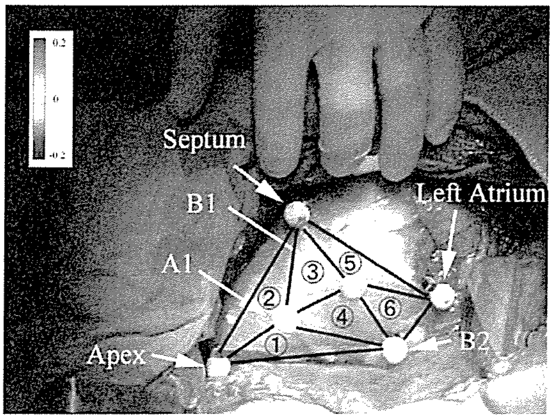

Fig.5 Visualization of distribution of myocardial strain of heart surface with colors

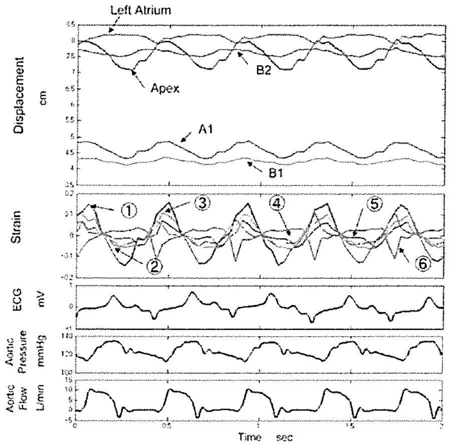

Fig 6 Comparison between displacement changes and hemodynamic data in goat

IV. DISCUSSION

Throughout the study, it was indicated that current optical location sensor could track the same specific points only to attach markers on the heart surface. This might be a promising method, but future work will be required to optimize the size, the number and the arrangement of markers. In the present system, markers were stitched onto the pericardium directly, but there is a possibility to eliminate markers to evaluate the heart function without physical contact, if a tendency of some relative changes between specific points can be quantified [6]. Of course, accumulation of present data using our new method must be required. Current method has not been able to measure the thickness of cardiac muscle, it will be possible based on the analysis of regional contractile data combined with anatomical, and ECHO data.

Nonetheless, the newly method will allow us to quantify the surgeons' skill and to support in the practical surgical field. For instance, it will provide effective dynamic parameters for the optimal control of the heart function externally in case of the usage of the ventricular assist device.

V. CONCLUSION

It is concluded that preliminary trials for the development of a surface measuring system were achieved as follows: 1) Heart surface deformation was obtained quantitatively by measuring the displacements of the anatomical points of cardiac muscular surface. 2) The differences of the displacements and phases were also observed among segments of heart surface under various circulatory conditions. 3) Strain changes in regional areas were calculated based on displacement changing data. 4) Strain change data was superimposed onto the video images of natural heart. It was helpful to understand a cardiac function visually.

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B117　形状記憶合金を応用した新しい心室収縮補助装置の開発

Development of a totally-implantable artificial myocardium using a shape memory alloy fiber

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Key words: artificial myocardium, shape memory alloy fiber, heart failure,

1.緒言

重症心不全患者に対する治療として，現在補助人工心臓を用いた治療や心臓移植を最終手段とする外科的な治療方法が広く行われている．しかしながら人工心臓などを用いた補助循環においては，人工物に由来する合併症が大きな問題となっており，またドナー心臓の不足から心移植が一般的な治療とはなりえていない．心不全の病態は本質的には心筋収縮力の低下に起因する血液拍出能力の減退にあることから，本研究では，形状記憶合金を応用した新しい人工心筋による循環補助装置の開発を行うことを目的とした[1]．Fig.1 にその概要を示す．補助を行う心臓より心電図を取得し，心臓の収縮と同期して，心室を取り囲んだ帯状の形状記憶合金を収縮伸張させて心室の収縮を補助する．

現在の心縮小法としては，ポリエステル性の伸縮性のある材料により心臓の外部より新たに包む方法やクリップ状の器具を用いて心室の内径を縮小する方法が用いられている[2]．短期的には収縮機能の改善があるものの，長期的には拡張障害の問題が存在し，心臓のポンプ機能としては低下を示す．

本研究において開発する装置は，従来の静的に心臓の縮小を促す方法に対して，動的に心臓の外部より圧力を加えることにより，心臓の拡張を阻害せず，心機能の回復が期待できる．

2. 方法

2.1 構造と駆動方法

本研究では，駆動要素として形状記憶合金(トキ・コーポレーション，Biometal BMF100)を用いて，人工心筋を構成した．主要な仕様をTable1 に，また試作した人工心筋装置の概要を Fig. 2 に示す．開発した心室補助装置は人工心筋を 10 本並列接続とした構造とした．心室外壁に設置するため，電気的絶縁が必要であり，円筒状シリコーンで各要素を被覆した．駆動回路構成は，直列に接続した 2 本を 1 組とした 5 組のユニットが並列接続され，直流通電によるジュール加熱により各ユニットが信号入力によって同時に収縮することが可能である．この心室補助装置は Fig. 1 に示すがごとく胸腔心膜内で心室を取り囲むように設置され，あらかじめ心臓のサイズに応じて長さの調節を行う．

2.2 基礎特性試験

開発する心室補助装置システムの駆動要素である形状記憶合金の基礎的な特性を調べるため，Fig.3 に示す試験装置を用いて通電加熱による収縮時の張力ひずみ特性を測定した．加熱は心室補助を想定して 0.5Hz の周期で行い，また収縮抗力として 2 種類の引っ張りばね(1.7 および 4.1N/mm)に対してデータ取得を行った．負荷はロードセル(共和電業，

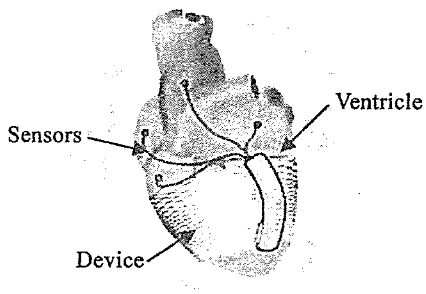

Fig.1 Schematic illustration of a concept of a totally-implantable artificial myocardium using a shape memory alloy fiber

Table1 An example of the specifications of artificial myocardium

Items		Values
Number of fibers		10
Diameter of each fiber	mm	0.10
Length of each fiber	mm	280
Weight of each fiber	mg	1.4

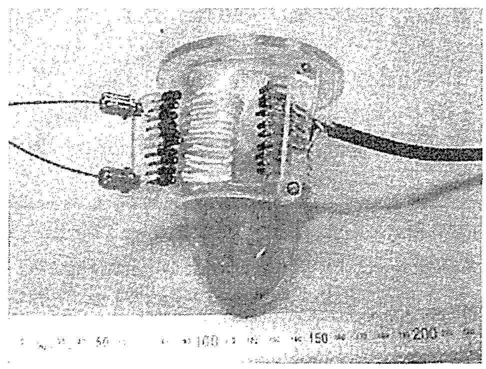

Fig.2 The artificial myocardium, which consisted of shape memory alloy fibers, and a silicone left ventricular model.

LUR-A-50SA1)，ひずみ量はレーザ変位センサ(Keyence, LB-01)により計測し，データはA/D変換後PCにサンプリング周期500Hzで記録した．

2.3 動物実験による血行力学的効果

開発した心室補助装置の血行力学的効果を調べるため，健常山羊(体重50kg)を用いて動物実験を行った．麻酔開胸下で心電図データに基づく心室収縮信号に同期させ本装置を駆動させた．大動脈圧，左心室圧，肺動脈圧はポリグラフ(Fukuda, MCS-5000)により，また基部大動脈流量を超音波血流計(Transonic systems, T430)により計測し，デジタルデータレコーダ(TEAC, LX-10)によりサンプリング周期1.5kHzで記録した．なお，本研究の動物実験は，東北大学医学部動物実験倫理委員会及び東北大学加齢医学研究所動物実験倫理委員会の基準に則って審査，承認の上行われた．

3.結果および考察

3.1 張力－ひずみ関係

引っ張り抵抗負荷の異なる2種類の系で取得された張力－ひずみ関係をFig.4に示す．変態による要素の最大ひずみは本実験の条件下では5%であり，また最大張力は28Nを示した．この結果から，本システムの対象となる心不全状態では，これらのアクチュエータ収縮能力は有効であることが考えられた．

3.2 血行力学的効果

動物実験において，非補助時(生体心のみの拍動)と人工心筋装置による補助時を比較した結果をFig. 5に示す．心電図データに基づく心室収縮信号に同期し，生体心臓3拍に対して1回の補助を行った．人工心筋駆動により大動脈圧は収縮期末において4%上昇し，大動脈基部流量から算出された心拍出量は約27%高値を示した．この結果は，心不全状態において本システムが有効であることを示唆するものであると考えられた．

4.結言

本研究では，形状記憶合金を応用した人工心筋による心室補助装置の開発を行い，基礎特性の取得と動物実験による心補助効果の評価を試みた．開発した人工心筋装置は5%程度の収縮が可能であったが，この値は健常安静時生体心室表面において計測される心筋の収縮率とほぼ同等であり，このことから，本システムが心不全状態の心機能を補助することに有効であることが考えられた．動物実験においても，血行力学的効果が得られたことから，今後さらに開発を進め，生体心臓の挙動と力学的整合性の高いシステムとして発展させるつもりである．

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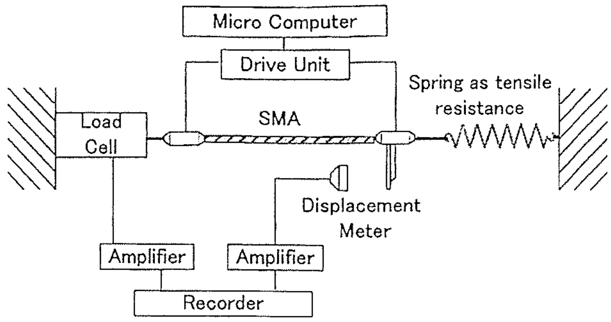


Fig.3 Schematic drawing of the measurement systems for the stress-strain characteristics of the shape memory alloy fibre.

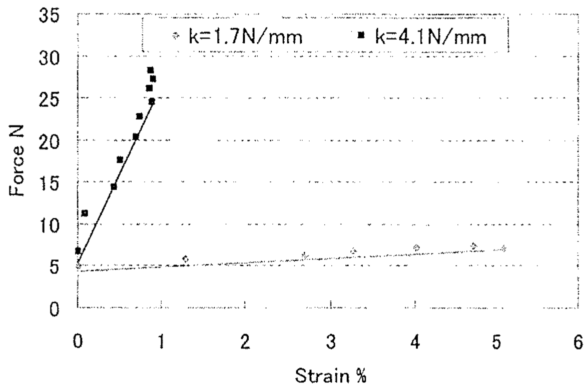
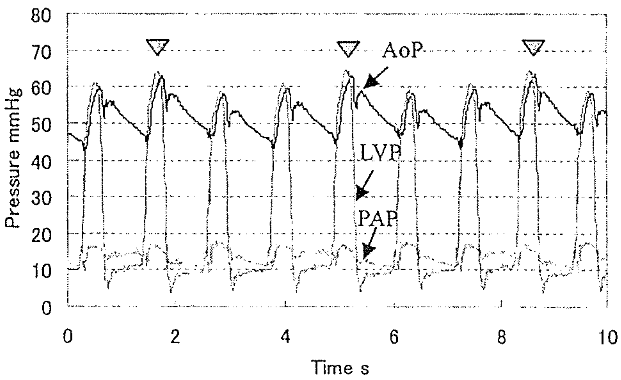
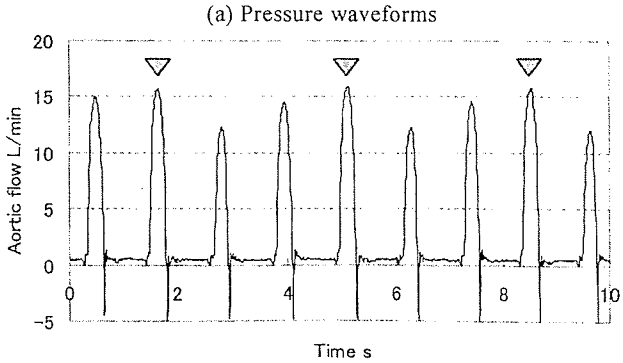


Fig.4 Stress-strain relationships obtained from the shape memory alloy fiber against different tensile resistance (k: spring constant for tensile resistance)



(a) Pressure waveforms



(b) Flow rate pressures

Fig.5 Changes in hemodynamic waveforms obtained in a goat; the arrows indicated the mechanical contractile assistance by the artificial myocardium developed.

REGIONAL MYOCARDIAL BEHAVIOUR ON CARDIAC SURFACE UNDER ARRHYTHMIC CONDITIONS

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Abstract: The authors have been developing a new evaluation method on cardiac function, which is based on surface measurement of the heart. With this system, an animal study was performed to examine heart function under a normal pulsating state and arrhythmic conditions. The physical data such as electrocardiogram, blood flow and pressure were simultaneously obtained and compared with this approach. It was found that there was a difference in displacements and phases from control to arrhythmia. With the physical data, it was confirmed that strain change in regional area was coincident with a contraction of natural heart. Moreover, the fusion images allowed us to understand the superficial strain of regional areas differs among the various heart functions visually. In the near future, this method will widely contribute to the clinical diagnosis of the patient.

Introduction

Generally, surgeons visualize the behaviour of the whole heart in their mind, by integrating the information of superficial and internal heart movement. Although the internal information of the heart can be captured as the structure and the movement by the echocardiography and as the pump function by the blood flow and pressure, the sequential changes of the surface configuration are qualitatively obtained as the surgeon's recognition. Therefore, the authors have attempted to measure the surface movement as the quantitative data. Besides, by corresponding it to the contractile patterns of the superficial myocardium, it is proposed that it may be considered as the evaluation indicators of the cardiac function [1].

This paper discusses the changes of the cardiac behaviours under the states from normal to arrhythmia by using the surface approach.

Materials and Methods

1. Preparation of animals

An anesthetized open-chest goat (weight: 51kg) was used for this experiment. Changes of the cardiac function were examined under the state from normal to arrhythmia. Arrhythmia was provoked by the administration of an overdose of epinephrine (0.002mg/kg) for a goat.

2. Measurement System of Superficial Cardiac Function

Figure.1 shows the system overview. Figure 1-a shows the experimental setup. An optical 3D location sensor (*Stereo Labeling Camera, CyVerse Inc.*) was utilized to measure the sequential displacement of the anatomically specific position of the cardiac surface. Simultaneously, the operative field was shot by a digital video camera.

3. Marker Settings

This study aimed at measuring the contractile function on the left atrium (LA) and the left ventricle (LV). Cardiac surface was divided into regional areas based on the anatomical structure. Anatomical points were specified to track the individual movement. Figure 1-b shows the location of the reflective ball markers on the operative field.

4. Calculation of Cardiac Function of the Regional Areas on the Surface

The cardiac surface was divided into twelve triangle areas by selecting three points from all specific points (Figure. 1-c). The cardiac function was induced by the calculation of the area changes on each regional area.

According to previous work [2], the integral of wall tension with respect to the area of a specific wall region during one cardiac cycle, which is equal to the area with a wall tension regional area (TA) loop, gives mechanical work performed by the region

$$RW = -\int_{t_1}^{t_2} T\left(\frac{dA}{dt}\right)dt \quad (1)$$

where RW is regional work, t_1 is onset of systole, t_2 is end of diastole, T is wall tension per unit length in the thin wall model, dA/dt is rate of change in regional area.

Assuming that the wall tension T is constant in one cardiac cycle, T will be expressed as follows:

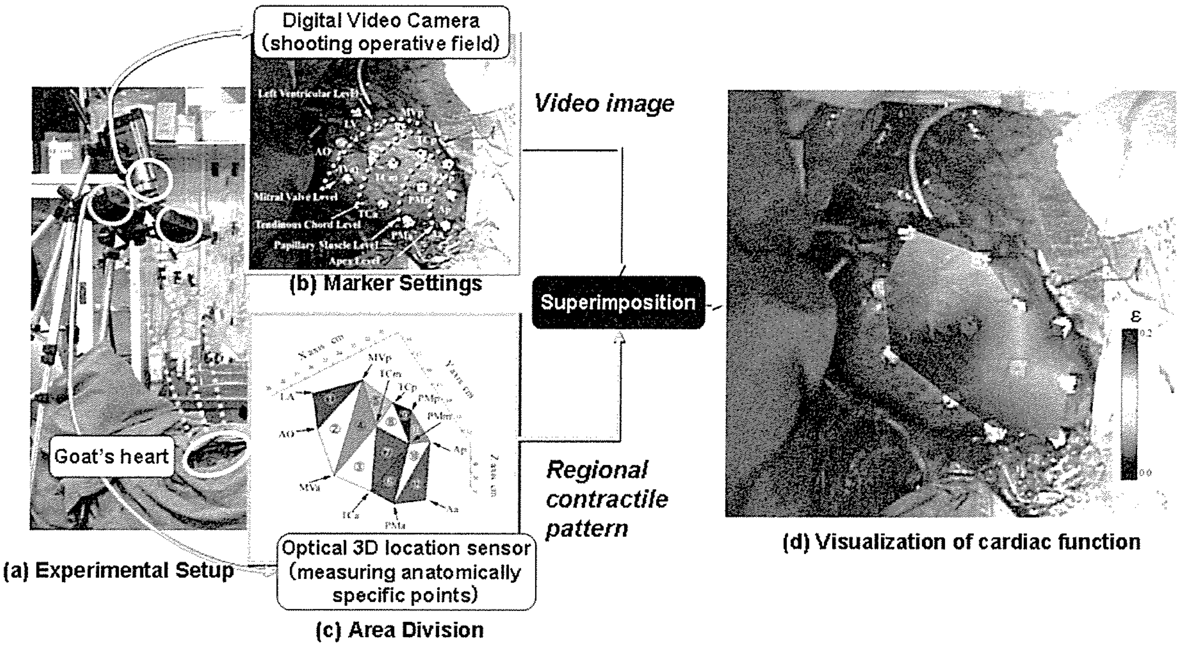

Figure 1. Data process of the evaluation system of cardiac function based on surface measurement

Twelve points were selected and reflective ball markers (diameter: 6mm) were stitched onto the myocardium as follows: one point of the first part of the aorta (AO), one point of the LA level (LA), two points of the mitral valve level (MVa, MVp), three points of the papirally muscle level (PMa, PMm, PMp), three points of the tendinous chord level (TCa, TCm, TCp), two points of the apex (Aa, Ap). It was successfully identified that these levels move concentrically around the septum by images obtained from echocardiography.

$$T = \overline{T} \quad (2)$$

Thus the expression (1) is lead to the expression (3).

$$RW = -\overline{T}\int_{1}^{2}\left(\frac{dA}{dt}\right)dt \quad (3)$$

The equation (3) is applied to this surface measurement system. Here, dA/dt means rate of change in regional area. In order to eliminate the differences between the sizes of the regional areas, the following steps were adopted.

When S_t is the area of a regional triangle for any time, $\overline{S}$ is the average of the S_t in one cardiac cycle, and ΔS_t is the difference between S_t and $\overline{S}$,

$$\Delta S_t = S_t - \overline{S} \quad (4)$$

If the cardiac muscular surface doesn't change drastically, ΔS will be described as $\Delta S \ll \overline{S}$. Therefore, the strain of regional surface area ε is define as,

$$\varepsilon = \Delta S / \overline{S} \quad (5)$$

5. Visualization of Cardiac Function of the Regional Areas on the Surface

In this system, there are two coordinate systems such as the optical 3D location sensor and the video camera. Fusion images were produced by these coordinates were integrated. The contractile patterns were shown in colours with a reasonable degree of transparency. It can be extremely helpful to understand a cardiac function visually.

Results

Figure 2 shows the movement at twelve specific points from the baseline (the origin of the optical 3D location sensor) during changing states from normal to arrhythmia. It was found that there were three phases from normal to arrhythmia as follows: control, transition, and arrhythmia. About twenty second later than the administration of an overdose of epinephrine for a goat, the blood pressure was risen sharply, arrhythmia was provoked. It was concurrently observed that the heart moved strongly.

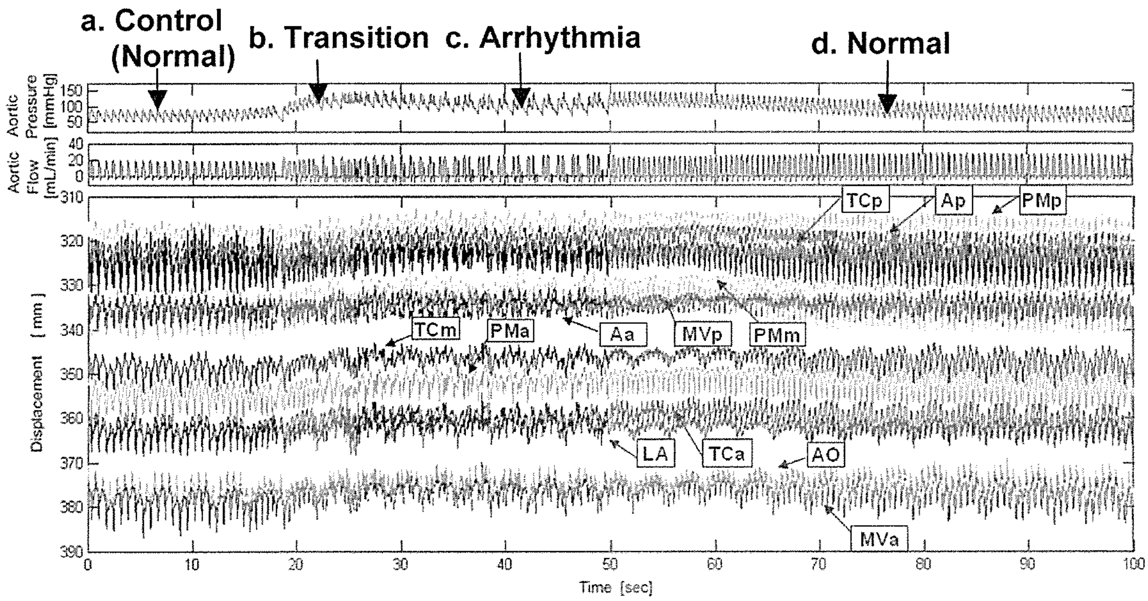

Figure 2. Displacement of the anatomically specific points from the baseline during the shift from normal to arrhythmia

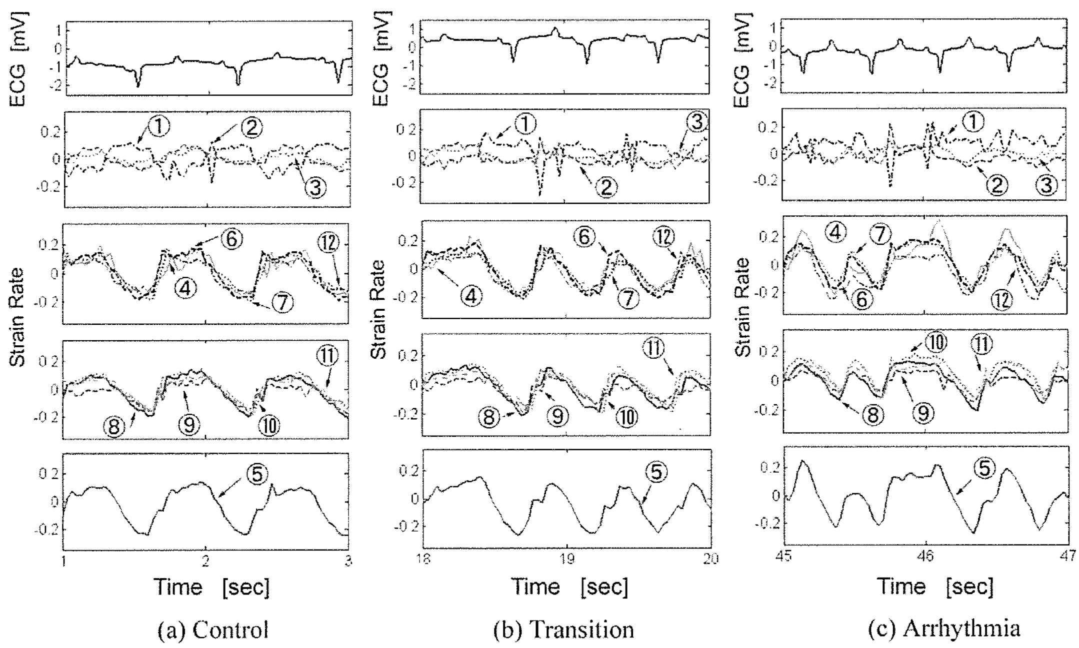

Figure 3. Sequential changes in the regional strain rate
The numbers (① - ⑫) shown in Figure 3 correspond to the ones of the areas in Figure 1-(c).

Figure 3 shows the strain rate and ECG in the three phases. In a normal state, each point varied periodically at a constant frequency in relation to pulsatile movement. It was considered that changes in the phase were transmitted from the septum to the whole heart. The results coincide with the conducting system of the heart.

Discussion

As regards to the evaluation of the myocardial contractile function in the regional area, there is an attempt to observe the regional wall motion by the sonomicrometry[8]. In this method, it needs that ultrasound crystals were embedded into the inner heart, although the crystals were small enough. Therefore, it is hard to utilise for a clinical application. On the other hand, only with our method, it is unable to obtain inner information of the heart. However, it can be overcome by using conventional method such as echocardiography.

In this experiment, the intervals between markers were specified twice longer than the diameter of the markers to distinct them even if markers move closer each other. For twelve specific points, it was appropriate that the diameter of sphere marker was defined as 6 mm. If the surface is segmentalized in more detail, downsizing of the markers is needed; however, it is not practical method due to the changes of cardiac function. For clinical use, marker less measurement is expected. In particular, anatomically specific points such as branches of coronary are marked in colors and the contrast is enhanced against the background, the difference of colors is used instead of markers[9]. Although the improvement in spatial and time resolution are current issues, they may be achiveable in near future by the adavancement of the resolution of image devices and /or the processing capacity of the computer.

Conclusions

It is found that there is a positive relationship between the cardiac function based on the surface measurement and the conventional understanding of the physiology. This method can provide the quantitative information during surgery. In the near future, it will widely contribute to the clinical diagnosis of the patient, when surgeons try to improve safety of the surgery.

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Development of "Patient Robot" ; Surgical Training Machine for Off-Pump Coronary Artery Bypass Grafting

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Abstract: As for a surgical treatment of coronary diseases Off-Pump Coronary Artery Bypass Grafting (Off-Pump CAB) has been adopted in recent years because of its less-invasive effect as compared with conventional CABG. However, sophisticated skill is required for Off-Pump CAB during on-beating condition. Although this technique has many advantages, a major problem is how to establish a training program for young surgeons.

To improve the situation, our group has been proposed a new concept: a "Patient Robot" which is an in-vitro mock circulatory system that provides various types of coronary disease as a training machine for cardiac surgeons. The "Patient Robot" consists of four parts. 1) Coronary vascular model, 2) Graft model, 3) Scoring System for self-evaluation and 4) Pulsation Unit. A general procedure is as follows: Firstly, trainee sets the "Coronary model" onto the Pulsation Unit". Next, the trainee makes an anastomosis between Coronary model and Graft model under pulsatile condition. Then, the anastomosis outcome is hydrodynamically evaluated by "Scoring System" from the view points of a relation between blood pressure and flow. As the first stage of the study, thin silicone tubes, which simulate a mechanical property and touch for real coronary and graft have been fabricated.

Introduction

As for a surgical treatment of coronary artery disease, Off-Pump Coronary Artery Bypass Grafting (Off-Pump CAB) has been adopted in recent years because of its less invasive effect as compared with conventional CABG. A major advantage of Off-Pump CAB is that patient has been able to avoid the invasion by extracorporeal circulation. Therefore Off-Pump CAB is usually employed for high-risk patients (: hepatic insufficiency, aged, etc). However, the Off-Pump CAB operation is much more difficult than conventional CABG because of the on-beating condition. Thus, Stabilizer is used to make the operative field stable for accurate anastomosis(Fig.1)[1]. Fig.2 shows that human heart cardiac muscle, which has been stabilized by Donut Stabilizer. There still exists a small pulsation on the operative field, even if the stabilizer has been installed. This small pulsation becomes one of the causes of critical damage to the recipient coronary artery by surgical needle. Generally, wall of coronary artery of Off-Pump CAB patients is very weak. Thus, sophisticated skill is required for the anastomosis. Accumulation of the surgeon's experience is very important for junior surgeons towards a well trained practical surgeons. However, there are not enough cases for each surgeon to brush up their skill at present situation. According to statistical survey, there are 2,937 cardiac surgeons in Japan.

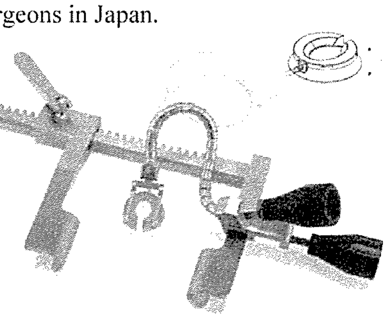

Fig.1 Donut type stabilizer

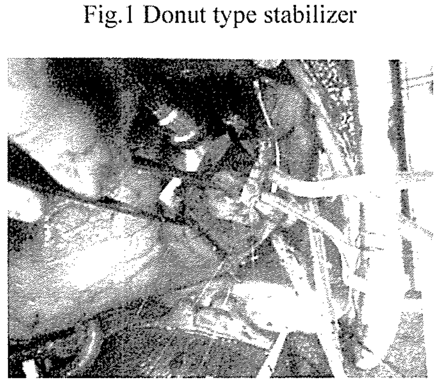

Fig.2 Anastomosis of operative field on human heart surface stabilized by Donut Stabilizer

And 20,095 CABG cases in 2002 were conducted in Japan[2]. A major problem is how to establish an effective program for young surgeons. To overcome the situation, our group has originally proposed a new concept: a "Patient Robot" which is an in-vitro mock circulatory system that provides various types of coronary disease as a training machine for cardiac surgeons. There are several design concepts for the development of the Patient Robot as below.

1) Real tactual feeling for anastomosis
2) Reproduction of various cardiac diseases
3) Quantitative evaluation for the outcome of anastomosis between coronary vascular model and graft model

Materials and Methods

The "Patient Robot" consists of four parts. 1) Coronary vascular model, 2) Graft model, 3) Scoring System for self-evaluation and 4) Pulsation Unit. A general procedure is as follows: Firstly, trainee sets the "Coronary model", which has desired clinical condition onto the "Pulsation Unit". The "Pulsation Unit" generates desired pulsatile motion as like stabilized cardiac muscle surface. Next, the trainee makes an anastomosis between coronary vascular model and graft model under pulsatile condition. Then, the anastomosis outcome is hydrodynamically evaluated by "Scoring System" from the view points of a relation between blood pressure and blood flow. Details about the components of the Patient Robot has been described as below.

1. Coronary vascular model and Graft model

Fig.3 shows an anatomy of coronary arteries. Left anterior descending artery (LAD) is a branch of the left coronary artery that runs to the apex of the heart in the anterior interventricular sulcus, supplying the ventricles, and most of the interventricular septum. Thus, stenosis of LAD often induces a severe ischemia. An anastomosis between recipient coronary artery (LAD), and graft artery: Left Internal Thoracic Artery (LITA), is the most common combination for CABG. As the initiation of this project, ligation was focused aimed on the area of LAD and LITA as a surgical training model. Silicone rubber (KE1603A/B, Shin-Etsu chemical co. ltd.) was chosen as a material for vascular models because of a feeling similarity of the touch. Fig.4 shows a schematic representation of coronary vascular model. Internal diameter of the model was 2mm. Coronary vascular model and graft model were fabricated by dipping method. Therefore, thickness of the models was adjustable. Moreover, Young's modulus was controllable by the ratio of silicone oil, which was compounded to the silicone. Followings are general procedure to develop vascular models, which satisfy the surgeons' tactile feeling reasonably.

1) An interview to cardiac surgeons who operates at least 100 cases per year: about the touch with several types of silicone tubes, that compound different oil ratio. Then determine a favourable parameter for oil ratio.
2) Measurements of the silicone models quantitatively. Defined the engineering parameter for the appropriate surgical training models such as effective Young's modulus through tensile test, and coefficient of visco-elasticity through visco-elastic test.
3) Measurements of the properties of native porcine organs, including myocardium around LAD, LAD, and LITA. The measurement procedure is the same as above 2). The sample organs must be fresh: less than 5 hours after pick up.
4) Fabrication of silicone vascular models with optimal oil ratio.
5) Interview to the surgeons with several silicone models, which compounded different oil ratio.

Fig.5 is a photograph during examination of various silicone models by cardiac surgeons. The examination had been taken under real operative condition. For example, the use of latex groves, forceps and a cardiac needle holder.

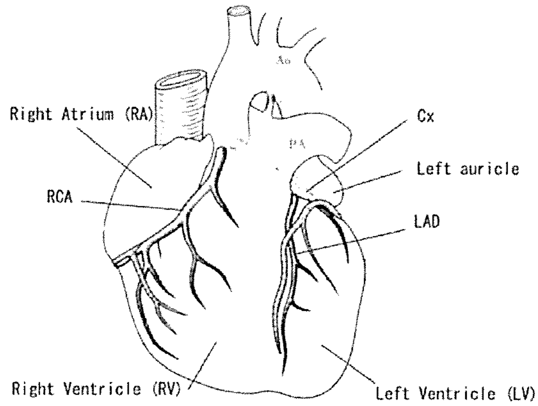

Fig.3 Anatomy of Coronary Arteries

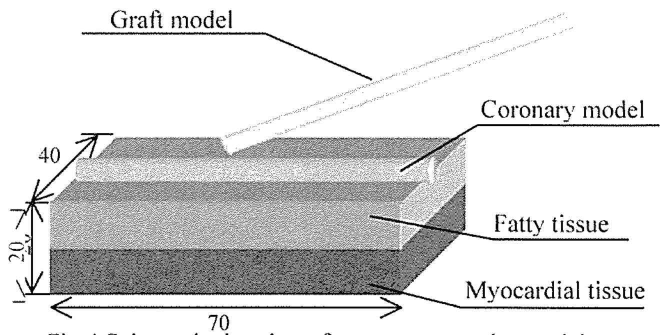

Fig.4 Schematic drawing of coronary vascular model and, graft model

Fig.5 Testing the silicone vascular models with forceps and needle-holder during real cardiac surgery

2. Scoring system

Fig.6 shows the "Scoring System", which includes a mock circulatory system for coronary circulation developed by Umezu lab., Waseda University[3]. Pneumatic controlled artificial heart, SV pump, also developed by Umezu lab., generates the human systemic circulation with the compliance and reservoir tank[4]. The PC controlled linear actuator generates coronary circulatory flow with full-wave rectification circuit, which consists of four check valves. The advantage of this system is that, coronary circulatory blood pressure and blood flow can be adjusted, independently. Desired waveforms, for example arteriosclerosis, are able to be entered to the PC by a trainee. The anastomosed silicone vascular model will be set in the test section. Then end of recipient and graft model must be connected to the "Scoring System". Trainees can evaluate their technique by monitoring pressure and flow waveform.

3. Pulsation unit

During Off-Pump CAB operation, Stabilizer is used to stabilize the operating field for anastomosis. It was confirmed that "Pulsation Unit" produced a practical on-beating situation. To obtain the design specification, acute animal experiment was performed to obtain suitable parameters to design "Pulsation Unit". In the experiment, 3D motion on goat's myocardial surface was captured by Stereo Labeling Camera (SLC)[5]. Fig.7 shows a goat's myocardial surface measured by SLC at Tohoku Univ. The reflective spheres were sewn on pericardium by polypropelene surgical strings.

Absolute displacements of these markers had been measured in real time. "Pulsation Unit" is design based on such in-vivo myocardial motion data. Actual procedure in training operation is that, trainee sets any coronary model onto "Pulsation Unit", and input the several parameters for myocardial surface motion.

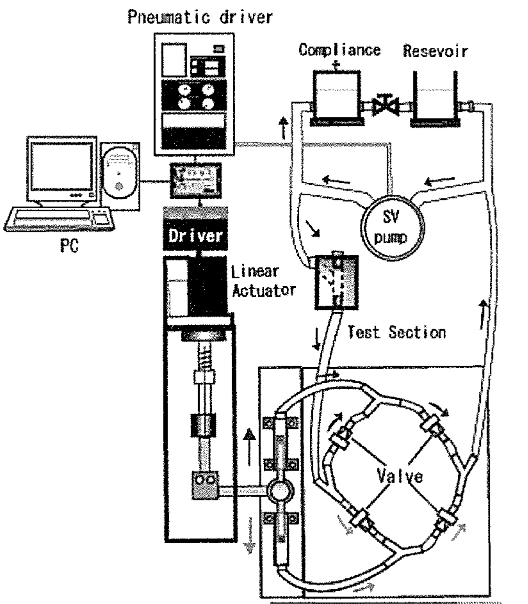

Fig.6 Evaluation system of anastomosis methods for CABG with the location of flow and pressure measured.

Results

Thin silicone tubes for "Coronary model" and "Graft model" have been fabricated based on quantitative data which was analysed by the comparison between the feeling of distinguished surgeons and tensile test of the silicone model. As a result of the interview to distinguished surgeons, it was found that there was optimal ratio of compounded oil for the silicone vascular models. Silicone tubes, contained silicone oil (silicone/oil <1.0 [g/g]), was the most favourable model. Through the tensile test of dumbbell shaped silicone specimen , the Young's modulus (where ε =1, n=5) was less than 0.1 N/mm^2(Fig.7). Fig.8 shows basic waveforms of coronary blood pressure and flow, generated by "Scoring System". The arrows express typical two-staged flow pattern, indicated a simulation.

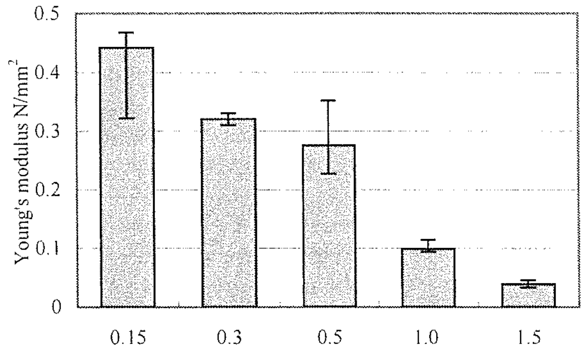

Fig.7 Relationship between *Young's modulus* (where ε =1) and oil ratio

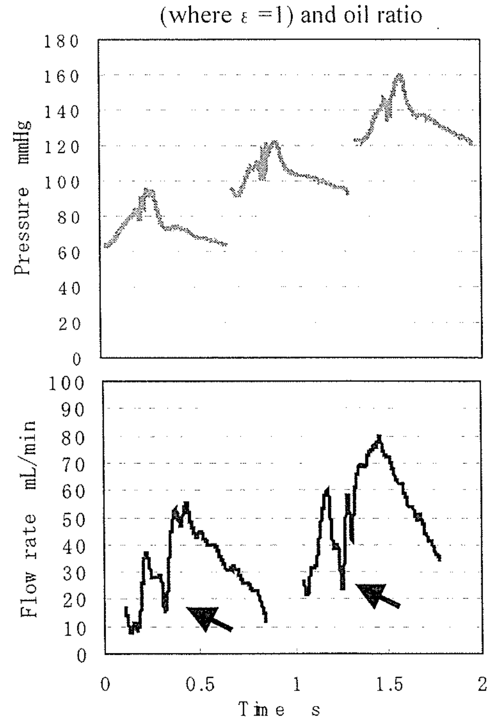

Fig.8 Basic waveforms of blood pressure (above) and flow (below) generated by "Scoring System"

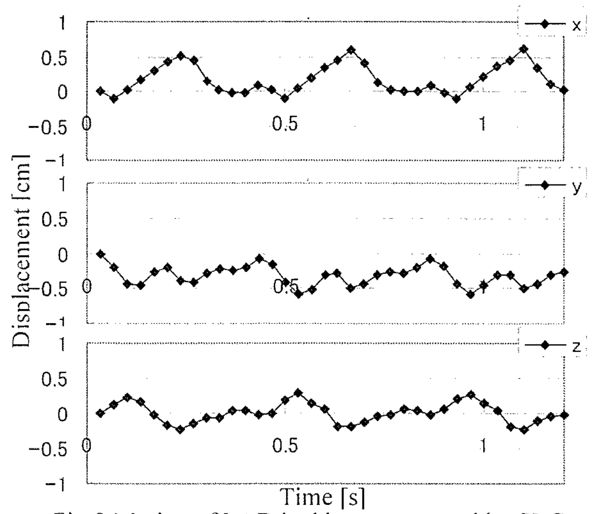

Fig.9 Motion of LAD had been measured by SLC

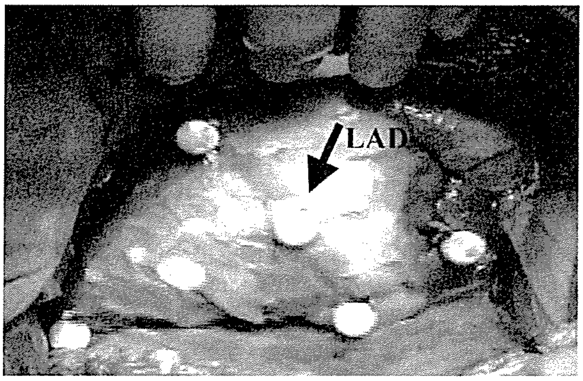

Fig.10 Acute animal experiment using goat's heart. SLC system with reflection spheres had been employed for a measurement of myocardial surface motion.

Fig.9 shows the reflective sphere motion on LAD measured in goat. The position of LAD is shown by an arrow in fig.10.

Discussion

1. Coronary vascular model and Graft model

Fig.7 shows a relation between oil ratio and Young's modulus. The Young's modulus had been employed where ε =1, because generally elasticity of native arteries drastically changed at this point. The result shows that there is an optimal range of Young's modulus (0.1N/mm^2) to develop a favourable vascular model for surgical training (Fig.7). However, Young's modulus of polymer has non-linear character subject to strain. In future experiment, the non-linearity should be considered to determine effective Young's modulus for development of surgical training vascular model.

2. Scoring System

The waveforms of blood pressure and flow, which has been shown by Fig.8, well simulated the real coronary circulation. Arrows in the figure show unique waveform of coronary. quantitative evaluation of an anastomosis will be expected in future experiments.

3. Pulsation Unit

Fig.9 shows that, native cardiac motion of goat's heart with in 0.5cm in each coordinate. It has been confirmed that, the design specification for Pulsation Unit. In future experiment, it is expected that, stabilized cardiac motion around LAD will be measured.

Conclusions

Development of "Patient Robot" had been started. Three components, vascular silicone model, Scoring System, and Pulsation Unit were designed in parallel. There was favourable range of Young's modulus for distinguished cardiac surgeons. Using Scoring System, human coronary circulation had been reproduced. Moreover, pressure and flow had been controlled independently. As a result of acute animal experiment, motion of cardiac surface had been quantitatively defined by SLC.

Acknowledgements

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Development of artificial esophagus with peristalsis using shape memory alloy

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Abstract: For patients of esophageal cancer, the most popular and reliable surgery is a restriction of abnormal parts of esophagus. But this treatment reduces quality of life for patients. To solve this problem, we have studied about an artificial peristaltic motion using helicoidal shape memory alloy (SMA). At this paper we have developed as an artificial esophagus using SMA to support drinking. A shape memory alloy (SMA) was used to make the peristaltic contraction. We use a special SMA, Bio Metal Helix 150. BMX150 has some high potential characteristics which could demonstrated as an artificial muscle. A half part of silicone pipe was covered and fixed with poly-ethylene terephthalate. BMX150 was crossed as half-pipe for silicone tube and fixed to the PET on the edge. 3 segment of BMX150 were sequentially set to the axial direction of silicone pipe. The SMA segments were heated for electrically to the variation alteration and 3 segment of BMX was sequentially contracted. The peristaltic actuator was demonstrated under the X-ray observation of contraction, and the inner pressure variation measurement test filled with saline.

The peristaltic actuator using BMX had shown good performances as a peristalsis device in vitro. The maximum contraction ratio of silicone pipe was around 75% and the maximum inner pressure was increased for 50 mmHg. But, farther investigation, e.g. artificial occlusion, or biocompatible and flexible esophageal pipe, should be needed for the development of artificial esophagus device.

Introduction

About ten thousands of patients have been diseased esophageal cancer in Japan. A surgical excision is the most popular and reliable treatment for esophageal carcinoma, because of excluding from the risk of metastatic carcinoma to regiones cervicales or pectorals. However, it causes a disadvantage, a rack of spontaneous dysphagia as is not able to regenerate the esophagus and surroundings including a mucosa[1,2]. To solve that problem, we have developed an artificial esophagus device to assist the swallow and to imitate a physiological peristalsis. From engineering aspect, development of peristaltic motion is very important for ingestion. So we focus on this event, basic properties have been studied to evaluate its mechanical peristaltic motion and artificial transportability. Furthermore, we have developed an artificial esophagus with peristalsis which could substitute for the resected esophagus to support digestive system for human, and to prevent thoracic choke.

Materials and Methods

Specially designed and manufactured shape memory alloy(SMA), BioMetalHelix(BMX; Toki Corporation, Tokyo, Japan) was used as an artificial muscle. On this study, we selected and used BMX150 which was composed and made helicoidal coil by 150 μm of wired SMA(Fig.1). The mechanical characteristics are shown in Table.1. The BMX produces by a far greater force when it contracts, and a remarkablely long stroke, 100%-200% of the length of the contracted BMX.

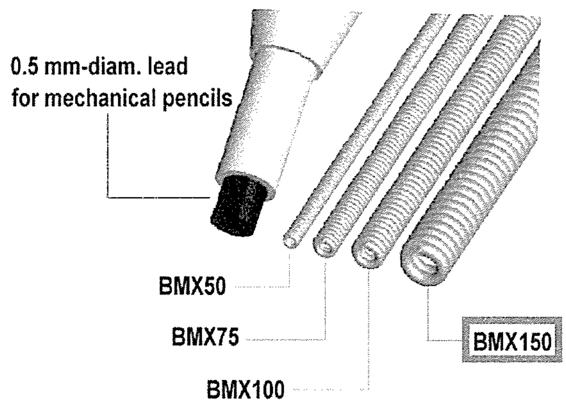

Fig.1

	BMX150
Standard coil diameter (mm)	0.62
Wire diameter (mm)	0.15
Maximum force produced (gf)	20~40
Change in length (%)	200
Maximum elongation ratio (mm/s/m)	900
Standard drive current (mA)	200~300
Standard electric resistance (ohm/m)	400

Durability (contraction times)	1,000,000

Table.1

The systolic motion of BMX is a non-linear and non-symmetric, and the working temperature of systolic action depends on the load. Furthermore, the magnitude of direct current input effects on the systolic force, the higher current run out, the faster SMA heat, so it derive high acceleration. To make sure the appropriate motion for the peristaltic motion, various maintenance of the value of current and the switching duty have been studied. From these studies, we decided the test condition(e.g. amplitude of current, current-on time, intervals of sequencial SMA action) of following tests.

The artificial esophagus canal was substituted by hand made silicone pipe by reason of its flexibility and biocompatibility. At this study, silicone pipe (OD20mm, ID19 mm) was used and wrapped round the half of pipe with half-piped poly-ethylene terephthalate(PET, t=0.5) body case. PET free side of combined silicone pipe was round with BMX150 per half winding and fixed with terminal on two point of PET symmetry. Two point of terminal was set apart an electrode for electrical pole. This half-piped SMA segment was prepared for multi-stage segments. Schematic structure is shown in Fig.2. The artificial peristaltic motion was made by multi-staged SMA segments and sequencial power input axially. The radial systolic force and sequencial time-delayed control is transduced to imitate a physiological peristaltic motion.

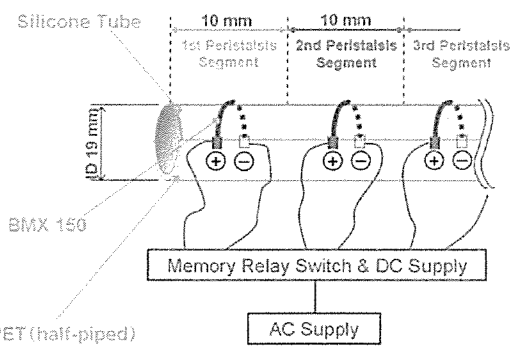

Fig.2

To study the characteristics of this actuator, in vitro peristaltic motion test was conducted on 2 dimensional(2-D) radiography, to estimate the contraction ratio of this actuator without inner pressure load. The test was conducted on cardiac catheter room of clinical installation with an assist of technical radiologist. The test condition was as follows; a) observation was only one direction from the way that place the edge of half-piped PET as a median line, to a cast shadow on the half side was shown SMA behaviour on the other half immovable PET. b) SMA was heated at a current of 400 mA per segment, and 0.6 s intervals of switching on, sequencially(Fig.3). c) the room temperature was set at 25 degree of Celcius. d) the contraction of actuator was observed and recorded with DV format(30 frame/s), and the variations on edge of SMA were analyzed on each SMA segments and frames.

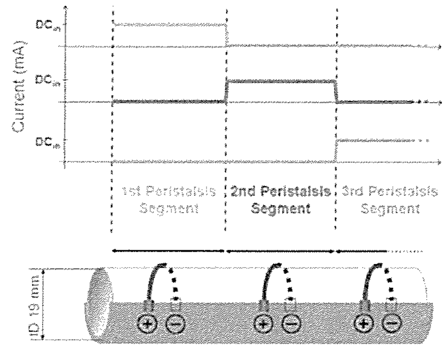

Fig.3

In the physiological aspect, the swallow is triggered by something of ingestion from an epiglottis. After that, the peristalsis of esophagus is derived by its own muscle relaxation and contraction. But, the peristalsis depend on not only motility of esophageal muscle, but also pharyngoesophageal thrust force. So we verify the inner pressure variation of this actuator whether it could be permit the normal level of the esophageal pressure, normally at a range of 10-30 mmHg[3,4]. The experimental schema is shown in Fig.4 A low compliance flexible tube (poly-urethane) was inserted into the silicone pipe, and a pressure transducer was also inserted inner side of the flexible tube with clamped on the one edge. The inner side of flexible tube was filled with saline, after that degassed to measure the systolic pressure precisely. The actuator was driven at several current setting, and the contraction interval of each SMA segments was set on 0.6 s. A test interval was set on 10 s to exclude the residual heat of the last test. The trend data of inner pressure change was amplified and recorded.

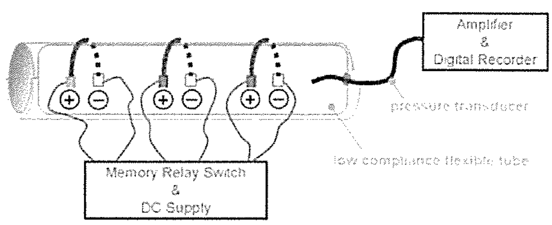

Fig.4

The most interesting point of view is whether the peristalsis actuator could transport food, as a typical motility of esophagus. To evaluate this factor, a swallow characteristic was studied. The inside of silicone pipe was filled with 20 mL of a nutrition supplement jerry as a kind of a weaning food for patients. The test was evaluated for 3 times of peristaltic motion and measured a total amount of the transported jerry and the residuals inside of silicone pipe. The test conditions were the same with above, 2D radiography observation.

Results

From 2D radiography observation, the contraction ratio of actuator was almost changed between 80% to 100%, and the maximum contraction was 73%. Typical results of one trial is shown in Fig.5. These appearances showed on all tests.

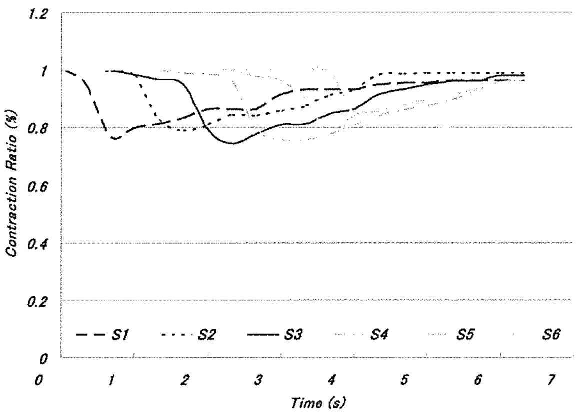

Fig.5

The inner pressure variation tests were conducted in several current conditions to observe typical results of this actuator. Fig.6 shows the results of maximum pressure at 500 mA of SMA heating. An arrow shows the systolic timing of SMA. One of the most important parameter of this actuator, the inner pressure of the peristaltic silicone pipe, shows an interesting results. The inner pressure was gradually increased with the sequence and time-delay contractions of silicone pipe. It derives the prevention of reflux from the start of artificial peristalsis to 3rd contraction.

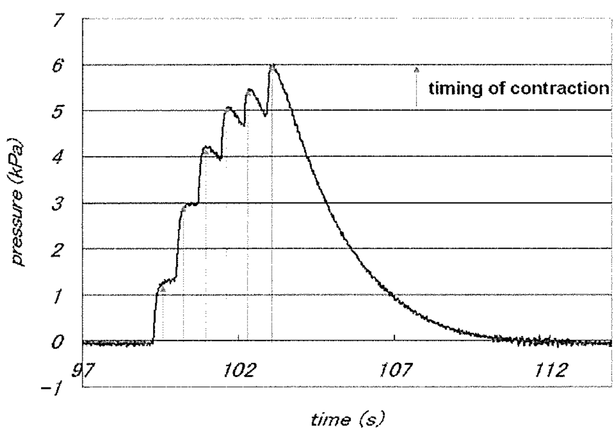

Fig.6

The food delivery tests conducted 10 times, and the delivered and residual jerry was measured. The mean amount of delivered jerry was 13.2 $\pm$2.1 mL (n=10). As far as the DV camera recording, no dynamic reflux was shown in all of tests. And the residuals were mainly remained through the whole area of the base on the PET side.

Discussion

The results of 2D radiography means an insufficient contraction of the silicone pipe, compared to our design concept that estimate at a 50% of contraction ratio. Such results was cause by that the silicone pipe we used as a substitute of esphagus pipe doesn't have elasticity but flexibility, relatively. So its solid characteristics behave as a resistance to systolic power of SMA. A new development of artificial substitute has a big problem, biocompatibility. These themes often has an controversy, so we use the silicone because that has a margin of safety on surgery or cardiology. So, the mechanical improvement should be done to imitate the human peristalsis with higher contraction ratio. On the contrary, the typical results of inner pressure variation shows the sufficient pressure amplitude compared to human pharyngoesophageal pressure and a stable esophageal pressure at the swallow. The maximum systolic pressure was about 50 mmHg at the end point of peristaltic duration. Furthermore, this study shows the prevention of reflux because of the relation to the time span of heating and cooling. From our preliminary study, a time constant at heating and cooling was studied using BMX150 at 40 degree of Celcius, based on physiological environment. These studies showed the short time of heating one. On the contrary, the cooling one showed about twice as long as heating. These results derived us a driving condition on this study. This reflux-safe driving mode has much efficiency as a artificial digestive system. This characteristic was effected and confirmed on a swallow test using nutrition supplement jerry. On observation of video frame of such imitative swallow, dynamic reflux has none, though it was only external view. On our next study, another parameter, e.g. outside pressure, should be detected to evaluate the effect of the reflux prevention.

In the whole aspects of this study, further improvement of mechanisms of artificial peristalsis should be considered including the field of biomechanics or biomaterials.

Conclusions

About ten thousands of patients have been diseased esophageal cancer in Japan. To save us from the high invasion surgery, we have developed an artificial esophagus device to assist the swallow and to imitate a physiological peristalsis. The inner pressure variation tests and the imitative swallow observation shows good performance and its potential characteristics of peristaltic device, though the 2D radiographic variation studies showed a low level of systolic ratio. It has smart mechanisms for driving and a small structure, and performed good characteristics compared to physiological parameters of esophagus. From these results, the peristaltic device using specialized SMA, BMX150, showed the possibility of implant as an artificial device.

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研究

左心室形成術における切除線決定のための診断法に関する基礎的検討

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Fundamental Study on the Development of a Diagnostic System for Left Ventricular Plastic Surgery of the Abscission Area

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Abstract Ventricular aneurysm is one of the complications that follow a myocardial infarction. Left ventricular (LV) plastic and reconstructive surgery, Dor procedure, is widely performed in order to improve patients' cardiac functions. However, it is anticipated that the abscission region of the ventricle might cause some complications, such as mitral valve regurgitation. Therefore, the decision of what to be done with that area might affect therapeutic consequences. In this study, the authors have developed a measurement system for surface movement and a display system to demonstrate decreased LV systolic function during surgery. This system is capable of evaluating the cardiac function using displacement data obtained from superficial motion of the specific regions. Prior to measurement, the reflective ball markers were sutured on the surface of the heart without any complications or infarctions. The point of the markers indicated the anatomically specific points, such as apex, septum, mitral valve, and papillary muscles. The location of points was sequentially measured by an optical three-dimensional location sensor. The superficial area of the left ventricle from the left thoracotomy view was divided into 12 triangular regions each composed of three markers. As the contraction of the regional area corresponds to the cardiac systolic function, the changes in each area were examined. The contraction rate of the heart was superimposed onto the video images of a natural heart, which were obtained simultaneously. An animal study was performed to compare heart functions under a normal pulsating state and during the time of a myocardial infarction. The physical data such as electrocardiogram, blood flow and pressure were simultaneously obtained and compared using this approach. With the physical data, it was confirmed that strain change in the regional area was coincident with a contraction of the actual heart. It was also found that this method is simple enough to set up in the operation theater. In the near future, this method will contribute widely to the clinical diagnoses of patients, when advanced surgery such as robot surgery and/or organ transplant become popular.

Keywords: cardiac function, left ventricular surgery, myocardial infarction, surface measurement, regional strain.

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1. は じ め に

心臓は血液を全身に循環させるためのポンプの役割を担っている．一方，心臓の動きを維持するために，左右の冠動脈を通して心筋へ血液が供給されている．冠動脈が狭窄し，さらに，血栓などにより閉塞すると，心筋梗塞が起こり，冠動脈が栄養していた範囲の心筋の壊死が生じてポンプ機能が低下する．広範囲にわたって心筋梗塞が生じると，その筋肉として機能できない部分は薄くなり，心臓のポンプとしての拍動と逆の動きをするようになる．この状態を心筋梗塞後の左心室瘤という．

左心室瘤が形成された場合，収縮挙動不全部位をパッチ

で補填するDor手術[1,2]が広く行われている．この際，心筋における正常部位と梗塞部位の境界を見極め，切除領域を決定することは手術予後の心機能改善の上で非常に重要な作業となっている．

現在，切除領域の同定は心筋の触診および超音波断層像の撮像をもとに行っている．超音波断層像による診断は非侵襲かつ安全で，時間的，空間的な分解能にも優れており，日常の診断においては非常に有用な診断法といえる．しかしながら，同じ部位を計測することが難しく，対象部位の描出は検者の技量に大きく依存するため，客観性に乏しい．また，左心室瘤が3次元的な広がりをもつ一方で，超音波断層像は平面の情報であることから，切除領域の同定には熟練した技術を要する．そのため，同時に複数部位を計測可能で，同一部位に関しては誰が計測しても同一の計測値として求められることが望まれる．

また，左室形成術は高度な技術を要し，危険度も高いため，熟練の医師によって執刀される．そこで，この困難な手術に対する医師の経験を補うため，手術訓練用のシステムの研究も行われている[3]．手術シミュレーションは術前に手術を模擬することはできるが，実際の術中の臓器の状態に応じて，判断を下すために用いることはできない．

そこで，筆者らは術中の臓器の状態を計測し，医師の判断を支援するシステムの開発を行っている[4,5]．本論文では光学的計測法を用いて心臓を表面から計測し，局所領域の挙動を計測したデータをもとに，心機能の低下部位を特定する．さらに，視覚的にわかりやすく表示することを目的とし，現実空間に仮想空間の情報を重畳することで現実の感覚を増強する複合現実感の技術[6-8]を用いて，実際の心臓のビデオ画像に心機能変化データを重畳する．

2. 方　法

2・1 システム構成

本システムの構成を図1に示す．心臓表面の局所点の位置計測には光学式の3次元位置計測器（ステレオラベリングカメラ，CyVerse Inc.）を用いた．この計測器は2基のCMOSカメラで構成されており，各カメラの周りには赤外線LEDが配置されている．計測時には赤外線LEDを発光させて再帰性反射ビーズを塗付したマーカ（ϕ6 mm）からの反射をカメラで撮像し，三角測量法によりマーカの位置を算出する．複数個のマーカをラベリングし，それぞれの3次元位置を約30 fpsで取得可能である．一方，実際の心臓上の局所点との対応をとるため，術野をデジタルビデオカメラで撮像した．事前に3次元位置計測器とデジタルビデオカメラのカメラパラメータをTsaiにより提案されたカメラキャリブレーションの手法[9]を用いて算出しておくことで，3次元位置計測器計測器とビデオカメラのそれぞれ異なる座標系を同一座標系に統合することができる．これにより，3次元位置計測器の計測結果をもとに算出する心臓表面上の歪み分布データを実際の心臓画像上に重畳した．

2・2 心臓表面における局所点の設定

本研究では僧帽弁を境界とし，左心房，左心室の局所表

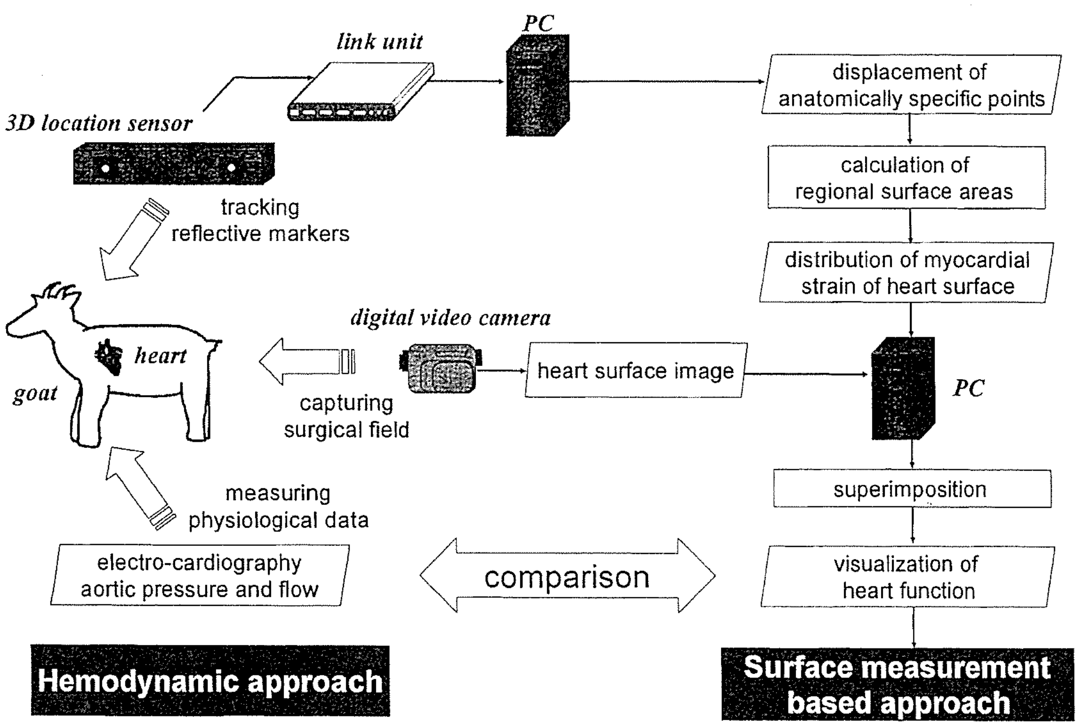

図1　システム概念図

Fig. 1　Schematic diagram of the experimental setup.

面領域における拡張収縮機能を計測した．心臓表面における計測点を特定するために反射球マーカを使用し，心膜に縫い付けた．反射球マーカの設置位置を図**2**に示す．

まず，左心房と左心室は各部位を隔てる僧帽弁の弁輪付近を基準にして分けた（図2実線部）．そして，左心室を超音波の断層法による左室計測の際に用いられる解剖学的な情報に基づき3つのレベルに分割した．左心室の動きは大動脈基部（AO）から心尖部（Ap，Aa）への長軸に対し，短軸方向へ同心円状に拡張収縮しており，短軸断面のレベルに基づき，乳頭筋レベル，腱索レベル，心尖レベルの3レベルに分けられる（図2点線部）．以上の解剖学的な情報に基づき選んだ12点の特徴点が以下である．大動脈基部に1点（AO），左心房レベルに1点（LA），僧帽弁レベルに2点（MVa，MVp），乳頭筋レベル3点（PMa，PMm，PMp），腱索レベルに3点（TCa，TCm，TCp），心尖レベルに2点（Aa，Ap）の計12点である．

また，全特徴点からそれぞれ近傍の3点を選び，心臓表面を局所的な三角形の領域で分割した．三角形領域に分割した結果を図**3**に示す．ここで原点は3次元位置計測器の原点とした．

2・3　心臓表面上の歪みの算出

先行研究[10]によれば，左心室壁の局所仕事量は局所領域における心壁張力の一心周期分の積分値で表される．

$$RW = -\int_{t_1}^{t_2} T\left(\frac{dA}{dt}\right)dt \qquad (1)$$

ここで，RWは局所仕事量であり，t_1は収縮期の開始時間，t_2は拡張期の終了時間，Tは単位長さあたりの張力，dA/dtは単位時間あたりの局所領域の変化率である．

いま，一心周期における張力Tがほぼ一定であるとし，

$$T = \overline{T} \qquad (2)$$

で表すならば，式(1)は式(3)のようになる．

$$RW = \overline{T} - \int_{t_1}^{t_2} T\left(\frac{dA}{dt}\right)dt \qquad (3)$$

よって，局所領域の拡張収縮機能は局所領域の時間的変化を計算し，一心周期分の積分値に対応する．

以上の理論を本計測法に用いる．式(3)におけるdA/dtは単位時間あたりの心臓表面における局所領域面積の時間的変化であるとする．ここで，各局所領域の大きさによる違いをなくすため，一心周期における平均値で単位時間当たりの局所領域の変化を割ることで無次元化した．一心周期における局所領域の面積の平均値を$\overline{S}$としたとき，ある時間における局所領域の面積との差ΔSは，

$$\Delta S = S - \overline{S} \qquad (4)$$

となる．これより，単位時間Δtにおける面積の歪み（strain rate：ε）は，

$$\varepsilon = \Delta S / \overline{S} \qquad (5)$$

となる．局所における心筋の収縮機能は時間歪みの絶対値をR波に合わせて検出した一心周期分にわたって積分し，

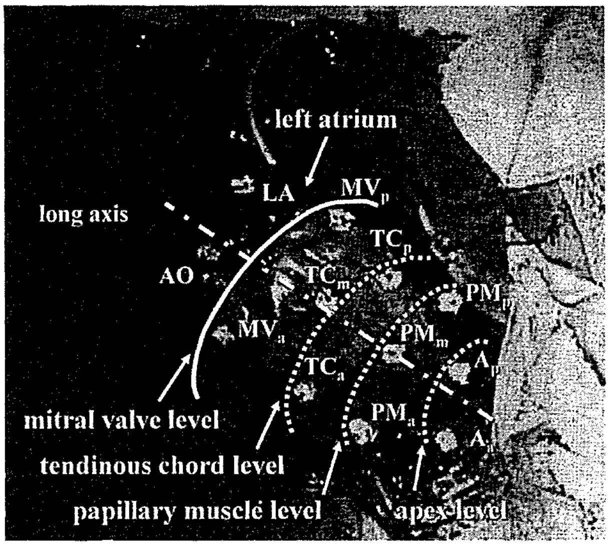

図2　心臓表面のマーカ配置
Fig. 2　Marker settings on the surface of the heart.

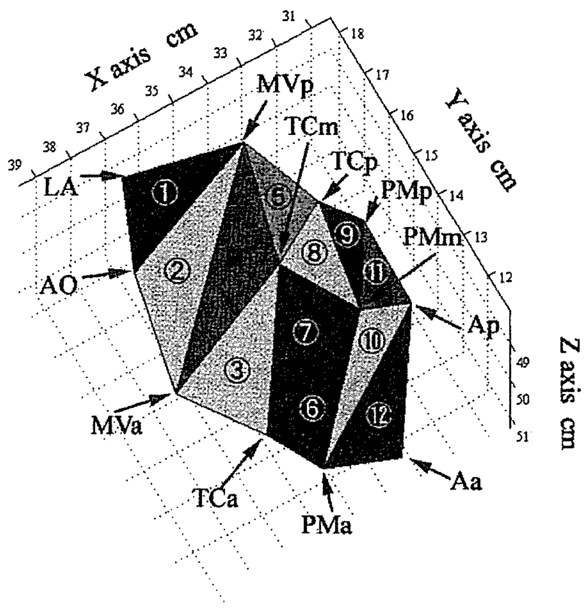

図3　心臓表面の領域分け
Fig. 3　Division proposed for the regional surface of the heart.

$$E = \frac{1}{\overline{S}}\int_{t_1}^{t_2} \frac{|dS|}{dt}dt \qquad (6)$$

として算出した．

2・4　動物実験

本研究では健常成山羊（メス，51.8 kg）を用いて行った．実験の様子を図**4**に示す．正常な拍動時と心筋梗塞作成時における心臓表面の拡張収縮機能変化を計測し，比較した．心筋梗塞に関しては麻酔開胸下の健常成山羊において，冠動脈左前下行枝の末梢側30%で結紮し血流を途絶させ，人工的に心尖部近傍の虚血部位を作成した[11]．また，麻酔開胸下の健常成山羊において，心筋保護下で細動

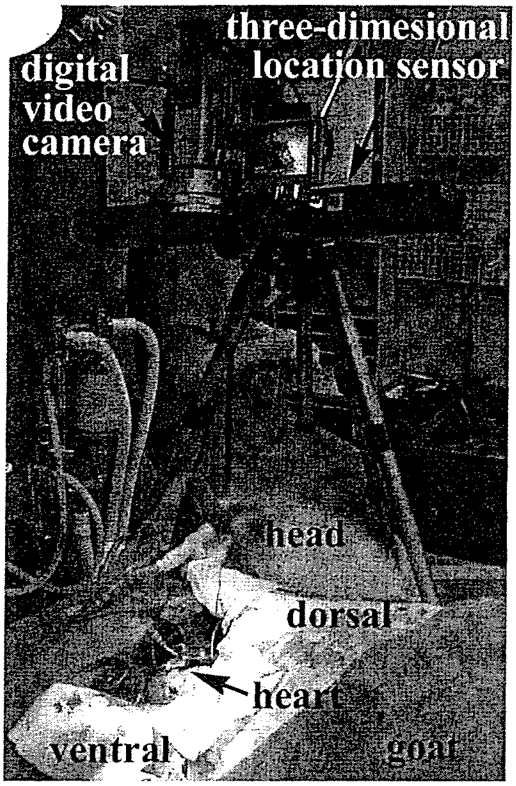

図4　実験配置図
Fig. 4　Equipment layout in the animal study.

装置を用いて人工的に心室細動を引き起こし，心臓の収縮拡張挙動が停止した状態でデータの取得を行った．なお，実験は短時間で行い，計測終了後直ちに除細動操作を行い，正常な調律へ回復させた．以上，本研究にかかわる動物実験は，東北大学大学院医学系研究科および加齢医学研究所動物実験倫理委員会の審査を受け，承認のもとに厳密に規定に則って行われた．

3. 結　　果

3・1　各部位の位置の時間的変化

心臓の各部位の動きの時間的変化に関して図5に示す．ここで，外的な影響のないコントロール時を(a)，心筋梗塞作成時を(b)に，さらに心室細動時を(c)に示す．上段は心電図を示しており，下段は特徴点の位置変化を示している．特徴点は以下の6つの領域ごとにわけて示した．左心房（LA，AO)，僧帽弁（MVa，MVp)，左室前壁の心室中隔付近（TCa，PMa)，左室前壁の中央部（TCm，PMm)，左室後壁（TCp，PMp)，および心尖（Aa，Ap）である．

コントロール時において，心電図における負のピークが大きく表れているQRS波が読み取れるが，心電図は周期的な波形をしており，正常な拍動のリズムが繰り返されていることがわかる．各部位の位置変化についてみると，位相の変化は中隔側から心室全体に向かって変化しており，心臓の刺激伝導系の機能とも一致している．

心筋梗塞時において，心電図より，QRS波の大きさが小さくなっていることから，左心室の拍出力が弱まり，ポンプ機能の低下が読み取れる．また，各部位の位置変化についてみると，心尖部の動きが低下しているのがわかる．

心室細動時において，心電図より，拍動のリズムが乱れているのがわかる．各部位の位置変化については，ほぼ変動がみられないのに対し，左心房近傍の点については周期的な動きが読み取れる．これより，左心房には電気的刺激が伝導しているものの，左心室では心筋が非同期的な動きとなっており，心室細動が起こっていることに対応しているといえる．

以上より，本計測法では心臓表面の複数の部位を同時に計測可能であり，その結果には，生理学的な指標との関連性がみられた．

3・2　様々な病態の違いに伴う収縮機能の変化

単位時間当たりの面積歪みの時間的変化を図6に示す．ここで，外的な影響のないコントロール時を(a)，心筋梗塞作成時を(b)に示した．ここで，①から⑫は図3の領域に対応している．

正常な拍動時と比較して，心筋梗塞作成時は梗塞部位付近から心尖部にかけての位相が変化している．梗塞部位付近では他領域に比べて収縮期に局所領域の面積が拡張の方向にあることが認められる．このことから収縮期における挙動の病的な不一致が起こっていることがわかる．

3・3　局所部位における心臓収縮機能の呈示

一心周期分の心筋の収縮機能をビデオ画像上に重畳した結果を図7に示す．ここで，心筋の動きやすさを表すEは無次元の単位をもつ．左心房近傍では収縮機能が高いのに対し，腱索レベルから心尖レベルにかけて収縮機能が低下している．収縮機能の低下部位は梗塞作成部位と一致しており，本手法により梗塞部位の特定が直感的に理解可能となった．

4. 考　　察

本手法の具体的な適用範囲としては，心室内部の僧帽弁挙動も含めた左室形成に有効な切除線の決定を支援するシステムを考えている．左室形成術の施行においては，術者が心室表面の具体的な切除部位を超音波断層像等の計測データと一致させることが重要である．心室切除手術中には人工心肺補助によって自己心の拍動はほとんどないことを考えると，切除線設定に有用なデータを提供できることが本手法の有効な点となる．

しかしながら，左室内腔の機能が心室挙動に対して影響が大きい場合，たとえば僧帽弁乳頭筋腱索断裂もしくは心室内膜に近い部位の虚血が病態の本態であるといった場合には，いわゆる心機能と可視的な心室表面の収縮変化との連関を工学的に示すことは容易ではなく，本法は適用範囲外となると考えられる．

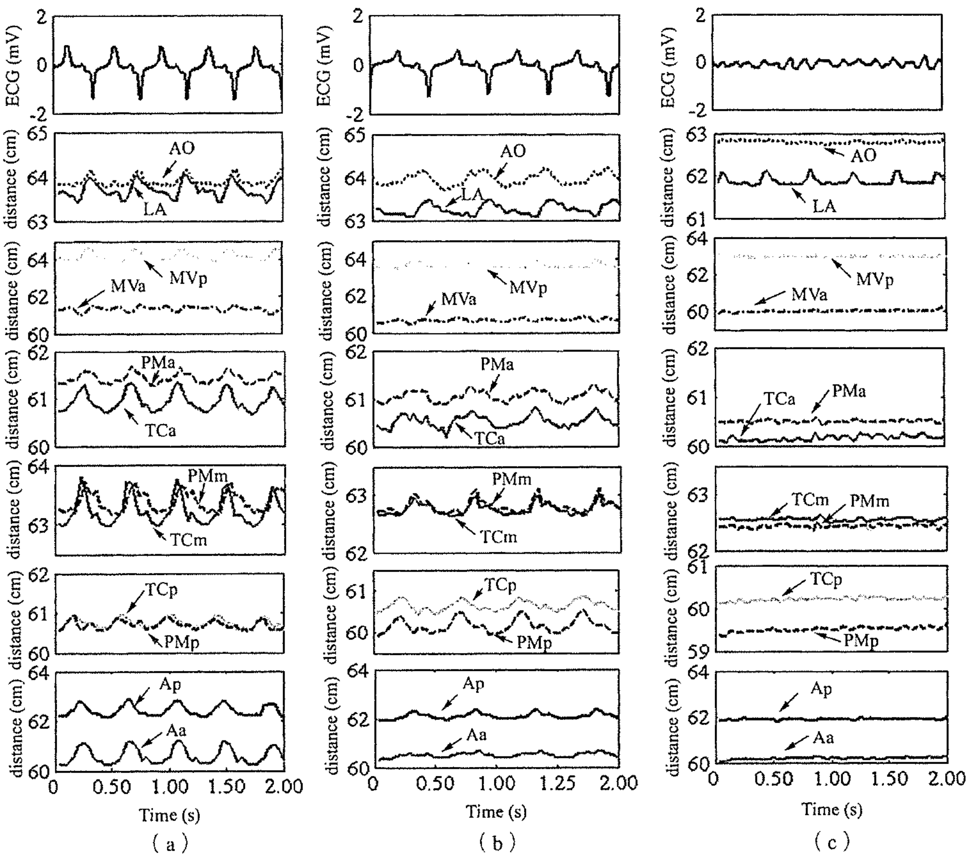

図5　解剖学的特徴点における位置の時間的変化
（a）正常拍動時，（b）心筋梗塞時，（c）心室細動時．
Fig. 5　Sequential changes in specific local points.
(a) Normal pulsatile, (b) Infarction, (c) Ventricular fibrillation.

本手法の臨床現場での具体的な用途としては以下の3つを考えている．

（i）心室の一部を切除する等の外科的な方法によって心機能の改善を図る際の切除部位の決定
（ii）術前の他の計測に基づく診断による外科手術方針の支援
（iii）術後治療評価の予測

（i）では動きの正常，異常を定量的に弁別して領域の変曲線を術者の視野と一致するよう呈示することが，（ii）では他の臨床評価指標との高精度な整合をとることが，さらに（iii）では計測データを分析し，外科的な心室形成による対象領域の選択の妥当性を評価することが求められる．本論文では（i）について重点的に述べてきた．（ii），（iii）については今後の研究課題となる．

本手法では心臓表面をステレオカメラで計測することにより3次元的な局所点の追跡を行った．ここで，特徴点を追跡するために使用したマーカについては，各マーカの位置が接近しすぎることがないよう，マーカ間隔をマーカの直径の2倍よりも大きくなるように設定した．心室瘤形成時に手術適応となるのは約3 cm四方の挙動不全部位である．心臓表面を約3 cmの間隔をもつ三角形領域で分割するとき，マーカの直径を6 mmとすれば，時系列上での各部位のマーカ探索においても十分な間隔が保てた．

心筋の局所収縮能を評価する方法としては，他にも，超音波を用いて壁運動を観察することで定量的に評価する試みがある[11, 12]．超音波クリスタルやビーズを心臓内部に埋め込み局所2点を定義し，その間の伸縮率を算出することで局所心筋の歪み率を計測する．特徴点追跡用のマーカが小型であるため，複数部位の計測が可能であり，また，表面のみならず心筋内部の計測も可能である，

しかしながら，筆者らの提案手法および超音波クリスタルを用いた方法は心臓に直接マーカを設置する必要があり，侵襲を伴うだけでなく．心臓の動きにも影響を与えることからそのままでは臨床への応用が難しい．臨床においては対象に直接触れることなく計測できることが望ましい．特徴的な点を利用した新たな変位検出の手法の検討が求められる．

筆者らは現在，画像処理の技術を応用し，色情報を利用したステレオ計測について検討中である．心臓の場合，冠動脈の分枝といった解剖学的な特徴点がすでに周りの組織