogeneity

Interventricular synchrony, defined as time difference between mean pulmonary and aortic pre-ejection periods (Q_{P-Ao}), was calculated based on conventional pulse

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wave-Doppler.

Intraventricular synchrony, defined as the standard deviation of the six segments time to reach peak strain (SDT-ε) at longitudinal (SDT-lε), circumferential (SDT-cε) and radial (SDT-rε) directions, and the range of the six segments time to peak strain (RT-ε) at longitudinal (RT-lε), circumferential (RT-cε) and radial (RT-rε) directions were also calculated.

Segmental heterogeneity (SH-ε), defined as the range of the peak strain of the six segments, and transmural heterogeneity (TH-cε), defined as the difference of peak circumferential strain between endocardium and epicardium were also calculated.

Statistical analysis

All statistical analyses were performed with commercial computer static software (SPSS 12.0 Inc., Chicago, Illinois, USA). Data are express as the mean ± standard deviation (SD).

Compare the strain, SR, SR_E and SR_A between six segments by one way-ANOVA and pairwise comparison by Scheffe's method as post-hoc analysis if variances agree to variance homogeneity test, if not, using Robust test (Brown-Forysthe test substitute for ANOVA) and Games-Howell method as post-hoc analysis. A 2-tailed *P*<0.05 was considered significant.

Spearman correlation was used to examine the linear association between continuous variables. A 2-tailed *P*<0.05 was considered significant.

Results

The descriptive statistics of the indices derived from conventional echocardiography indices are listed in Table 1.

The intra-observer CV of 2D-STE variables are almost less than 25% except

RSR$_{-Ag}$ was 25.39% (Table 2).

Myocardial strain and strain rate

Based on the direction, values for circumferential and longitudinal peak systolic strain and strain rate were negative and values for radial peak systolic strain and peak systolic strain rate were positive for all cats (Table 3). Heterogeneity of strain and strain rate values across the 6 myocardial segments in the longitudinal analysis was found.

In general, circumferential, radial and longitudinal strain and strain rate were not affected by age, bodyweight, heart rate or blood pressure, except LSR$_{-Eg}$ was negatively correlated with the heart rate (r=-0.591, P=0.002, Table 4). Global circumferential (P=0.015) and radial strain (P=0.018) were lower in male.

Indices of 2D-STE and conventional echocardiography

Either systolic or diastolic indices derive from B- or M-mode echocardiography was not correlated with indices of STE. The Vcf (FS/ET), derived from pw-Doppler and M-mode, was correlated with LSg (r=0.437), LSRg (r=0.518) and CSR$_{-Ag}$ (r=0.524), and AVp, also an index derived from pw-Doppler, was correlated with CSR$_{-Ag}$(r=0.478), RSg (r=-0.432), LSg (r=0.473) and LSRg (r=0.454, Table 5).

The T$_{E/A}$ was correlated to CSRg (r=-0.440), CSR$_{-Ag}$ (r=-0.695) and LSR$_{-Ag}$ (r=-0.593). The M$_{E/A}$ was correlated to LSg (r=-0.482) and LSRg (r=-0.591). In addition, MAVp was correlated to LSRg (r=0.434, Table 6).

Segmental heterogeneity and synchrony

The segmental heterogeneity (SH-ε) of SH-cε, SH-rε and SH-lε was 13.1 ± 5.9%, 19.1 ± 10.3%, and 15.4 ± 6.8%, respectively. The TH-cε was -14.3 ± 4.6% in circumferential direction (Table 7). The TH-cε was correlated to body weight (r=-0.471, P=0.027) (Table 8).

The synchrony of SDT-cε, SDT-rε, and SDT-lε was 11.7 ± 4.2 ms, 16.5 ± 13.4 ms, and 19.4 ± 8.5 ms, respectively; RT-cε, RT-rε, and RT-lε was 32.5 ± 9.3 ms, 40.2 ± 28.7 ms, and 44.2 ± 22.6 ms, respectively (Table 7). The SDT-lε was correlated to heart rate (r=-0.433, P=0.044, Table 8).

Segmental heterogeneity/synchrony and indices of conventional echocardiography

Radial heterogeneity and synchrony were not correlated to systolic indices of conventional echocardiography. Circumferential transmural heterogeneity was well correlated to FAC (r=-0.841, P<0.001). Longitudinal synchrony (RT-lε, SDT-lε) were affected by AAT, AVp and AGp (Table 9).

Circumferential heterogeneity (SH-cε) was correlated to $T_{E/A}$ (r=0.434). Radial synchrony (RT-rε) was correlated to $M_{E/A}$ (r=-0.470). Longitudinal synchrony (RT-lε, SDT-lε) were correlated to IVRT (r=0.489, r=0.461) respectively (Table 10).

Segmental heterogeneity/synchrony and indices of 2D-STE

Radial/longitudinal strain and strain rate were almost not correlated to synchrony. Heterogeneity (SH-cε, SH-lε) were correlated to CSg and LSg, respectively, and heterogeneity (TH-cε) was correlated to CSg (r=-0.817, P<0.001), CSRg (r=-0.816, P<0.001), and CSR$_{-Eg}$ (r=-0.747, P<0.001) significantly (Table 11).

Discussion

Left ventricular strain and strain rate have been reported to be significantly associated with various physical characteristics. In human patients left ventricular strain and strain rate are affected by heart rate, but also by age, gender and body weight [27-32]. The effects of physical status on Indices of strain and strain rate in dogs are less consistent. Myocardial strain and strain rate may not be affected age in

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dogs [28], the effects of body weight and heart rate remains inconclusive [28, 33-35]. In this study, left ventricular strain and strain rate in cats were not affected by age, body weight, heart rate or blood pressure, except peak longitudinal early diastolic strain rate was affected by heart rate. A significant association between age and diastolic myocardial velocity was reported in cats [36]. However, the effect of age on myocardial motion remains controversial [36, 37]. In this study, gender appeared to affect myocardial strain. Based on these findings, the effects of physical characteristics on myocardial strain and strain rate should be taken into consideration, strain and strain rate might appear correlation with physiological factors if age or body weight range is expanded.

In general, cardiac systolic function is evaluated as contractility by pressure formation (PEP: ET and AAT derived from pulse-wave Doppler) or by deformation (EF_M and FS derived from M-mode) [38]. The mechanics of segmental myocardium (elasticity deformation) are complied wall stress and contractile force (Hooke's Law) [39]. Deformation of segmental myocardium cannot directly represent contractility, it is affected by wall stress (loading, overall cardiac volume changes), neighboring segments interaction (tension), cardiac geometry and elasticity (tissue properties).

The relationship between the left ventricular strain and the indices derived from conventional echocardiography (B- and M-mode) was weak and inconsistent in this study. It was not surprised that no significant association between the indices of 2D-STE and conventional echocardiography was found. Ventricular deformation is complemented in three directions. No single direction of the myocardial was assigned to a larger proportion of systolic function. Thus, conventional echocardiography is insensitive to detect regional dysfunction [40]. On the other hand, the EF_{ste} and FAC derived from 2D-STE are highly correlated to the estimated volume by MRI and

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3D-STE in human patients [41]. In this study, correlation between EF_{ste}/FAC and myocardial strain were found in cats. Correlations between LS, LSR and $M_{E/A}$, MAVp have also been reported in human patients [30]. Several systolic indices derived from pulse-wave Doppler were correlated to myocardial strain.

Based on these findings, both systolic and diastolic parameters derived from Doppler echocardiography might closely reflect systolic and diastolic strain rate. More cases with different cardiac conditions are needed to clarify the accuracy of the pressure gradient measured from Doppler echocardiography in association of myocardial strain rate.

Heterogeneity and synchrony

In this study, both transmural and segmental heterogeneity of ventricle were demonstrated in clinically healthy cats. The characteristic of transmural heterogeneity of cats showed similar pattern of human subjects. The difference of TH-cε between endocardium and epicardium in this study was approximately 64% (TH-cε/Cg X 100%) in contrast to 36% in human subjects [42]. And CS was decreasing from endocardium to epicardium, which also consistent with the pattern of human studies [42,43].

In this study, FAC was negatively correlated with TH-cε. The effect of transmural heterogeneity has to be taken consideration when FAC is changed. Heterogeneity of longitudinal direction was also found, significantly lower in the apex. Left ventricular heterogeneity in longitudinal direction has also been reported in human patients, however the pattern is inconsistent [27, 43-45].

In general, ventricular synchrony was not affected by age, body weight and strain, strain rate, heart rate, except SDT-lε was negatively associated with heart rate. SDT-lε and RT- lε were positively correlated to IVRT [46]. The intraventricular synchrony in

our studies was 32.5 ± 9.3 ms in RT-cε, 40.2 ± 8.7 ms in RT-rε and 44.2 ± 22.6 ms in RT-lε, in contrast to value derived from in dogs with wide range of mean RT-rε varied from 15 to 41.8 ms (SD varied from 2 to 17.9 ms) [28, 47, 48]. Although ventricular synchrony was not affected by strain in this study, the ranges for segmental intraventricular synchrony in clinically healthy cats were wide and the clinical application could be limited. However, the normal range of synchrohy in cat was similar to dog and human, the possibility of species conservatives made application of synchrony with cut off value to diagnose or predict outcome of cardiac diseases implementable because human medicine have already used cut off value in resynchronization therapy field successfully.

Conclusion

Longitudinal strain and strain rate was low in the segment of apex, CS decreasing from endocardium to epicardium. Left ventricular segmental and transmural heterogeneity was found in clinically healthy cats. Global myocardial strain and strain rate, heterogeneity and synchrony were nearly independent to age, body weight and heart rate.

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Table 1. The descriptive statistics of the population characteristic and conventional echocardiography indices of 34 clinically healthy cats

Parameter	Value
Age (years)	3.11 ± 2.17
Body weight (kg)	4.32 ± 1.32
sex	Male: n=18 (52.9%) Female: n=16 (47.1%)
Heart rate (beats/min)	171.97 ± 27.23
Systemic blood pressure (mmHg)	119.47 ± 15.15
IVSd (mm)	4.08 ± 0.61
LVFWd (mm)	4.17 ± 0.65
LVDd (mm)	14.98 ± 1.63
LVDs (mm)	6.81 ± 1.58
LA/Ao	1.35 ± 0.16
LVMI (g/m^2)	28.53 ± 7.31
EPSS (mm)	0.43 ± 0.25
IVS% (%)	69.66 ± 17.84
LVFW% (%)	63.19 ± 15.24
FS (%)	54.74 ± 8.01
EF$_M$ (%)	87.24 ± 6.53
Vcf (circumferences/s)	0.38 ± 0.07
PEP:ET	0.29 ± 0.08
AAT (ms)	25.53 ± 7.74
AVp (m/s)	0.95 ± 0.20
AGp (mmHg)	1.12 ± 0.43
PVp (m/s)	0.90 ± 0.18
SV (ml)	354.1 ± 97.93
ESVI (ml/m^2)	5.11 ± 1.96
MEVp (m/s)	0.82 ± 0.14
MAVp (m/s)	0.68 ± 0.16
M$_{E/A}$	1.25 ± 0.27
TEVp (m/s)	0.65 ± 0.15
TAVp (m/s)	0.52 ± 0.14
T$_{E/A}$	1.29 ± 0.27
IVRT (ms)	44.17 ± 7.42
Tei index	0.51 ± 0.09
Q$_{P-Ao}$ (ms)	-3.90 ± 13.22

AAT: aortic outflow acceleration time, AGp: aortic outflow peak velocity pressure gradient, AVp: aortic outflow peak velocity, EF_M: ejection fraction derived from m-mode, EPSS: E point to septal separation, ESVI: end systolic volume index, FS: fractional shortening, IVRT: isovolumic relaxation time, IVS%: percentage thickening of the interventricular septum, IVSd: interventricular septum thickness in end-diastole, LA/Ao: the ratio of left atrium and aortic diameter, LVDd: left ventricular dimension in end-diastole, LVDs: left ventricular dimension in end-systole, LVFW%: percentage thickening of the left ventricular free wall, LVFWd: left ventricular free wall thickness in end-diastole, LVMI: left ventricular mass index, MAVp: peak late mitral inflow velocity, $M_{E/A}$: early and late mitral inflow ratio, MEVp: peak early mitral inflow velocity, PEP:ET: pre-ejection time period and ejection time ratio, PVp: pulmonary outflow peak velocity, Q_{P-Ao}: difference between pulmonary pre-ejection time and aortic pre-ejection time, SV: stroke volume, TAVp: peak late tricuspid inflow velocity, $T_{E/A}$: early and late tricuspid inflow ratio, Tei index: myocardial performance index, TEVp: peak early tricuspid inflow velocity, Vcf: velocity of circumferential fiber shortening.

Table 2. The intra-observer coefficient of variance (CV) of 2D-STE variables

	Intra-observer CV %)		Intra-observer CV %)		Intra-observer CV (%)
CSg	6.43	RSg	10.24	LSg	4.56
CSRg	5.92	RSRg	14.91	LSRg	9.16
CSR$_{-Eg}$	12.37	RSR$_{-Eg}$	9.55	LSR$_{-Eg}$	21.08
CSR$_{-Ag}$	18.58	RSR$_{-Ag}$	25.39	LSR$_{-Ag}$	12.26

CSg: global peak circumferential strain, CSR$_{-Ag}$: global peak circumferential late diastolic strain rate, CSR$_{-Eg}$: global peak circumferential early diastolic strain rate, CSRg: global peak circumferential systolic strain rate, LSg: global peak longitudinal strain, LSR$_{-Ag}$: global peak longitudinal late diastolic strain rate, LSR$_{-Eg}$: global peak longitudinal early diastolic strain rate, LSRg: global peak longitudinal systolic strain rate, RSg: global peak radial strain, RSR$_{-Ag}$: global peak radial late diastolic strain rate, RSR$_{-Eg}$: global peak radial early diastolic strain rate, RSRg: global peak radial systolic strain rate.

Table 3. Circumferential, radial and longitudinal strain and systolic strain rate values for regional left ventricular segments determined using two-dimensional speckle tracking echocardiography in 34 clinical healthy cats

CS (%)		CSR (s^{-1})		RS (%)		RSR (s^{-1})		LS (%)		LSR (s^{-1})	
CS_1	-21.87 ± 6.69	CSR_1	-2.60 ± 0.78	RS_1	26.32 ± 11.64	RSR_1	2.40 ± 0.82	LS_1	-18.69 ± 4.92	LSR_1	-2.23 ± 0.70
$\backslash CS_2$	-21.83 ± 6.40	CSR_2	-2.73 ± 0.97	RS_2	25.50 ± 13.58	RSR_2	2.38 ± 1.02	LS_2	-18.85 ± 4.46	LSR_2	-2.33 ± 0.59
CS_3	-21.82 ± 5.97	CSR_3	-2.77 ± 0.95	RS_3	27.12 ± 12.76	RSR_3	2.46 ± 0.95	LS_3	-15.36 ± 6.30	LSR_3	-1.87 ± 0.84†
CS_4	-21.98 ± 7.81	CSR_4	-2.75 ± 1.21	RS_4	27.38 ± 10.36	RSR_4	2.43 ± 0.84	LS_4	-13.67 ± 5.37*	LSR_4	-1.63 ± 0.66*
CS_5	-21.90 ± 8.52	CSR_5	-2.73 ± 1.17	RS_5	28.68 ± 10.04	RSR_5	2.67 ± 1.00	LS_5	-19.84 ± 8.00	LSR_5	-2.42 ± 1.00
CS_6	-23.03 ± 7.15	CSR_6	-2.61 ± 0.87	RS_6	29.46 ± 12.71	RSR_6	2.74 ± 1.00	LS_6	-22.93 ± 10.80	LSR_6	-2.80 ± 1.24
CSg	-22.26 ± 5.01	CSRg	-2.7 ± 0.72	RSg	26.08 ± 8.18	RSRg	2.51 ± 0.71	LSg	-18.22 ± 4.78	LSRg	-2.21 ± 0.58
ANOVA	$P=0.997$		$P=0.996$		$P=0.913$		$P=0.793$		$P<0.001$		$P<0.001$

CSR_{-E} (s^{-1})		CSR_{-A} (s^{-1})		RSR_{-E} (s^{-1})		RSR_{-A} (s^{-1})		LSR_{-E} (s^{-1})		LSR_{-A} (s^{-1})	
CSR_{-E1}	2.71 ± 1.33	CSR_{-A1}	0.99 ± 0.38	RSR_{-E1}	-2.18 ± 1.59	RSR_{-A1}	-1.62 ± 0.93	LSR_{-E1}	1.88 ± 0.81	LSR_{-A1}	1.55 ± 0.98
CSR_{-E2}	2.33 ± 1.09	CSR_{-A2}	0.99 ± 0.23	RSR_{-E2}	-2.09 ± 1.20	RSR_{-A2}	-1.55 ± 0.82	LSR_{-E2}	1.89 ± 0.65	LSR_{-A2}	1.45 ± 0.45
CSR_{-E3}	2.35 ± 1.00	CSR_{-A3}	1.13 ± 0.51	RSR_{-E3}	-2.28 ± 1.06	RSR_{-A3}	-1.69 ± 0.93	LSR_{-E3}	1.55 ± 0.81	LSR_{-A3}	0.92 ± 0.52
CSR_{-E4}	2.22 ± 1.41	CSR_{-A4}	1.15 ± 0.74	RSR_{-E4}	-1.89 ± 1.01	RSR_{-A4}	-1.70 ± 0.90	LSR_{-E4}	1.29 ± 0.82	LSR_{-A4}	0.93 ± 0.55
CSR_{-E5}	2.33 ± 1.39	CSR_{-A5}	1.33 ± 0.63	RSR_{-E5}	-1.92 ± 1.26	RSR_{-A5}	-1.80 ± 0.88	LSR_{-E5}	1.78 ± 1.12	LSR_{-A5}	1.28 ± 0.94
CSR_{-E6}	2.53 ± 0.91	CSR_{-A6}	1.21 ± 0.48	RSR_{-E6}	-2.06 ± 1.56	RSR_{-A6}	-1.92 ± 1.10	LSR_{-E6}	1.80 ± 1.37	LSR_{-A6}	1.42 ± 1.16
CSR_{-Eg}	2.39 ± 0.81	CSR_{-Ag}	1.16 ± 0.32	RSR_{-Eg}	-1.99 ± 1.12	RSR_{-Ag}	-1.82 ± 0.85	LSR_{-Eg}	1.52 ± 0.73	LSR_{-Ag}	1.21 ± 0.57
ANOVA	$P=0.920$		$P=0.536$		$P=0.980$		$P=0.930$		$P=0.664$		$P=0.393$

C_1: cranio-septal, C_2: cranial, C_3: lateral, C_4: caudal, C_5: ventral, C_6: septal, Cg: global, CS: peak circumferential strain, CSR: peak circumferential strain rate, CSR_{-A}: peak circumferential late diastolic strain rate, CSR_{-E}: peak circumferential early diastolic strain rate, L_1: basal septa, L_2: mid septal, L_3: apical septal, L_4: apical lateral, L_5: mid lateral, L_6: basal lateral, Lg: global, LS: peak longitudinal strain, LSR: peak longitudinal strain rate, LSR_{-A}: peak longitudinal late diastolic strain rate, LSR_{-E}: peak longitudinal early diastolic strain rate, R_1: cranio-septal, R_2: cranial, R_3: lateral, R_4: caudal, R_5: ventral, R_6: septal, Rg: global, RS: peak radial strain, RSR: peak radial strain rate, RSR_{-A}: peak radial late diastolic strain rate, RSR_{-E}: peak radial early diastolic strain rate.

*LS/$LSR_{1,2,5,6,g}$ were different from LS_4 significantly ($P<0.05$) and †LSR_3 was significantly different from LS_6 in post hoc pairwise comparison by Game's-Howell.

Table 4. Characteristics of cats and indices of strain and strain rate

	Age		Body weight		Heart rate		Blood pressure	
	r	*P*	*r*	*P*	*r*	*P*	*r*	*P*
CSg	0.125	0.580	0.133	0.556	-0.076	0.736	0.060	0.801
CSRg	0.182	0.418	0.248	0.266	0.211	0.346	-0.029	0.905
CSR$_{-Eg}$	0.015	0.948	0.347	0.123	0.157	0.496	0.008	0.974
CSR$_{-Ag}$	-0.245	0.284	0.146	0.529	0.398	0.074	-0.299	0.214
RSg	-0.096	0.672	-0.014	0.952	-0.302	0.172	-0.409	0.073
RSRg	0.050	0.826	0.225	0.313	-0.017	0.941	-0.377	0.101
RSR$_{-Eg}$	0.068	0.777	0.388	0.091	-0.187	0.429	0.034	0.893
RSR$_{-Ag}$	-0.002	0.992	0.172	0.470	0.309	0.184	-0.285	0.251
LSg	0.189	0.365	-0.078	0.718	-0.064	0.760	0.020	0.926
LSRg	0.227	0.276	-0.094	0.662	0.060	0.776	-0.014	0.949
LSR$_{-Eg}$	-0.094	0.739	0.077	0.785	-0.591	0.020*	0.021	0.943
LSR$_{-Ag}$	0.312	0.278	-0.013	0.964	0.200	0.493	0.314	0.297

CSg: global peak circumferential strain, CSR$_{-Ag}$: global peak circumferential late diastolic strain rate, CSR$_{-Eg}$: global peak circumferential early diastolic strain rate, CSRg: global peak circumferential systolic strain rate, LSg: global peak longitudinal strain, LSR$_{-Ag}$: global peak longitudinal late diastolic strain rate, LSR$_{-Eg}$: global peak longitudinal early diastolic strain rate, LSRg: global peak longitudinal strain rate, RSg: global peak radial strain, RSR$_{-Ag}$: global peak radial late diastolic strain rate, RSR$_{-Eg}$: global peak radial early diastolic strain rate, RSRg: global peak radial systolic stain rate.

r=Spearman correlation coefficient, *P*<0.05 (two tail), significant correlation.

Table 5. Relationship between indices derived from conventional echocardiography and strain and strain rate

		LVMI	EPSS	IVS%	LVFW%	FS	EF_M	Vcf	PEP:ET	AAT	AVp	AGp	PVp	SV	ESVI	FAC
CSg	r	0.206	-0.152	0.049	0.110	0.206	0.175	0.086	0.191	-0.294	0.233	-0.101	0.056	0.235	0.200	0.937
	P	0.371	0.499	0.832	0.634	0.357	0.437	0.711	0.408	0.196	0.296	0.662	0.805	0.305	0.411	0.000*
CSRg	r	0.014	-0.340	0.005	0.162	0.29	0.272	0.254	0.031	-0.387	0.386	0.087	0.174	0.148	0.294	0.874
	P	0.953	0.121	0.982	0.482	0.190	0.221	0.267	0.893	0.083	0.076	0.709	0.440	0.522	0.222	0.000*
CSR_{-Eg}	r	-0.036	-0.342	0.079	0.060	0.128	0.117	0.075	0.117	-0.225	0.192	-0.024	0.323	0.033	0.228	0.635
	P	0.880	0.129	0.741	0.801	0.58	0.613	0.754	0.622	0.340	0.405	0.920	0.154	0.890	0.363	0.002*
CSR_{-Ag}	r	0.029	-0.336	0.191	0.289	0.28	0.314	0.524	-0.213	-0.307	0.478	0.319	0.250	0.280	0.346	0.361
	P	0.905	0.137	0.420	0.217	0.219	0.166	0.018*	0.367	0.188	0.028*	0.171	0.275	0.232	0.160	0.108
RSg	r	0.242	0.096	0.372	0.042	0.292	0.234	0.104	0.217	0.134	-0.432	-0.338	-0.181	0.139	0.242	0.562
	P	0.290	0.670	0.097	0.858	0.187	0.294	0.655	0.344	0.564	0.044*	0.134	0.420	0.548	0.318	0.007*
RSRg	r	0.146	-0.076	0.258	0.205	0.374	0.351	0.396	0.205	-0.098	-0.198	-0.127	0.201	-0.031	0.116	0.513
	P	0.527	0.738	0.259	0.374	0.086	0.109	0.076	0.374	0.672	0.377	0.585	0.369	0.895	0.637	0.015*
RSR_{-Eg}	r	0.049	-0.123	0.075	-0.037	-0.001	-0.032	0.135	0.326	0.056	-0.136	-0.451	-0.140	-0.284	-0.336	0.307
	P	0.842	0.607	0.762	0.881	0.997	0.892	0.583	0.173	0.819	0.567	0.053	0.556	0.238	0.187	0.188
RSR_{-Ag}	r	0.006	0.221	-0.134	0.432	0.288	0.264	0.401	-0.101	-0.100	0.026	0.366	0.367	0.232	0.416	0.409
	P	0.980	0.349	0.584	0.065	0.218	0.260	0.089	0.681	0.682	0.912	0.124	0.111	0.340	0.097	0.073
LSg	r	-0.231	-0.047	-0.136	0.057	0.236	0.145	0.437	-0.006	-0.059	0.473	0.104	0.212	0.079	-0.258	0.713
	P	0.277	0.823	0.526	0.790	0.257	0.490	0.037*	0.979	0.784	0.020*	0.630	0.310	0.713	0.224	0.000*
LSRg	r	-0.302	-0.026	-0.094	0.123	0.276	0.171	0.518	-0.038	-0.195	0.454	0.128	0.346	0.060	-0.361	0.719
	P	0.152	0.904	0.662	0.568	0.182	0.414	0.011*	0.859	0.362	0.026*	0.552	0.090	0.781	0.083	0.000*
LSR_{-Eg}	r	0.064	0.113	-0.416	-0.345	-0.136	-0.199	-0.248	0.269	0.363	0.176	-0.179	-0.182	0.101	0.154	0.484
	P	0.820	0.688	0.139	0.226	0.629	0.478	0.414	0.353	0.202	0.547	0.540	0.515	0.731	0.584	0.067
LSR_{-Ag}	r	-0.297	0.005	-0.154	0.478	0.411	0.453	0.543	-0.017	-0.327	0.495	0.124	0.469	-0.132	-0.600	0.420
	P	0.303	0.988	0.616	0.098	0.144	0.104	0.068	0.957	0.275	0.085	0.685	0.091	0.668	0.023*	0.135

AAT: aortic outflow acceleration time, AGp: aortic outflow peak velocity pressure gradient, AVp: aortic outflow peak velocity, CSg: global peak circumferential strain, CSRg: global peak circumferential systolic strain rate, CSR_{-Ag}: global peak circumferential late diastolic strain rate, CSR_{-Eg}: global peak circumferential early diastolic strain rate, EF_M: ejection fraction derived from m-mode, EPSS: E point to septal separation, ESVI: end systolic volume index, FAC: fractional area change, FS: fractional shortening, IVS%: percentage thickening of the interventricular septum, LSg: global peak longitudinal strain, LSRg: global peak longitudinal systolic strain rate, LSR_{-Ag}: global peak longitudinal late diastolic strain rate, LSR_{-E}: longitudinal early diastolic strain rate, LVFW%: percentage thickening of the left ventricular free wall, LVMI: left ventricular mass index, PEP:ET: pre-ejection time period and ejection time ratio, PVp: pulmonary outflow peak velocity, SV: stroke volume, RSg: global peak radial strain, RSRg: global peak radial systolic strain rate, RSR_{-Ag}: global peak radial late diastolic strain rate, RSR_{-Eg}: global peak radial early diastolic strain rate, Vcf: velocity of circumferential fiber shortening.

r=Spearman correlation coefficient, *P <0.05 (two tail), significant correlation.
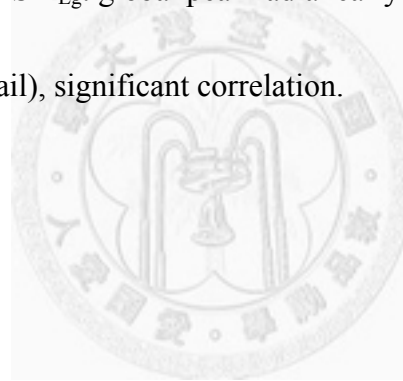
Table 6. Relationship between indices derived from Doppler echocardiography and strain and strain rate

		MEVp	MAVp	$M_{E/A}$	TEVp	TAVp	$T_{E/A}$	IVRT	Tei index
CSg	r	0.186	0.123	0.034	0.027	0.144	-0.258	0.124	0.068
	P	0.407	0.584	0.879	0.906	0.533	0.259	0.614	0.781
CSRg	r	0.355	0.309	-0.072	0.170	0.370	-0.440	0.140	0.262
	P	0.105	0.162	0.749	0.460	0.099	0.046*	0.569	0.279
CSR$_{-Eg}$	r	0.243	0.110	-0.019	0.248	0.316	-0.165	0.045	0.135
	P	0.289	0.635	0.935	0.291	0.174	0.488	0.858	0.592
CSR$_{-Ag}$	r	0.317	0.084	0.053	-0.081	0.330	-0.695	0.332	0.313
	P	0.162	0.717	0.821	0.733	0.155	0.001*	0.179	0.206
RSg	r	-0.041	-0.286	0.375	0.004	-0.028	0.079	0.024	-0.196
	P	0.857	0.196	0.086	0.987	0.904	0.733	0.923	0.422
RSRg	r	0.176	-0.117	0.372	0.073	0.231	-0.259	0.000	-0.051
	P	0.432	0.603	0.089	0.752	0.314	0.257	1.000	0.836
RSR$_{-Eg}$	r	0.114	-0.062	0.243	-0.04	0.267	-0.193	-0.093	-0.061
	P	0.633	0.796	0.302	0.869	0.269	0.428	0.714	0.810
RSR$_{-Ag}$	r	0.378	0.268	-0.096	0.302	0.389	-0.397	-0.157	-0.262
	P	0.100	0.253	0.686	0.208	0.100	0.093	0.534	0.293
LSg	r	0.108	0.374	-0.482	0.046	0.182	-0.252	0.189	0.250
	P	0.608	0.066	0.015*	0.826	0.384	0.224	0.411	0.275
LSRg	r	0.060	0.434	-0.591	0.074	0.204	-0.288	0.161	0.249
	P	0.775	0.030*	0.002*	0.726	0.329	0.163	0.486	0.277
LSR$_{-Eg}$	r	0.044	0.059	-0.152	-0.170	-0.203	0.000	0.182	0.056
	P	0.876	0.834	0.589	0.544	0.468	1.000	0.570	0.862
LSR$_{-Ag}$	r	-0.212	0.301	-0.414	-0.046	0.499	-0.593	0.132	0.246
	P	0.468	0.296	0.142	0.875	0.069	0.026*	0.699	0.466

CSg: global peak circumferential strain, CSRg: global peak circumferential systolic strain rate, CSR$_{-Ag}$: global peak circumferential late diastolic strain rate, CSR$_{-Eg}$: global peak circumferential early diastolic strain rate, IVRT: isovolumic relaxation time, LSg: global peak longitudinal strain, LSRg: global peak longitudinal systolic strain rate, LSR$_{-Ag}$: global peak longitudinal late diastolic strain rate, LSR$_{-Eg}$: global peak longitudinal early diastolic strain rate, MAVp: peak late mitral inflow velocity, $M_{E/A}$: early and late mitral inflow ratio, MEVp: peak early mitral inflow velocity, RSg: global peak radial strain, RSRg: global peak radial systolic strain rate, RSR$_{-Ag}$: global peak radial late diastolic strain rate, RSR$_{-Eg}$: global peak radial early diastolic strain rate, TAVp: peak late tricuspid inflow velocity, $T_{E/A}$: early and late tricuspid inflow ratio, Tei index: myocardial performance index, TEVp: peak early tricuspid inflow velocity.

r=Spearman correlation coefficient, *P<0.05 (two tail), significant correlation.

Table 7. Descriptive statistics of ventricular heterogeneity and synchrony in clinically healthy cats

Circumference		Radiation		Longitude	
RT-cε (ms)	32.49 ± 9.32	RT-rε (ms)	40.21 ± 28.72	RT-lε (ms)	44.24 ± 22.62
SDT-cε (ms)	11.74 ± 4.16	SDT-rε (ms)	16.48 ± 13.41	SDT-lε (ms)	19.38 ± 8.52
SH-cε (%)	13.05 ± 5.86	SH-rε (%)	19.06 ± 10.34	SH-lε (%)	15.38 ± 6.81
TH-cε (%)	-14.28 ± 4.60				

Q$_{P-Ao}$: -3.9 ± 13.22 ms

Q$_{P-Ao}$: difference between pulmonary pre-ejection time and aortic pre-ejection time, RT-cε: range of the 6 segment time to peak circumferential strain, RT-rε: range of the 6 segment time to peak radial strain, RT-lε: range of the 6 segment time to peak longitudinal strain, SDT-cε: standard deviation of the 6 segment time to peak circumferential strain, SDT-rε: standard deviation of the 6 segment time to peak radial strain, SDT-lε: standard deviation of the 6 segment time to peak longitudinal strain, SH-cε: circumferential segmental heterogeneity, SH-rε: radial segmental heterogeneity, SH-lε: longitudinal segmental heterogeneity, TH-cε: circumferential transmural heterogeneity.

Table 8. Characteristics of cats and ventricular synchrony (RT-ε, SDT-ε) and heterogeneity (SH-ε, TH-cε)

	Age		Body weight		Heart rate		Blood pressure	
	r	*P*	*r*	*P*	*r*	*P*	*r*	*P*
RT-cε	0.168	0.455	0.012	0.957	-0.05	0.824	-0.005	0.982
SDT-cε	0.244	0.274	-0.038	0.867	-0.011	0.962	-0.008	0.975
SH-cε	0.161	0.475	0.246	0.269	0.102	0.65	0.121	0.611
TH-cε	-0.175	0.436	-0.471	0.027*	-0.137	0.542	-0.151	0.524
RT-rε	0.025	0.914	0.058	0.799	0.221	0.322	-0.072	0.764
SDT-rε	0.015	0.949	0.046	0.838	0.124	0.584	-0.052	0.828
SH- rε	0.095	0.675	-0.249	0.265	-0.221	0.323	-0.079	0.740
RT-lε	0.214	0.316	0.027	0.901	-0.273	0.197	0.136	0.538
SDT-lε	0.280	0.207	0.123	0.594	-0.433	0.044*	0.197	0.393
SH-lε	-0.235	0.258	-0.208	0.329	-0.246	0.235	-0.071	0.743
Q$_{P-Ao}$	0.185	0.376	-0.320	0.119	-0.319	0.138	0.227	0.298

Q$_{P-Ao}$: difference between pulmonary pre-ejection time and aortic pre-ejection time, RT-cε: range of time to peak circumferential strain, RT-lε: range of time to peak longitudinal strain, RT-rε: range of time to peak radial strain, SDT-cε: standard deviation of time to peak circumferential strain, SDT-lε: standard deviation of time to peak longitudinal strain, SDT-rε: standard deviation of time to peak radial strain, SH-cε: segmental heterogeneity in circumferential strain, SH-lε: segmental heterogeneity in longitudinal strain, SH-rε: segmental heterogeneity in radial strain, TH-cε: transmural heterogeneity in circumferential strain,*P<0.05 (two tail), correlation significant, *r*=Spearman correlation coefficient.

Table 9. Relationship between indices derived from conventional echocardiography and left ventricular synchrony and heterogeneity

		LVMI	EPSS	IVS%	LVFW%	FS	EF$_M$	Vcf	PEP:ET	AAT	AVp	AGp	PVp	SV	ESVI	FAC
RT-cε	r	-0.096	0.257	0.075	0.267	0.195	0.202	0.200	-0.139	0.236	-0.213	-0.179	0.360	0.089	-0.297	-0.266
	P	0.680	0.248	0.747	0.242	0.383	0.368	0.385	0.548	0.303	0.342	0.437	0.100	0.701	0.216	0.231
SDT-cε	r	-0.030	0.144	0.043	0.275	0.172	0.190	0.230	-0.034	0.096	-0.083	-0.095	0.339	0.003	-0.133	-0.216
	P	0.898	0.523	0.854	0.228	0.444	0.398	0.316	0.884	0.679	0.712	0.681	0.123	0.989	0.588	0.334
SH-cε	r	-0.118	-0.029	-0.112	-0.004	0.058	0.040	0.187	-0.072	-0.334	0.240	-0.048	0.097	-0.255	-0.144	0.308
	P	0.612	0.900	0.628	0.987	0.799	0.859	0.417	0.758	0.139	0.283	0.836	0.669	0.265	0.557	0.164
TH-cε	r	0.149	0.378	-0.160	-0.083	-0.296	-0.282	-0.209	-0.248	0.264	-0.190	0.239	-0.063	-0.006	-0.044	-0.841
	P	0.518	0.083	0.487	0.720	0.182	0.203	0.364	0.279	0.247	0.397	0.297	0.779	0.978	0.858	0.000*
RT-rε	r	-0.137	0.163	-0.348	-0.112	-0.076	-0.038	0.045	-0.382	0.012	0.215	0.416	0.157	0.114	0.211	0.027
	P	0.552	0.468	0.122	0.630	0.736	0.867	0.845	0.087	0.959	0.335	0.061	0.485	0.624	0.386	0.907
SDT-rε	r	-0.067	0.230	-0.380	-0.144	-0.110	-0.072	0.020	-0.300	0.016	0.187	0.363	0.132	0.120	0.132	0.097
	P	0.773	0.303	0.089	0.535	0.625	0.751	0.931	0.187	0.945	0.404	0.105	0.557	0.606	0.591	0.667
SH-rε	r	0.290	0.087	-0.061	0.257	0.250	0.219	0.265	0.189	-0.156	0.040	-0.012	0.072	-0.325	0.065	0.147
	P	0.202	0.699	0.793	0.260	0.262	0.328	0.245	0.413	0.500	0.861	0.960	0.749	0.151	0.792	0.513
RT-lε	r	0.017	-0.135	0.237	0.248	0.187	0.165	-0.046	0.160	0.451	-0.456	-0.490	0.105	0.038	-0.154	0.168
	P	0.939	0.530	0.276	0.253	0.382	0.441	0.839	0.467	0.031*	0.029*	0.018*	0.626	0.865	0.482	0.432
SDT-lε	r	0.108	-0.038	0.129	0.162	0.221	0.225	-0.087	0.150	0.472	-0.514	-0.485	-0.027	-0.008	-0.222	-0.020
	P	0.642	0.866	0.576	0.482	0.323	0.314	0.707	0.506	0.027*	0.014*	0.022*	0.905	0.970	0.333	0.930
SH-lε	r	0.199	-0.095	-0.024	0.150	0.119	0.270	0.155	-0.046	0.081	0.068	-0.345	0.009	-0.161	-0.067	0.362
	P	0.351	0.652	0.912	0.483	0.572	0.193	0.480	0.830	0.706	0.754	0.098	0.965	0.453	0.754	0.076
Q$_{P-Ao}$	r	0.327	0.230	-0.089	-0.147	-0.171	-0.232	-0.292	0.724	0.205	-0.133	-0.201	-0.421	0.005	-0.127	0.060
	P	0.111	0.268	0.674	0.482	0.414	0.265	0.157	0.000*	0.325	0.525	0.335	0.036*	0.983	0.563	0.819

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AAT: aortic outflow acceleration time, AGp: aortic outflow peak velocity pressure gradient, AVp: aortic outflow peak velocity, EF_M: ejection fraction derived from m-mode, EPSS: E point to septal separation, ESVI: end systolic volume index, FAC: fractional area change, FS: fractional shortening, IVS%: percentage thickening of the interventricular septum, LVFW%: percentage thickening of the left ventricular free wall, LVMI: left ventricular mass index, PEP:ET: pre-ejection time period and ejection time ratio, PVp: pulmonary outflow peak velocity, Q_{P-Ao}: difference between pulmonary pre-ejection time, SV: stroke volume, RT-cε: range of time to peak circumferential strain, RT-lε: range of time to peak longitudinal strain, RT-rε: range of time to peak radial strain, SDT-cε: standard deviation of time to peak circumferential strain, SDT-lε: standard deviation of time to peak longitudinal strain, SDT-rε: standard deviation of time to peak radial strain, SH-cε: segmental heterogeneity in circumferential strain, SH-lε: segmental heterogeneity in longitudinal strain, SH-rε:segmental heterogeneity in radial strain, SV: stroke volume, TH-cε: transmural heterogeneity in circumferential strain, Vcf: velocity of circumferential fiber shortening; *r*=Spearman correlation coefficient, *P*<0.05 (two tail), correlation significant.

Table 10. Comparison MEVp, MAVp, $M_{E/A}$, TEVp, TAVp, $T_{E/A}$, Q_{P-Ao}, IVRT, Tei index with heterogeneity (SH-ε, TH-ε) synchrony (RT-ε, SDT-ε)

	MEVp		MAVp		$M_{E/A}$		TEVp		TAVp		$T_{E/A}$		IVRT		Tei index	
	r	P	r	P	r	P	r	P	r	P	r	P	r	P	r	P
RT-cε	-0.087	0.699	-0.141	0.530	0.123	0.585	-0.148	0.523	-0.237	0.300	0.394	0.077	0.098	0.688	0.055	0.822
SDT-cε	-0.066	0.770	-0.176	0.432	0.189	0.400	-0.016	0.944	-0.200	0.385	0.398	0.074	0.025	0.918	-0.036	0.884
SH-cε	0.042	0.851	0.191	0.395	-0.220	0.326	0.434	0.049*	0.330	0.144	0.077	0.739	-0.340	0.155	-0.042	0.864
TH-cε	-0.187	0.406	-0.040	0.861	-0.085	0.708	-0.103	0.658	-0.335	0.138	0.342	0.129	-0.206	0.397	-0.177	0.468
RT-rε	-0.123	0.585	0.298	0.178	-0.470	0.027*	0.154	0.506	0.225	0.326	-0.211	0.359	-0.275	0.254	0.050	0.839
SDT-rε	-0.208	0.352	0.199	0.375	-0.412	0.056	0.100	0.668	0.157	0.496	-0.174	0.452	-0.282	0.242	0.031	0.901
SH-rε	-0.011	0.962	0.062	0.783	-0.075	0.740	0.124	0.594	0.020	0.931	0.010	0.964	-0.363	0.126	-0.411	0.081
RT-lε	-0.207	0.331	-0.109	0.613	-0.077	0.720	-0.307	0.145	-0.109	0.613	-0.110	0.610	0.489	0.025*	-0.047	0.841
SDT-lε	-0.378	0.083	-0.228	0.307	-0.008	0.972	-0.397	0.067	-0.276	0.214	0.045	0.842	0.461	0.041*	-0.026	0.912
SH-lε	-0.033	0.875	-0.092	0.661	-0.061	0.771	-0.215	0.302	-0.062	0.768	-0.176	0.399	0.011	0.962	-0.359	0.110
Q_{P-Ao}	-0.212	0.309	-0.304	0.140	0.270	0.192	-0.151	0.482	-0.396	0.055	0.543	0.006*	0.313	0.137	0.157	0.464

IVRT: isovolumic relaxation time, MAVp: peak late mitral inflow velocity, $M_{E/A}$: early and late mitral inflow ratio, MEVp: peak early mitral inflow velocity, Q_{P-Ao}: difference between pulmonary pre-ejection time, RT-cε: range of time to peak circumferential strain, RT-lε: range of time to peak longitudinal strain, RT-rε: range of time to peak radial strain, SDT-cε: standard deviation of time to peak circumferential strain, SDT-lε: standard deviation of time to peak longitudinal strain, SDT-rε: standard deviation of time to peak radial strain, SH-cε: segmental heterogeneity in circumferential strain, SH-lε: segmental heterogeneity in longitudinal strain, SH-rε: segmental heterogeneity in radial strain, TAVp: peak late tricuspid inflow velocity, $T_{E/A}$: early and late tricuspid inflow ratio, Tei index: myocardial performance index, TEVp: peak early tricuspid inflow velocity, TH-cε: transmural heterogeneity in circumferential strain.
r=Spearman correlation coefficient,*$P<0.05$ (two tail), correlation significant.

Table 11. Relationship between indices of strain and strain rate and left ventricular synchrony and heterogeneity
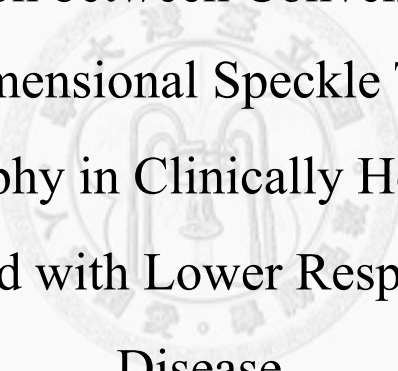
	Q_{P-Ao}		RT-cε		SDT-cε		SH-cε		TH-cε	
	r	P	r	P	r	P	r	P	r	P
CSg	0.130	0.619	-0.150	0.504	-0.078	0.730	0.455	0.034*	-0.817	0.000*
CSRg	-0.010	0.970	-0.210	0.348	-0.128	0.571	0.392	0.071	-0.816	0.000*
CSR$_{-Eg}$	0.155	0.567	-0.043	0.854	0.055	0.812	0.377	0.092	-0.747	0.000*
CSR$_{-Ag}$	-0.498	0.050*	-0.378	0.091	-0.322	0.154	-0.179	0.437	-0.291	0.201
	Q_{P-Ao}		RT-rε		SDT-rε		SH-rε			
RSg	0.065	0.804	-0.349	0.111	-0.283	0.202	0.356	0.104		
RSRg	-0.131	0.615	-0.079	0.728	-0.043	0.850	0.230	0.303		
RSR$_{-Eg}$	0.135	0.617	-0.291	0.213	-0.259	0.271	0.078	0.743		
RSR$_{-Ag}$	-0.401	0.124	0.223	0.345	0.229	0.332	0.215	0.363		
	Q_{P-Ao}		RT-lε		SDT-lε		SH-lε			
LSg	0.118	0.642	0.010	0.961	-0.138	0.539	0.481	0.015*		
LSRg	0.040	0.874	0.059	0.784	-0.081	0.721	0.389	0.054		
LSR$_{-Eg}$	0.137	0.672	0.006	0.982	-0.040	0.893	0.291	0.292		
LSR$_{-Ag}$	-0.132	0.699	0.335	0.242	0.401	0.174	0.055	0.852		

CS: global peak circumferential strain, CSR$_{-Ag}$: global peak circumferential late diastolic strain rate, CSR$_{-Eg}$: global peak circumferential early diastolic strain rate, CSRg: global peak circumferential systolic strain rate, LS: longitudinal strain, LSR$_{-Ag}$: global peak longitudinal late diastolic strain rate, LSR$_{-Eg}$: global peak longitudinal early diastolic strain rate, LSRg: global peak longitudinal systolic strain rate, Q_{P-Ao}: difference between pulmonary pre-ejection time and aortic pre-ejection time, RS: radial strain, RSR$_{-Ag}$: global peak radial late diastolic strain rate, RSR$_{-Eg}$: global peak radial early diastolic strain rate, RSRg: global peak radial systolic strain rate, RT-cε: range of time to peak circumferential strain, RT-lε: range of time to peak longitudinal strain, RT-rε: range of time to peak radial strain, SDT-cε: standard deviation of time to peak circumferential strain, SDT-lε: standard deviation of time to peak longitudinal strain, SDT-rε: standard deviation of time to peak radial strain, SH-cε: segmental heterogeneity in circumferential strain, SH-lε: segmental heterogeneity in longitudinal strain, SH-rε: segmental heterogeneity in radial strain, TH-cε: transmural heterogeneity in circumferential strain.

r=Spearman correlation coefficient,*P<0.05 (two tail), significant correlation.

Chapter III

Comparison between Conventional and
Two-Dimensional Speckle Tracking
Echocardiography in Clinically Healthy Cats and
Cats Affected with Lower Respiratory Tract
Disease

Key to abbreviations

2D-STE	Two-dimensional speckle tracking echocardiography
AAT	Aortic outflow acceleration time
AGp	Aortic outflow peak velocity pressure gradient
AVp	Aortic outflow peak velocity
BW	Body weight
CS	Peak circumferential strain
CSg	Global peak circumferential strain
CSR	Peak circumferential systolic strain rate
CSR_{-A}	Peak circumferential late diastolic strain rate
CSR_{-Ag}	Global peak circumferential late diastolic strain rate
CSR_{-E}	Peak circumferential early diastolic strain rate
CSR_{-Eg}	Global peak circumferential early diastolic strain rate
CSRg	Global peak circumferential systolic strain rate
EF_M	Ejection fraction derived from m-mode
EF_{ste}	Ejection fraction derived from speckle tracking echocardiography
EPSS	E point to septal separation
ESVI	End systolic volume index
FAC	Fractional area change
FS	Fractional shortening
HR	Heart rate
IVRT	Isovolumic relaxation time
IVS%	Percentage thickening of the interventricular septum
IVSd	Interventricular septal thickness in end diastole
LA/Ao	The ratio of left atrium and aortic diameter
LS	Peak longitudinal strain
LSg	Global peak longitudinal strain
LSR	Peak longitudinal systolic strain rate
LSR_{-A}	Peak longitudinal late diastolic strain rate
LSR_{-Ag}	Global peak longitudinal late diastolic strain rate
LSR_{-E}	Peak longitudinal early diastolic strain rate
LSR_{-Eg}	Global peak longitudinal early diastolic strain rate
LSRg	Global peak longitudinal systolic strain rate
LVDd	Left ventricular dimension in end-diastole
LVDs	Left ventricular dimension in end-systole
LVFW%	Percentage thickening of the left ventricular free wall
LVFWd	Left ventricular free wall thickness in end-diastole

LVFWs	Left ventricular free wall thickness in end-systole
LVMI	Left ventricular mass index
MAvp	Peak late mitral inflow velocity
$M_{E/A}$	Early and late mitral inflow ratio
MEVp	Peak early mitral inflow velocity
PEP:ET	Pre-ejection time period and ejection time ratio
PVp	Pulmonary outflow peak velocity
Q_{P-Ao}	Difference between pulmonary pre-ejection time and aortic pre-ejection time
RS	Peak radial strain
RSg	Global peak radial strain
RSR	Peak radial systolic strain rate
RSR_A	Peak radial late diastolic strain rate
RSR_{Ag}	Global peak radial late diastolic strain rate
RSR_E	Peak radial early diastolic strain rate
RSR_{Eg}	Global peak radial early diastolic strain rate
RSRg	Global peak radial systolic strain rate
RT-cε	Range of the 6 segment time to peak circumferential strain
RT-lε	Range of the 6 segment time to peak longitudinal strain
RT-rε	Range of the 6 segment time to peak radial strain
RT-ε	Range of the 6 segment time to peak strain
SDT-cε	Standard deviation of the 6 segment time to peak circumferential strain
SDT-lε	Standard deviation of the 6 segment time to peak longitudinal strain
SDT-rε	Standard deviation of the 6 segment time to peak radial strain
SDT-ε	Standard deviation of the 6 segment time to peak strain
Sg	Global peak strain
SH-cε	Circumferential segmental heterogeneity
SH-lε	Longitudinal segmental heterogeneity
SH-rε	Radial segmental heterogeneity
SH-ε	Segmental heterogeneity
SR	Peak systolic strain rate
SR_A	Peak late diastolic strain rate
SR_{Ag}	Global peak late diastolic strain rate
SR_E	Peak early diastolic strain rate
SR_{Eg}	Global peak early diastolic strain rate
SRg	Global peak strain rate
SV	Stroke volume

TAVp   Peak late tricuspid inflow velocity

$T_{E/A}$ Early and late tricuspid inflow ratio

Tei index   Myocardial performance index

TEVp   Peak early tricuspid inflow velocity

TH-ε   Transmural heterogeneity

Vcf   Velocity of circumferential fiber shortening

ε   Langarian strain

Comparison between Conventional and Two-Dimensional Speckle Tracking Echocardiography in Clinically Healthy Cats and Cats Affected with Lower Respiratory Tract Disease

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Abstract

Feline lower respiratory tract disease (LRTD), also known as asthma, is a syndrome characterized by acute bronchoconstriction, the clinical sigh of which is similar to cardiac failure. The aim of this study was to analysis left ventricular deformation change by application 2D-STE in cat with LRTD.

Fifty-six cats were included in this study. These cats were further categorized to clinically healthy control (n=34) and LRTD (n=22). Physical examinations, blood pressure measurement, routine blood examinations, chest radiographs, conventional echocardiography and 2D-STE were carried out in all cats in both groups.

Indices of conventional echocardiography were not different between two groups, but impaired systolic and diastolic function was detected in LRTD based on using circumferential/longitudinal strain of 2D-STE. Decreased transmural heterogeneity and ejection fraction/fractional area change those were derived from 2D-STE were also found. No difference of synchrony and heterogeneity were detected between two groups.

The deformation changes mainly affected the segments of left ventricle free wall. In the cats with LRTD, no change of stroke volume and end diastolic dimension were detected, no pulmonary to tricuspid regurgitation were identified either. These findings suggested that even in a very mild degree of lower respiratory tract disease the function of left ventricle could be affected.

Key words: cat, left ventricle, lower respiratory tract disease, two-dimensional speckle tracking echocardiography

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Introduction

The impact of respiratory diseases on cardiac function has been intensively discussed in past fifty years in human patients. Changes in the volume or pressure of right ventricular may affect the condition of systole and diastole in left ventricle via pericardium and interventricular septum (ventricular interdependence) [1-5].

Feline lower respiratory tract disease (LRTD), also known as asthma, is a syndrome characterized by acute bronchoconstriction that can lead to cough and respiratory distress [6]. These clinical signs are also consistent with left sided heart failure in cats [7]. Study regarding cardiac function in association with respiratory diseases in cats is very limited. The aims of this study were to assess cardiac function and myocardial deformation in cats with lower respiratory tract using different modalities of echocardiography.
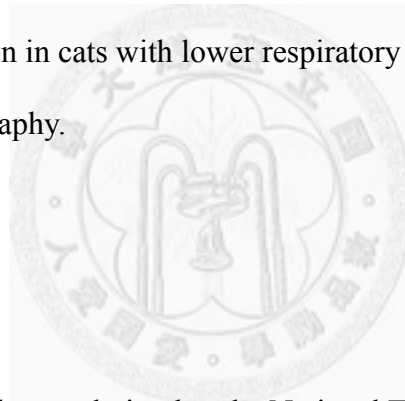
Material and Method

Animals

Fifty-six client-owned cats admitted to the National Taiwan University Veterinary Hospital during 2010-2012 were included for this perspective study. These cats were further categorized into groups of clinically healthy control and LRTD. All cats underwent a complete physical examination, blood pressure measurements, routine blood work (complete blood counts and biochemical profiles) examinations, chest radiography, conventional echocardiography, and two-dimensional speckle-tracking echocardiography (2D-STE).

Clinically healthy cats (control)

Among these 56 cats, 34 that were clinically healthy cats for annual wellness recheck and without history of respiratory signs were deemed as healthy controls in

this study. The mean age was 3.1 ± 2.2 years (range 6 months to 8 years old), with a mean body weight of 4.3 ± 1.3 kg; 18 were males, and 16 were females. Breeds represented in this group were 19 Domestic Short-hairs, 6 American Short-hairs, 7 Persians, 1 Bengal cat and 1 British Blue.

Cats with lower respiratory tract disease (LRTD)

The remaining 22 cats that were presented with intermittent to continuous respiratory signs (cough, respiratory distress and open mouth breathing) were categorized into LRTD group. The inclusion criteria of LRTD in this group were based on clinical signs, chest radiographs [8, 9], and results of provocative barometric whole-body plethysmography test. The mean age of this group was 5.0 ± 3.4 (range of 5 month to 12 years). A mean body weight was 4.5 ± 0.9 kg, 12 were males, and 10 were females. The represented breeds were 12 Domestic short-hairs, 3 each of Persians and Himalayas, 2 American short-hairs, and 1 each of English short-haired and Siamese crossed bred

Clinical evaluation

Conventional echocardiography

Ultrasound examinations were performed without sedation with gentle restrain in lateral recumbency [10].

Indices of left ventricle was including left ventricular diastolic dimension (LVDd), left ventricular systolic dimension (LVDs), the ratio of Left atrium and aortic diameter (LA/Ao), interventricular septal thickness in diastole (IVSd), left ventricular free wall thickness in diastole (LVFWd), and left ventricular mass index (LVMI) were obtained from the standard views [11, 12].

Parameters of left ventricular systolic function were derived from M-mode, including end-posterior E point to septal separation (EPSS), percentage thickening of

the interventricular septum (IVS%), percentage thickening of the left ventricular free wall(LVFW%), fractional shortening (FS), ejection fraction by M-mode (EF_M); parameters were derived from pulse-wave Doppler including velocity of circumferential fiber shortening (Vcf), the ratio of pre-ejection period an ejectiontime (PEP:ET), Aortic outflow acceleration time (AAT), including aortic outflow peak velocity (AVp), aortic outflow peak velocity pressure gradient (AGp), pulmonary outflow peak velocity (PVp), stroke volume (SV), and derived from B mode, including end systolic volume index (ESVI) were obtained from the standard views [12-21].

Parameters of left ventricular diastolic function were including mitral early and late diastolic inflow velocity (MEVp, MAVp), and tricuspid early and late diastolic inflow velocity (TEVp, TAVp), the ratio between MEVp and MAVp ($M_{E/A}$), the ratio between TEVp and TAVp ($T_{E/A}$), isovolumic relaxation time (IVRT), and myocardial performance index (Tei index) were obtained from the standard views [14, 22, 23].

Interventricular synchrony, the difference between pulmonary pre-ejection time and aortic pre-ejection time (Q_{P-Ao}) was obtained from standard views [24].

Two-dimensional speckle tracking echocardiography

Measurement regional strain and strain rate

Indices of left ventricular longitudinal and circumferential/radial/longitudinal strain and strain rates were obtained using right parasternal apical 4-chamber and short axis views, respectively. All images were acquired in cine loops of 3 cardiac cycles recorded at frame rate of 54-111 frames per seconds, saved in digital format, and analyzed by off-line software ($XStrain^{TM}$ software for MyLabTM50 X Vision).

In quantification of strain and strain, 6 segments (cranio-septum, cranial, lateral, caudal, ventral, and septal) of endocardium and another 6 segments of epicardium for

epicardial circumferential strain were semi-automatically selected by Aided Heart

Segmentation (AHS) for analysis; 6 segments (craniao-septum, cranial, lateral, caudal,

ventral, and septal) across endocardium to epicardium were semi-automatically

selected by AHS for radial strain analysis. In left ventricular longitudinal strain and

strain rate, 6 segments (basal-septal, mid-septal, apical-septal, apical-lateral,

mid-lateral, basal-lateral) of endocardium were semi-automatically automatically

selected by the AHS tool for analysis. Left ventricular ejection volume (EF_{ste}) and

fraction area change (FAC) were also calculated by modified Simpson's rule.

The STE indices included in this study were circumferential/radial/longitudinal

systolic peak strain (CS/RS/LS), circumferential/radial/longitudinal systolic peak

strain rate (CRS/RSR/LSR), circumferential/radial/longitudinal peak early diastolic

strain rate ($CSR_E/RSR_E/LSR_E$) and circumferential/radial/longitudinal peak late

diastolic strain rate ($CSR_A/RSR_A/LSR_A$). The STE off-line analysis was performed

by 1 examiner (YLH)

The images without adequate visualization of one or more segments of the

endocardium were excluded from this study.

Measurement of synchrony and heterogeneity

Interventricular synchrony, defined as time difference between mean pulmonary

and aortic pre-ejection periods (Q_{P-Ao}), was calculated based on conventional pulse

wave-Doppler. Intraventricular synchrony, defined as the standard deviation of the six

segments time to reach peak strain (SDT-ε) at longitudinal (SDT-lε), circumferential

(SDT-cε) and radial (SDT- rε) directions, and the range of the six segments time to

peak strain (RT-ε) at longitudinal (RT-lε), circumferential (RT-cε) and radial (RT-rε)

directions were also calculated. Segmental heterogeneity (SH-ε), defined as the range

of the peak strain of the six segments, and transmural heterogeneity (TH-ε), defined as

the difference strain between endocardium and epicardium were also calculated

Statistical analysis

Continuous data are presented as mean ± SD. Normality was assessed by using Kolmogorov-Smirnov test. Group data of conventional echocardiography (LVMI, IVSd, LFFWd, LVDd, LVDs, LA/Ao; EPSS, IVS%, LVFW%, FS, EF_M; PEP:ET, AAT, AVp, AGp, PVp SV, mitral inflow, tricuspid inflow, IVRT and Tei index; Vcf) and STE (strain, SR, FAC, EF_{ste})were compared using 2-tailed independent Student t-test. In the event of cohorts of variables without a normal distribution, comparisons were done with Mann-Whitney U test. $P<0.05$ were considered to be statistically significant.

Results

The demographic information of control and LRTD is listed at Table 1. Gender (P=0.906) and age (P=0.054) were not different between these two groups, heart rate was significantly higher in LRTD (P<0.005, Table 4-6).

Indices of conventional echocardiography

Differences of left ventricular indices, including LVMI, IVSd, LVFWd, LVDd, LVDs and LA/Ao were all not significant (Table 2). Indices derived from M-mode (EPSS, IVS%, LVFW%, FS and EF_M), and from pulse-wave Doppler (PEP: ET, AAT, AVp, AGp, PVp SV, mitral inflow, tricuspid inflow, IVRT and Tei index) and Vcf were not different between these 2 groups (Table 3).

Indices derived from myocardial strain

Global CS, CSRg, and CSR-Eg were significantly decreased in LRTD group (Table 4). Global radial strain and strain rate were not different between control and

LRTD (Table 5). Global LS and LSRg were significantly decreased in LRTD group (Table 6).

EF$_{ste}$ and FAC

The EF$_{ste}$ and FAC derived from speckle tracking echocardiography were significantly decreased in LRTD (Table 7).

Synchrony and heterogeneity

Indices of ventricular synchrony were not different between control and LRTD (Table 8). Segmental heterogeneity was not different between control and LRTD (Table 8). Circumferential transmural heterogeneity was significantly decreased in LRTD (*P*=0.034, Table 8).

Discussion

Left sided heart failure and LRTD share similar clinical signs, cough and respiratory distress. These two conditions cannot be discriminated by the heart rate or absence of cardiac murmurs. Absence of murmur is prevalent in cats with clinical signs of heart failure [25-28]. In this study, indices derived from conventional echocardiography in control and LRTD were not different. This finding suggests that echocardiography may distinguish LRTD from left sided heart failure if results of physical examination or chest radiographs are not conclusive. Indices of echocardiography are normal in coughing cats are highly unlikely to be affected with cardiac disease.

Although no difference of indices derived from conventional echocardiography was found between control and LRTD, significantly decreased left ventricular strain in circumferential and longitudinal systole and significantly decreased circumferential

early diastole were found in this study. Decreased transmural heterogeneity was also found in cats with LRTD. Changes in the volume or pressure of right ventricular may influence the condition of systole and diastole in left ventricle via the pericardium and interventricular septum. In this study, decreasing systolic function in terms of reduces EF_{ste} / FAC, also reflected the decreasing transmural heterogeneity in cats with LRTD[29]. The decreasing pattern of our finding was different comparing with the human patients suffering from pulmonary disorders/hypertension [30-32]. Ventricular interdependence has been exhibited in human patients with pulmonary hypertension [33]. Interventricular septum plays an important role in ventricular interdependence. Impact of pressure gradient between right and left ventricles, pulmonary hypertension resulted from chronic hypoxia and volume expansion of right ventricle may indirectly affect compliance of interventricular septum and left ventricular deformation [2, 3, 5, 33-35]. Left ventricular dyssynchrony may develop eventually [36]. However, in this study no ventricular dyssynchrony and segmental heterogeneity was detected in LRTD. The affected segments were mainly on the free wall of left ventricle. The mechanism of the discrepancies was not clear. Nevertheless, no pulmonary or tricuspid regurgitation was detected in our cases. In addition, the end diastole dimension and stroke volume were not different from the control. This suggested that pulmonary hypertension had not yet developed in these cases. Impact of pressure or volume right ventricle on the interventricular septum and left ventricle might be subtle at this stage. Only decreased myocardial strain and EF_{ste}/FAC derived from strain were detected. These findings supported that the LS of left ventricle has decreased before decreasing systolic function right ventricle has developed in asthma patients [32].

Longitudinal study is needed to clarify the impact of decreasing strain and strain

rate in LRTD group and further provide prognostic and diagnostic value in clinical application.

Conclusion

Impaired systolic and diastolic function of left ventricle was developed as mild as the secondary pulmonary hypertension and ventricular interdependence could not be detected by the conventional echocardiography.

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Table 1. Comparison of demographics between clinically healthy cats (control) and acts with lower respiratory tract disease (LRTD)

	Control (n=34)	LRTD (n=22)	*P*
Age (years)	3.11 ± 2.17	4.96 ± 3.42	0.054
Body weight (kg)	4.32 ± 1.32	4.46 ± 0.94	0.661
Sex	Male : female =18 : 16	Male : female =12 : 10	0.906
Heart rate (beats/min)	171.97 ± 27.23	182.05 ± 29.23	0.151
Systemic blood pressure (mmHg)	119.47 ± 15.15	115.24 ± 29.79	0.985

P<0.05 (two tail), statistically significant.

Table 2. Comparison of left ventricular indices between clinically healthy cats (control) and acts with lower respiratory tract disease (LRTD)

	Control (n=34)	LRTD (n=22)	*P*
LVMI (g/m^2)	28.53 ± 7.31	27.19 ± 6.08	0.484
IVSd (mm)	4.08 ± 0.61	3.87 ± 0.54	0.236
LVFWd (mm)	4.17 ± 0.65	4.14 ± 0.62	0.889
LVDd (mm)	14.98 ± 1.63	15.21 ± 1.73	0.624
LVDs (mm)	6.81 ± 1.58	6.89 ± 1.47	0.854
LA/Ao	1.35 ± 0.16	1.36 ± 0.17	0.811

IVSd: interventricular septal thickness in end diastole, LA/Ao: the ratio of left atrium and aortic diameter, LVDd: left ventricular dimension in end-diastole, LVDs: left ventricular dimension in end-systole, LVFWd: left ventricular free wall thickness in end-diastole, LVMI: left ventricular mass index.

P<0.05 (two tail), statistically significant.

Table 3. Comparison of indices derived from conventional echocardiography between clinically healthy cats (control) and acts with lower respiratory tract disease (LRTD)

	Control (n=34)	LRTD (n=22)	*P*
EPSS (mm)	0.43 ± 0.25	0.52 ± 0.29	0.451
IVS % (%)	69.66 ± 17.84	72.61 ± 1.35	0.583
LVFW% (%)	63.19 ± 15.24	63.12 ± 18.28	0.989
FS (%)	54.74 ± 8.01	54.30 ± 6.75	0.832
EF_M (%)	87.24 ± 6.53	87.52 ± 5.63	0.866
Vcf (circumferences/s)	0.38 ± 0.07	0.39 ± 0.08	0.693
PEP:ET	0.29 ± 0.08	0.29 ± 0.07	0.869
AAT (ms)	25.53 ± 7.74	26.93 ± 12.10	0.870
AVp (m/s)	0.95 ± 0.20	0.93 ± 0.22	0.762
AGp (mmHg)	1.12 ± 0.43	1.13 ± 0.51	0.820
PVp (m/s)	0.90 ± 0.18	0.93 ± 0.22	0.565
SV (ml)	354.1 ± 97.93	364.88 ± 7.86	0.785
ESVI (ml/m^2)	5.11 ± 1.96	6.12 ± 2.77	0.145
MEVp (m/s)	0.82 ± 0.14	0.82 ± 0.15	0.863
MAVp (m/s)	0.68 ± 0.16	0.74 ± 0.23	0.282
$M_{E/A}$	1.25 ± 0.27	1.19 ± 0.31	0.474
TEVp (m/s)	0.65 ± 0.15	0.59 ± 0.13	0.102
TAVp (m/s)	0.52 ± 0.14	0.50 ± 0.14	0.424
$T_{E/A}$	1.29 ± 0.27	1.21 ± 0.27	0.297
Q_{P-Ao} (ms)	-3.90 ± 13.22	-5.46 ± 13.06	0.708
IVRT (ms)	44.17 ± 7.42	42.54 ± 8.35	0.480
Tei index	0.51 ± 0.09	0.86 ± 1.44	0.586

AAT: aortic outflow acceleration time, AGp: aortic outflow peak velocity pressure gradient, AVp: aortic outflow peak velocity, EF_M: ejection fraction derived from m-mode, EPSS: E point to septal separation, ESVI: end systolic volume index,

FS: fractional shortening, IVRT: isovolumic relaxation time, IVS %: percentage thickening of the interventricular septum, LVFW%: percentage thickening of the left ventricular free wall, MAVp: peak late mitral inflow velocity, $M_{E/A}$: early and late mitral inflow ratio, MEVp: peak early mitral inflow velocity, PEP:ET: pre-ejection time period and ejection time ratio, PVp: pulmonary outflow peak velocity, Q_{P-Ao}: difference between pulmonary pre-ejection time and aortic pre-ejection time, SV: stroke volume, TAVp: peak late tricuspid inflow velocity, $T_{E/A}$: early and late tricuspid inflow ratio, Tei index: myocardial performance index, TEVp: peak early tricuspid inflow velocity, Vcf: velocity of circumferential fiber shortening.

P<0.05 (two tail), statistically significant.

Table 4. Comparison of circumferential strain and strain rate between clinically healthy cats (control) and acts with lower respiratory tract disease (LRTD)

Circumferential	Control (n=34)	LRTD (n=22)	*P*
Heart rate (bpm)	161.27 ± 23.38	187.62 ± 28.80	*0.002*
CS_1 (%)	-21.87 ± 6.69	-14.92 ± 5.72	*0.001*
CS_2 (%)	-21.83 ± 6.40	-14.86 ± 4.29	*0.000*
CS_3 (%)	-21.82 ± 5.97	-15.87 ± 6.05	*0.002*
CS_4 (%)	-21.98 ± 7.81	-17.46 ± 5.44	*0.034*
CS_5 (%)	-21.90 ± 8.52	-19.67 ± 6.91	0.466
CS_6 (%)	-23.03 ± 7.15	-18.94 ± 7.42	0.073
CSg (%)	-22.26 ± 5.01	-16.95 ± 4.15	*0.001*
CSR_1 (s^{-1})	-2.60 ± 0.78	-1.74 ± 0.53	*0.00014*
CSR_2 (s^{-1})	-2.73 ± 0.97	-1.87 ± 0.37	*0.001*
CSR_3 (s^{-1})	-2.77 ± 0.95	-2.11 ± 0.89	*0.024*
CSR_4 (s^{-1})	-2.75 ± 1.21	-2.22 ± 0.81	0.152
CSR_5 (s^{-1})	-2.73 ± 1.17	-2.58 ± 0.95	0.952
CSR_6 (s^{-1})	-2.61 ± 0.87	-2.28 ± 0.97	0.244
CSRg	-2.7 ± 0.72	-2.13 ± 0.51	*0.005*
CSR_{-E1} (s^{-1})	2.71 ± 1.33	1.45 ± 0.83	*0.007*
CSR_{-E2} (s^{-1})	2.33 ± 1.09	1.45 ± 0.63	*0.014*
CSR_{-E3} (s^{-1})	2.35 ± 1.00	1.60 ± 0.62	*0.026*
CSR_{-E4} (s^{-1})	2.22 ± 1.41	1.91 ± 0.75	0.503
CSR_{-E5} (s^{-1})	2.33 ± 1.39	1.76 ± 0.83	0.213
CSR_{-E6} (s^{-1})	2.53 ± 0.91	1.65 ± 0.86	*0.010*
CSR_{-Eg} (s^{-1})	2.39 ± 0.81	1.59 ± 0.70	*0.003*
CSR_{-A1} (s^{-1})	0.99 ± 0.38	1.12 ± 0.71	0.561
CSR_{-A2} (s^{-1})	0.99 ± 0.23	0.95 ± 0.53	0.794
CSR_{-A3} (s^{-1})	1.13 ± 0.51	1.66 ± 1.66	0.410
CSR_{-A4} (s^{-1})	1.15 ± 0.74	1.43 ± 1.35	0.517
CSR_{-A5} (s^{-1})	1.33 ± 0.63	1.42 ± 0.88	0.762
CSR_{-A6} (s^{-1})	1.21 ± 0.48	1.53 ± 0.82	0.335
CSR_{-Ag} (s^{-1})	1.16 ± 0.32	1.34 ± 0.95	0.470

C_1: cranio-septal, C_2: cranial, C_3: lateral, C_4: caudal, C_5: ventral, C_6: septal, Cg: global, CS: peak circumferential strain, CSR: peak circumferential strain rate, CSR_{-A}: peak circumferential late diastolic strain rate, CSR_{-E}: peak circumferential early diastolic strain rate.

P<0.05 (two tail), statistically significant.

Table 5. Comparison of radial strain and strain rate between clinically healthy cats (control) and acts with lower respiratory tract disease (LRTD)

Radial	Control (n=34)	LRTD (n=22)	*P*
Heart rate(bpm)	162.00 ± 22.92	188.86 ± 31.51	*0.003*
RS_1 (%)	26.32 ± 11.64	21.34 ± 17.62	0.279
RS_2 (%)	25.50 ± 13.58	21.17 ± 18.06	0.378
RS_3 (%)	27.12 ± 12.76	21.30 ± 18.07	0.228
RS_4 (%)	27.38 ± 10.36	19.56 ± 17.30	0.198
RS_5 (%)	28.68 ± 10.04	21.20 ± 19.25	0.123
RS_6 (%)	29.46 ± 12.71	23.19 ± 19.86	0.229
RSg (%)	26.08 ± 8.18	21.29 ± 16.51	0.241
RSR_1 (s^{-1})	2.40 ± 0.82	2.53 ± 1.08	0.961
RSR_2 (s^{-1})	2.38 ± 1.02	2.53 ± 1.04	0.680
RSR_3 (s^{-1})	2.46 ± 0.95	2.62 ± 1.10	0.608
RSR_4 (s^{-1})	2.43 ± 0.84	2.55 ± 1.10	0.686
RSR_5 (s^{-1})	2.67 ± 1.00	2.84 ± 1.30	0.615
RSR_6 (s^{-1})	2.74 ± 1.00	2.85 ± 1.37	0.781
RSR_g (s^{-1})	2.51 ± 0.71	2.65 ± 0.98	0.591
RSR_{-E1} (s^{-1})	-2.18 ± 1.59	-1.67 ± 1.01	0.358
RSR_{-E2} (s^{-1})	-2.09 ± 1.20	-1.68 ± 0.91	0.376
RSR_{-E3} (s^{-1})	-2.28 ± 1.06	-1.54 ± 0.94	0.107
RSR_{-E4} (s^{-1})	-1.89 ± 1.01	-1.96 ± 1.48	0.888
RSR_{-E5} (s^{-1})	-1.92 ± 1.26	-2.15 ± 0.90	0.632
RSR_{-E6} (s^{-1})	-2.06 ± 1.56	-1.71 ± 1.14	0.492
RSR_{-Eg} (s^{-1})	-1.99 ± 1.12	-1.61 ± 0.80	0.246
RSR_{-A1} (s^{-1})	-1.62 ± 0.93	-2.14 ± 1.36	0.227
RSR_{-A2} (s^{-1})	-1.55 ± 0.82	-1.97 ± 1.55	0.386
RSR_{-A3} (s^{-1})	-1.69 ± 0.93	-2.48 ± 1.76	0.166
RSR_{-A4} (s^{-1})	-1.70 ± 0.90	-1.82 ± 1.26	0.790
RSR_{-A5} (s^{-1})	-1.80 ± 0.88	-1.19 ± 0.52	0.079
RSR_{-A6} (s^{-1})	-1.92 ± 1.10	-1.69 ± 1.76	0.674
RSR_{-Ag} (s^{-1})	-1.82 ± 0.85	-1.74 ± 1.62	0.852

R_1: cranio-septal, R_2: cranial, R_3: lateral, R_4: caudal, R_5: ventral, R_6: septal, Rg: global, RS: peak radial strain, RSR: peak radial strain rate, RSR_{-A}: peak radial late diastolic strain rate, RSR_{-E}: peak radial early diastolic strain rate.

P<0.05 (two tail), statistically significant.

Table 6. Comparison of longitudinal strain and strain rate between clinically healthy cats (control) and acts with lower respiratory tract disease (LRTD)

Longitudinal	Control (n=34))	LRTD (n=22)	*P*
Heart rate (bpm)	182.60 ± 28.04	188.67 ± 29.45	0.519
LS_1 (%)	-18.69 ± 4.92	-17.16 ± 6.31	0.396
LS_2 (%)	-18.85 ± 4.46	-17.28 ± 4.41	0.286
LS_3 (%)	-15.36 ± 6.30	-13.80 ± 3.84	0.392
LS_4 (%)	-13.67 ± 5.37	-10.07 ± 4.05	*0.031*
LS_5 (%)	-19.84 ± 8.00	-14.05 ± 5.13	*0.017*
LS_6 (%)	-22.93 ± 10.80	-16.84 ± 5.86	*0.027*
LS_g (%)	-18.22 ± 4.78	-14.87 ± 2.86	*0.008*
LSR_1 (s^{-1})	-2.23 ± 0.70	-2.03 ± 0.89	0.423
LSR_2 (s^{-1})	-2.33 ± 0.59	-1.97 ± 0.73	0.098
LSR_3 (s^{-1})	-1.87 ± 0.84	-1.70 ± 0.63	0.505
LSR_4 (s^{-1})	-1.63 ± 0.66	-1.23 ± 0.52	0.053
LSR_5 (s^{-1})	-2.42 ± 1.00	-1.70 ± 0.66	*0.017*
LSR_6 (s^{-1})	-2.80 ± 1.24	-1.95 ± 0.64	*0.049*
LSR_g (s^{-1})	-2.21 ± 0.58	-1.76 ± 0.49	*0.016*
LSR_{-E1} (s^{-1})	1.88 ± 0.81	1.15 ± 0.55	0.088
LSR_{-E2} (s^{-1})	1.89 ± 0.65	1.29 ± 0.25	0.151
LSR_{-E3} (s^{-1})	1.55 ± 0.81	1.54 ± 0.43	0.981
LSR_{-E4} (s^{-1})	1.29 ± 0.82	1.40 ± 0.86	0.806
LSR_{-E5} (s^{-1})	1.78 ± 1.12	2.08 ± 0.72	0.594
LSR_{-E6} (s^{-1})	1.80 ± 1.37	2.08 ± 1.19	0.703
LSR_{-Eg} (s^{-1})	1.52 ± 0.73	1.59 ± 0.60	0.827
LSR_{-A1} (s^{-1})	1.55 ± 0.98	1.16 ± 0.38	0.465
LSR_{-A2} (s^{-1})	1.45 ± 0.45	0.82 ± 0.68	0.236
LSR_{-A3} (s^{-1})	0.92 ± 0.52	1.36 ± 0.76	0.199
LSR_{-A4} (s^{-1})	0.93 ± 0.55	0.26 ± 0.15	*0.038*
LSR_{-A5} (s^{-1})	1.28 ± 0.94	0.44 ± 0.57	0.096
LSR_{-A6} (s^{-1})	1.42 ± 1.16	1.14 ± 0.85	0.642
LSR_{-Ag} (s^{-1})	1.21 ± 0.57	1.04 ± 0.48	0.475

L_1: basal septal, L_2: mid septal, L_3: apical septal, L_4: apical lateral, L_5: mid lateral, L_6: basal lateral, L_g: global, LS: peak longitudinal strain, LSR: peak longitudinal strain rate, LSR_{-A}: peak longitudinal late diastolic strain rate, LSR_{-E}: peak longitudinal early diastolic strain rate.

P<0.05 (two tail), statistically significant.

Table 7. Comparison of left ventricular ejection volume (EF$_{ste}$) and fraction area change (FAC) between clinically healthy cats (control) and cats with lower respiratory tract disease (LRTD)

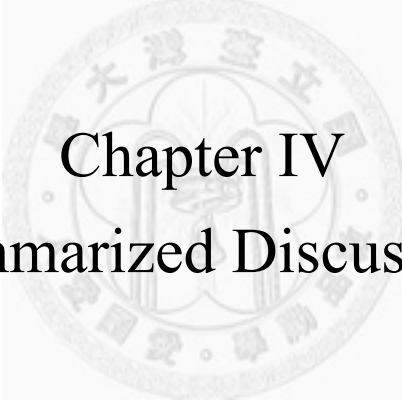|	Control (n=34)	LRTD (n=22)	*P*
FAC (%)	44.63 ± 8.36	36.30 ± 6.60	*0.001*
EF$_{ste}$ (%)	48.81 ± 9.61	41.43 ± 10.50	*0.029*

EF$_{ste}$: Ejection fraction derived from speckle tracking echocardiography, FAC: Fractional area change derived from speckle tracking echocardiography.

$P<0.05$ (two tail), statistically significant.

Table 8. Comparison of ventricular synchrony (RT-cε, SDT-cε) and heterogeneity (SH-ε and TH-ε) between clinically healthy cats (control) and cats with lower respiratory tract disease (LRTD)

Parameter	Control (n=34)	LRTD (n=22)	*P*
RT-cε (ms)	32.49 ± 9.32	37.78 ± 20.56	0.576
RT-rε (ms)	40.21 ± 28.72	46.79 ± 52.27	0.836
RT-lε (ms)	44.24 ± 22.62	49.45 ± 28.34	0.530
SDT-cε (ms)	11.74 ± 4.16	14.27 ± 7.55	0.481
SDT-rε (ms)	16.48 ± 13.41	17.76 ± 19.45	0.752
SDT-lε (ms)	19.38 ± 8.52	19.65 ± 10.90	0.933
SH-cε (%)	13.05 ± 5.86	11.18 ± 7.39	0.362
SH-rε (%)	19.06 ± 10.34	18.83 ± 10.30	0.942
SH-lε (%)	15.38 ± 6.81	11.54 ± 6.12	0.081
TH-cε (%)	-14.28 ± 4.60	-11.43 ± 3.53	*0.034*

RT-cε: range of time to peak circumferential strain, RT-lε: range of time to peak longitudinal strain, RT-rε: range of time to peak radial strain, SDT-cε: standard deviation of time to peak circumferential strain, SDT-lε: standard deviation of time to peak longitudinal strain, SDT-rε: standard deviation of time to peak radial strain, SH-cε: segmental heterogeneity in circumferential strain, SH-lε: segmental heterogeneity in longitudinal strain, SH-rε: segmental heterogeneity in radial strain TH-cε: transmural heterogeneity in circumferential strain.

$P<0.05$ (two tail), statistically significant.

Chapter IV
Summarized Discussion

Summarized discussion

Myocardial strain and strain rate in cats was almost independent to age, body weight and heart. However, circumferential strain was lower in male. Based on the finding of ventricular heterogeneity and synchrony circumferential strain was decreasing from subendocardium to subepicardium, and lower strain was at cardiac apex.

Systolic strain was correlated to diastolic indices in conventional echocardiography. It is indicated that systolic deformation was in associated with overall diastolic function. More cases in both diseased and clinically healthy cats are needed define the link [1].

Impact of lower respiratory tract disease on left ventricular deformation in cats was assessed. Impaired systolic and diastolic function was not detected by conventional echocardiography but myocardial strain. No change of right ventricular functions or pulmonary hypertension was detected using conventional echocardiography. It is implied that the advantage of speckle tracking echocardiography in detection of early left ventricular deformation before cardiac geometry changed by volume or pressure overloading from right heart. However, the affected segments of myocardium were in the free wall, which different from human patients with pulmonary hypertension [2-4]. The exact mechanism was not answered.

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