のアクセスポイントの配置状況では、約5m程度の誤差で各機器の所在が中央で監視できることがわかった。またこの画面は5秒ごとにリフレッシュ表示可能なので、リアルタイム位置検出上の問題は特にない。

電波強度に関しては、図2、3に示されるように無線LANアクセスポイントの配置は慎重に検討されるべきである。たとえばほとんどの病室た治療室をカバーしていても、両者に隔てられた廊下などが死角になることが起こりうる。

D.考察

今回の試行により、輸液ポンプなどの移動性の医療機器や患者、医療スタッフに WiFi タグを取りつけることにより、ほぼ通常の業務用に設置された無線 LAN アクセスポイントを活用すれば必要な精度の位置検出が集中的に可能であることがわかった。この位置情報を、警告通報や異常状態が発生している場所の所在という観点から有意義かどうかであるが、1フロア内の人や物の位置を視覚的に表現できるマクロなレベルの精度では，十分にそのおよその所在を認識可能な状態である。ただし，警告監視システムといった数値情報として位置を扱う対象に対してはさらに精度を高め、どの部屋に人や物が存在するかが識別可能なレベルを実現できる必要があると考える。このためには、アクセスポイントの配置位置、配置数についても今後さらに検討をくわえる必要がある。緊急時のアクセスは、たとえば壁を隔ててどちら側に人や機器が存在するかを識別することが重要で、たとえ距離的には1mしかはなれていなくても、駆けつけた場所には所在しておらず、壁を隔てた向こう側に所在しているのではアプローチミスが発生する。

　また，今回試行した位置特定ソフトウェアは Web 画面でリアルタイムに観測可能な機能を有するが，特定の人や物の移動経路といった時系列の情報を蓄積できないため，人や物の動き経路からの事故予測や通報といった機能を警告監視システムに実現するためには，位置情報の数値化とともに、時系列データの蓄積も実現すべき課題である。

E. 結論

無線LANの既存のアクセスポイントを活用して、約5m程度の誤差で各機器の所在が中央で監視できることがわかった。またこの画面は5秒ごとにリフレッシュ表示可能なので、リアルタイム位置検出上の問題はなかった。しかし電波死角の解消や、通路や壁を隔ててどちら側に対象物が存在するかを的確に判断するには、時系列的な蓄積データを活用して軌跡からそれを判定するような機能の開発も必要になる。このような課題を解決していくことによって、医療安全のための集中監視システムの実現は十分可能になると考えられた。

G. 業績

(学会発表)

田中勝弥、耿景海、松谷司郎、大江和彦: 医療安全を目的とした輸液ポンプ動作監視システムの開発．第 26 回医療情報学連合大会論文集,925-926,2006.

H. 知的財産権の出願・登録状況

（予定を含む。）

なし

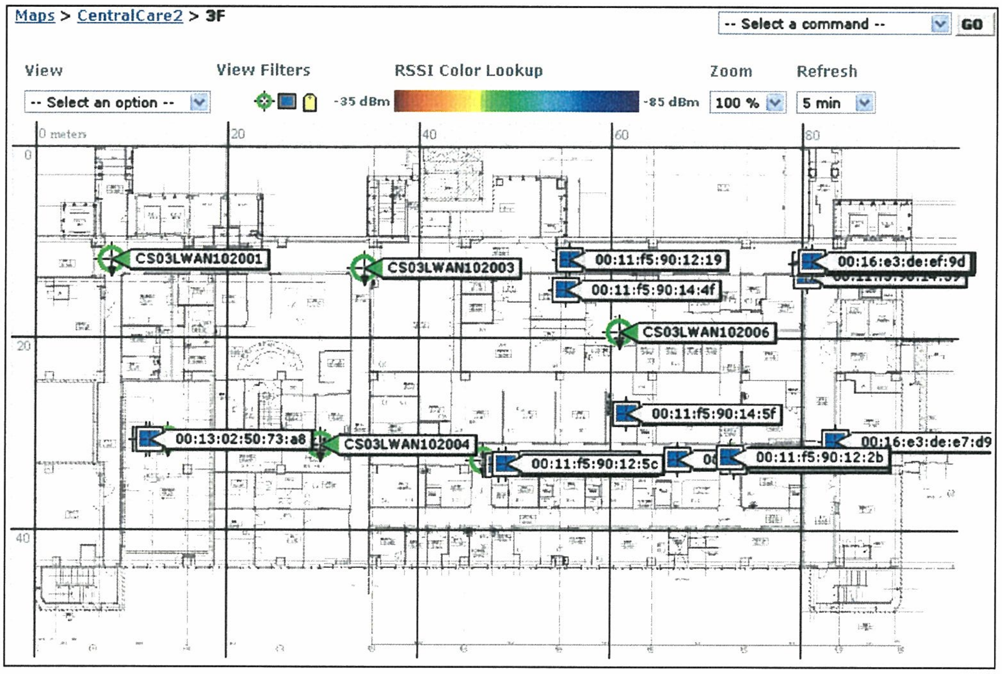

図1. フロア内のアクセスポイントの位置（緑○印）と、機器の位置（青■）の表示例
このフロアでは、アクセスポイントが5箇所にあり、 機器10箇所に分散配置されている状況であることがわかる。個々の機器にある数字情報は機器の Mac アドレスである。

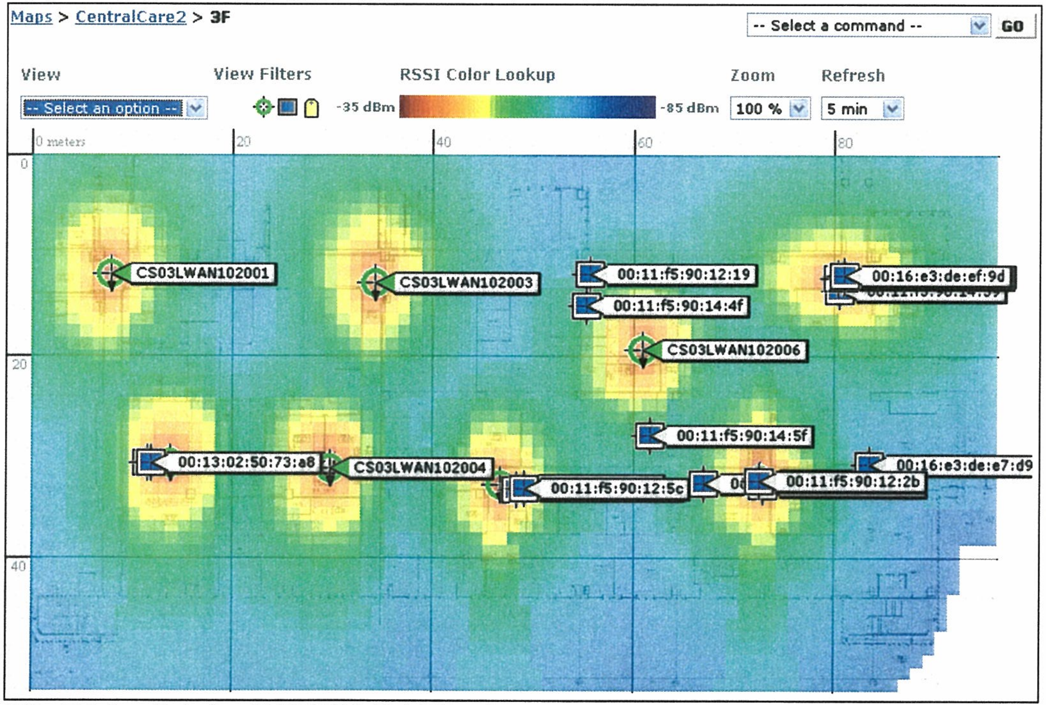

図2. アクセスポイントの受信強度を示す図（3F）

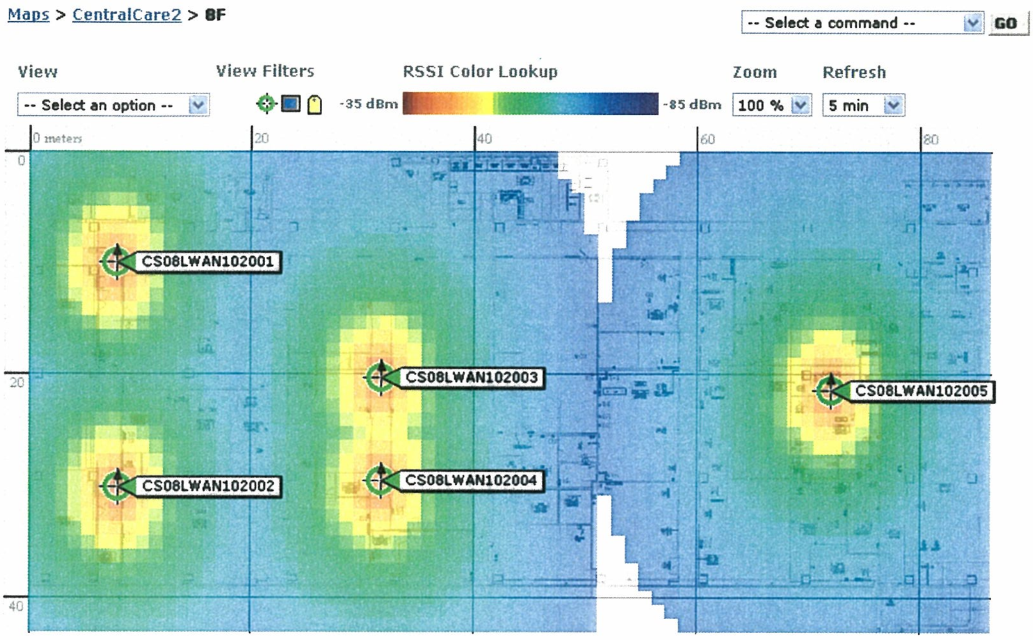

図3. アクセスポイントの受信強度を示す図（8F）
アクセスポイントの配置によりカバー範囲の違いが図2と比べるとよくわかる。

厚生労働科学研究費補助金（医療安全・医療技術評価総合研究事業）分担研究報告書

分担研究課題名：医療安全のためのリアルタイムオーダ照合機能とその知識ベース構築の検討

分担研究者名：松谷司郎　東京大学大学院医学系研究科・特任助手

研究要旨

注射や輸液の誤投与は、医療ミスの中でも最も頻度が多く発生しており、これを防止するシステムを構築することが急務となっている。本研究では輸液ポンプの動作監視システムの開発し、オーダー情報との整合性チェックを自動的に実施する方法（リアルタイムオーダ照合機能）を考案し試験開発を行う。またこれらを支援する知識ベースにあり方についても検討した。今回の実験は輸液ポンプに限られているものの、その誤設定をほとんど瞬時に発見しナースセンターや当該医師に自動通報できる可能性を示した。今後さらにシステム的に検討し改善すべき点としては、1）輸液ポンプと患者との対応データを簡単な方法で確実かつリアルタイムに取得する方法の開発、2）警告情報の通報の方法、3）何が警告すべき状態であるかをシステムがどのように学習するか、である。また2）に関連して医療安全監視センターのような集中監視センターに通報しておき、そこからは人が連絡をとるという方法も併用することが現実的であると考える。また3）については事例データベースの構築と、知識ベースとの併用が必要である。

A.背景と目的

医療の高度化・専門化の進展や、病院情報システムの整備拡大に伴い、事故防止に有効な情報システムの構築が進んできている。これは従来の「医療事故は起こってはならないものだ」という理想論的な仮定から「医療は人間により行われる限り、エラーを完全に無くすことは困難である」という現実的な仮定に基づき、IT技術を駆使してエラーの発生を防いだり（エラーレジデント）エラーが事故に結びつかないようにすることにより事故を防止する（エラートレラント）ということが重要であるということが広く認知されてきたことによる。

注射や輸液の誤投与は、医療ミスの中でも最も頻度が多く発生しており、これを防止するシステムを構築することが急務となっている。本研究では輸液ポンプの動作監視システムの開発し、オーダー情報との整合性チェックを自動的に実施する方法（リアルタイムオーダ照合機能）を考案し試験開発を行う。またこれらを支援する知識ベースにあり方についても検討する。

B.方法

輸液ポンプの外部通信端子を用い、ポンプの動作状況（流量・予定量・積算量・動作状態、警報状態）をリアルタイムに取得可能であり、誤投与の警告を発生させるシステムを構築し検証する。具体的には昨年度開発した輸液ポンプ動作状態を無線LANで自動送信する装置を輸液ポンプに接続し、ポンプ状態を周期的に本システムに自動送信する。本システムは受信した輸液ポンプ状態情報に対応づけられている患者について、その患者に発行されている注射点滴オーダー実施情報をHIS(病院情報システム)に問い合わせ、当該時刻に実施されているはずのオーダーと照合し、輸液速度の設定が誤っていないかを検出する。

C.結果

図1は開発したシステムの構成図、図2に示すように輸液ポンプ状態情報を送信してくる装置のIPアドレスを患者に割り当てる初期設定が必要である。これにより受信した情報がどの患者の情報であるかを対応づけさせることができるようになる。図3は、実験的に受信しているポンプ状態情報を表示しつつ、注射点滴オーダー情報とのチェックを行い警告を表示している画面である。流量警告は設定状態とオーダー状態との差が10％を超える場合に警告を出すようにした。

開発したシステムでは、患者IDと輸液ポンプとの対応付けをあらかじめシステム上で設定し、輸液ポンプから一定時間間隔で自動送信されてくる状態情報をシステムが自動受信し、この状態とその患者に発行されているオーダー情報との整合性チェックを自動的に行い、10％以上乖離している場合には輸液ポンプの設定異常の可能性があると判断して画面上に警告することが可能であった。

D.考察

オーダにもとづく医療行為（たとえば点滴の実施）の実施情報とオーダ情報とのリアルタイムに自動照合することは、これからの医療安全のITによる貢献の非常に重要な一面となることが期待される。今回の実験は輸液ポンプに限られているものの、その誤設定をほとんど瞬時に発見しナースセンターや当該医師に自動通報できる可能性を示した。

今後さらないシステム的に検討し改善すべき点としては、1）輸液ポンプと患者との対応データを簡単な方法で確実かつリアルタイムに取得する方法の開発、2）警告情報の通報の方法、3）何が警告すべき状態であるかをシステムがどのように学習するか、である。1）については、輸液ポンプにICタグなどをあらかじめつけておき、輸液ポンプをベッドサイドで患者につないだときに自動的に認識する手法の開発が考えられる。2）については、すでに本研究班で田中らが検討しているように、スタッフの位置検出システムを活用する方法、スタッフのPHSやメールを活用する方法などのくみあわせにより実現することが考えられる。

また主任研究者の大江が提唱するように、医療安全監視センターのような集中監視センターに通報しておき、そこからは人が連絡をとるという方法も併用することが現実的であろう。

3）については、病院情報システムのオーダ情報と連携しオーダと実施の整合性をチェックすることや、輸液での過去の事故発生状況を事例データベース化しエラー発生パターンの解析、投与状況毎のきめ細かいエラー防止策の作成などを実施することが重要である。

しかし、このような分析・解析のためのデータベースは病院情報システムの情報だけでは不十分であり、今回のような輸液の実際にどのように投与されたのかという情報（ファクト）を取り込んで作成する必要がある。オーダ情報、実施入力、実際のファクトデータ、及びインシデント・アクシデントレポートを統合した分析用の事例データベースを作成することにより、エラーの発生パターンの分類及びエラー防止対策の立案が可能となると考える。

具体的には、病名、薬剤名、流量、予定量、積算量、薬剤名、病名、患者性別、患者年齢、看護師性別、看護師年齢、投与開始時刻、終了時刻、点滴の場所、輸液ポンプ機器名、オーダ情報、実施入力情報、インシデントやアクシデントの文字情報を対象として、データマイニング手法（アソシエーションやクラスタリング等）を適用することにより、エラーの発生傾向やパターン分類を客観的に評価ことが期待される。インシデントやアクシデントの個々の事例集も医療安全のために有効であるが、それらを集約・抽象化してルールやパターンとして知識ベース化することで現場でより使用しやすくなると考える。また、エラーが人的要因なのか、時間的制約なのか、あるいは機器のエラーなのか、などという原因を特定しやすくなり、事前にエラー防止の対策が立案しやすくなる可能性がある。

さらに、このような事例データベースの分析を基に構築される知識ベースがあると病院情報システムから輸液のオーダが出された際、類似のオーダでの過去のインシデントやアクシデントや注意事項といった情報を自動的に付加することが可能となり、現場での輸液実施時の安全性向上のための注意喚起を促すことが可能となる。今後は事例及び知識ベースの本格的な構築とともに、輸液の場合の「類似」という概念のソフトウェアとしての実装、過度の警告や脅し（狼少年シンドローム）をどう防ぐか、などの検討課題である。

E.結論

本研究では輸液ポンプの動作監視システムの開発し、オーダー情報との整合性チェックを自動的に実施する方法（リアルタイムオーダ照合機能）を考案し試験開発を行った。今回の実験は輸液ポンプに限られているものの、その誤設定をほとんど瞬時に発見しナースセンターや当該医師に自動通報できる可能性を示した。

今後さらにシステム的に検討し改善すべき点としては、1）輸液ポンプと患者との対応データを簡単な方法で確実かつリアルタイムに取得する方法の開発、2）警告情報の通報の方法、3）何が警告すべき状態であるかをシステムがどのように学習するか、である。また2）に関連して医療安全監視センターのような集中監視センターに通報しておき、そこからは人が連絡をとるという方法も併用することが現実的であると考える。また3）については事例データベースの構築と、知識ベースとの併用が必要である。

G. 業績

（学会発表）

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発．第 26 回医療情報学連合大会論文集,925-926,2006.

篠原信夫、松谷司郎、小山博史、大江和彦: 病院情報システムデータを利用した患者の状態の分類手法についての検討．第26回医療情報学連合大会論文集,537-539,2006.

H. 知的財産権の出願・登録状況

(予定を含む。)

なし

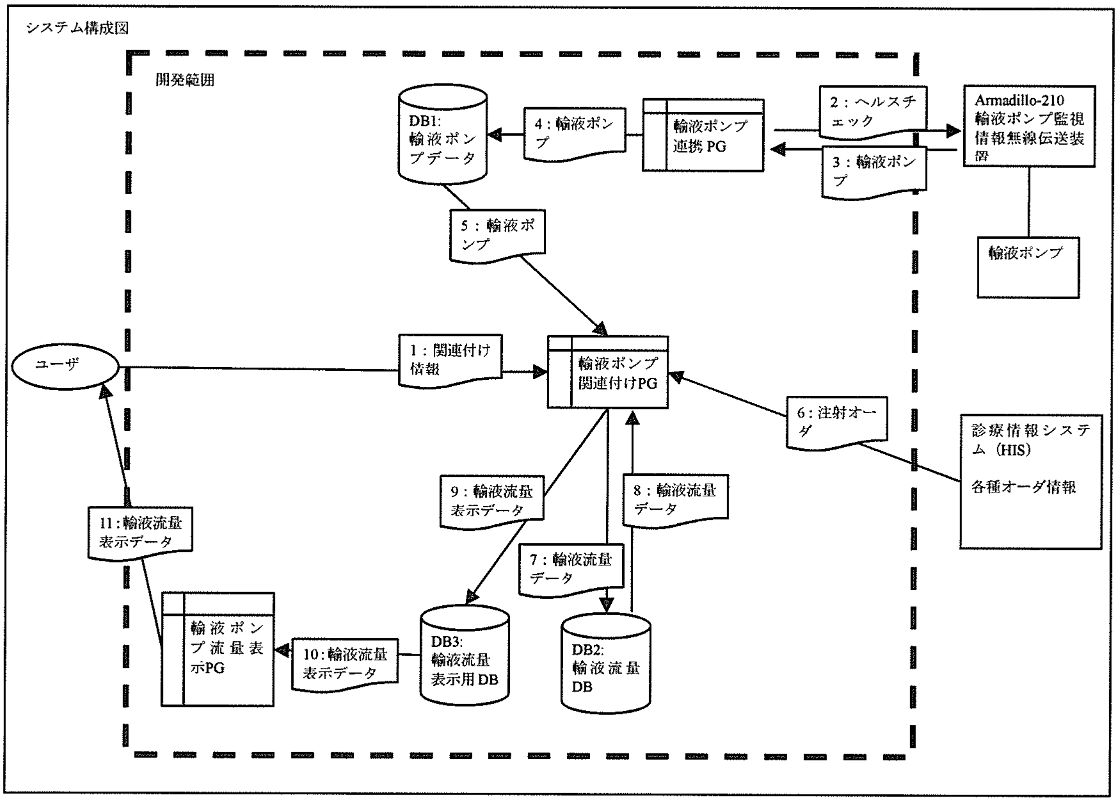
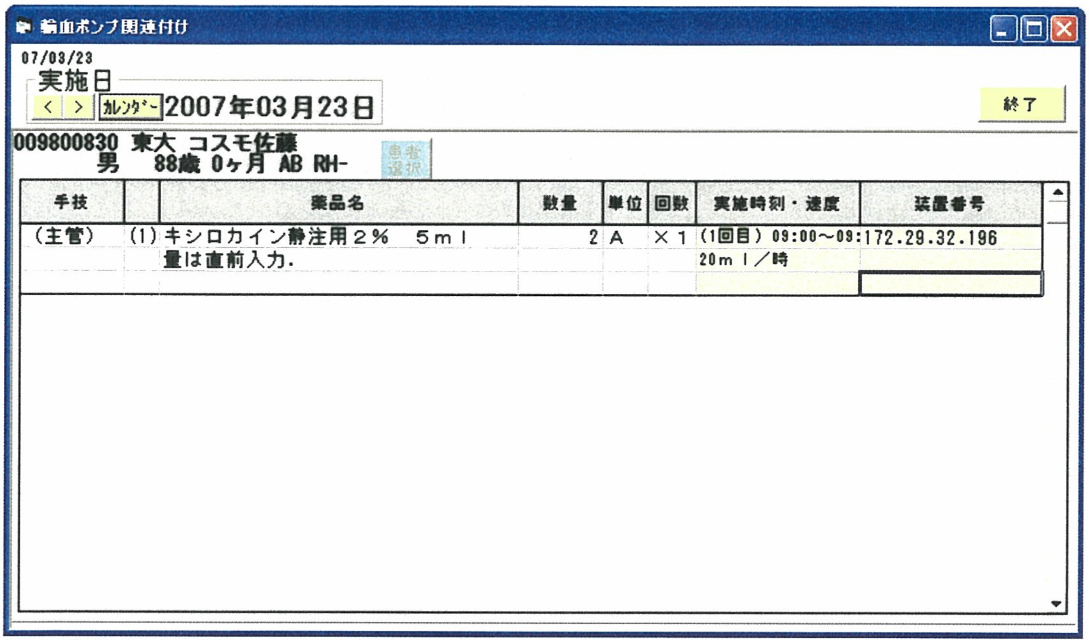


図1．輸液ポンプ状態と診療情報システムの自動情報照合システムの構成図



07/03/23

実施日

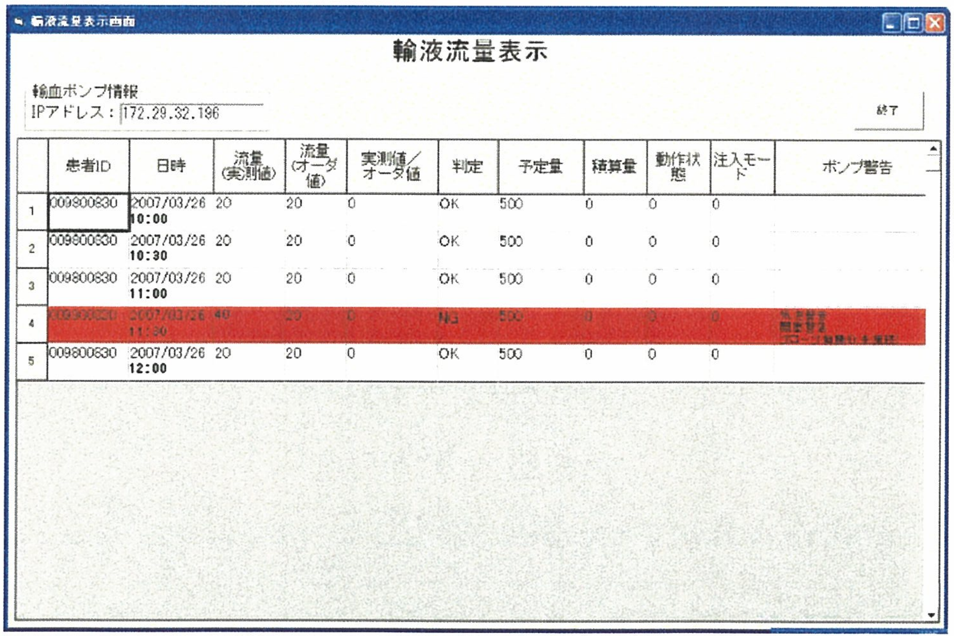
2007年03月23日

009800830 東大 コスモ佐藤
男 88歳 0ヶ月 AB RH-

手技		薬品名	数量	単位	回数	実施時刻・速度	装置番号
（主管）	(1)	キシロカイン静注用２％　５ｍｌ 量は直前入力.	2	A	×１	(1回目) 09:00～09: 20ｍｌ／時	172.29.32.196

図2. 輸液ポンプと患者 ID とを対応づける画面

輸液ポンプに接続されている輸液ポンプ監視情報無線伝送装置の IP アドレスを患者に発行されているオーダーに一度入力する必要がある。



輸液流量表示

輸血ポンプ情報

IPアドレス：172.29.32.196

	患者ID	日時	流量(実測値)	流量(オーダ値)	実測値／オーダ値	判定	予定量	積算量	動作状態	注入モード	ポンプ警告
1	009800830	2007/03/26 10:00	20	20	0	OK	500	0	0	0	
2	009800830	2007/03/26 10:30	20	20	0	OK	500	0	0	0	
3	009800830	2007/03/26 11:00	20	20	0	OK	500	0	0	0	
4	009800830	2007/03/26 11:30	40	20	0	NG	500	0	0	0	[illegible]
5	009800830	2007/03/26 12:00	20	20	0	OK	500	0	0	0	

図3. 当該装置からの輸液ポンプ状態情報を30分ごとに表示している画面

11:30の時点でオーダ20ml／hに対し流量設定値が40となっており警告が表示されている。

研究成果の刊行に関する一覧表

書籍

著者氏名	論文タイトル名	書籍全体の編集者名	書籍名	出版社名	出版地	出版年	ページ
なし							

雑誌

発表者氏名	論文タイトル名	発表誌名	巻号	ページ	出版年
Nakao M, Kuroda T, Oyama H, Sakaguchi G, Komeda M	Physics-based simulation of surgical fields for preoperative strategic planning.	J Med Syst	30(5)	371-380	2006
Nakao M, Minato K, Kuroda T, Komori M, Oyama H, Takahashi T	Transferring Bioelasticity Knowledge through Haptic Interaction.	IEEE Multimedia	13(3)	50-60	2006
大江和彦	医療情報システムと医療の質・安全	品質	36(2)	175-182	2006
田中勝弥、耿景海、松谷司郎、大江和彦	医療安全を目的とした輸液ポンプ動作監視システムの開発	第 26 回医療情報学連合大会論文集	なし	925-926	2006
篠原信夫、松谷司郎、小山博史、大江和彦	病院情報システムデータを利用した患者の状態の分類手法についての検討	第 26 回医療情報学連合大会論文集	なし	537-539	2006

J Med Syst (2006) 30:371–380
DOI 10.1007/s10916-006-9021-4

ORIGINAL PAPER

Physics-Based Simulation of Surgical Fields for Preoperative Strategic Planning

**Megumi Nakao · Tomohiro Kuroda · Hiroshi Oyama ·
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Abstract Although careful planning of surgical approach is a key for success of surgery, conventional planning and simulation tools cannot support detailed discussion. This issue is derived from the difficulty of estimating complex physical behavior of soft tissues provided by a series of surgical procedures like cutting and deformation. This paper proposes an adaptive physics-based framework that simulates both interactive cutting and accurate deformation on virtual bodies, and performs preoperative planning for supporting strategic discussion. We focus on limited use of the two models: A particle-based model and an FEM-based model considering required quality and performance in different situations. FEM-based deformation of incision accurately produces estimated surgical fields. Based on the framework, a strategic planning system was developed for supporting decision of surgical approach using 3D representation of the surgical fields. We applied clinical CT dataset of an aortic aneurysm case to the system. Some experiments and usability tests confirmed that the system contributes to grasping 3D shape and location of the target organs and performs detailed discussion on patient-specific surgical approaches.

Keywords Preoperative planning · Surgical simulation · Physics-based modeling

Introduction

Computer graphics (CG) and virtual reality (VR) are finding increasing uses in the medical field. The visual and interactive characteristics of virtual reality are effective in understanding complex 3D structures of human bodies [1–3] Computer-assisted systems based on VR techniques are widely utilized as essential tools for surgical planning and for evaluation of surgical intervention [4–6]. At present, some clinical uses have been reported especially in orthopaedic and plastic surgery [7].

Planning systems are also desired in the fields of cardiovascular and abdominal surgery. On the basis of our analysis, this demand is specifically derived from difficulty of deciding patient-specific best surgical approach. Surgical fields and obtainable view during surgery are clearly different due to various kinds of surgical approaches. Once the surgical field is adequately prepared and sufficient space is kept for manipulation, overall procedures become easy to perform.

Skilled surgeons proficiently estimate 3D surgical fields from 2D images using knowledge and experience, and determine the best surgical strategy. In spite of their effort, however, some unsuccessful results have been reported. Several reports describe that additional incision and emergent operation were sometimes required for complete treatment [8]. Although a variety of approaches are standardized based on

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diseases, decision of the patient-specific best approach is a difficult task even for skilful surgeon. Especially, this trend appears in minimally invasive surgery and in rare cases with anamorphous.

Generally in surgery, cutting a body (e.g., skin and fat) and opening the incision create 3D geometry of the surgical field. Absolute location of the target organ, like an aorta or a heart in cardiovascular surgery, does not change unless the geometry is strongly affected by ablation process. Considering this feature, simulating above-mentioned surgical process provides effective estimation of surgical field, which is indispensable for detailed strategic planning of surgical approaches. However, the foregoing systems [3–7] cannot be applied to such planning use. To increase applicability of current planning tools, combination with accurate physics-based simulation is desired.

This study aims to establish a new approach to support planning of patient-specific surgical strategy using virtual reality-based simulation. An adaptive physics-based framework is proposed for simulating the essential procedures in constructing a surgical field. The proposed methods enable both interactive soft tissue cutting and finite element-based deformation of incision on virtual patient models. Based on the framework, we developed a strategic planning system that supports decision of surgical approach in cardiovascular surgery. This paper evaluates clinical significance of the system using patient CT dataset of an actual aneurysm case. Field trials are given with some cardiovascular surgeons, and characteristic effect of the strategic planning is confirmed.

Related work

Both soft tissue cutting and deformation of incision on virtual bodies efficiently simulates surgical procedures in constructing surgical fields. The estimated surgical field gives effective information to plan surgical strategy. Because surgeons desire to discuss and to rehearse various approaches while observing the estimated 3D surgical field, accurate and interactive simulation is required.

A volumetric and efficient topological modeling is essential to create incision based on a physics-based manner. So far, several approaches have been proposed to perform virtual cutting. Most foregoing methods that handle only surfaces of virtual objects are not useful for generating a deformed deep cut surface of incision where inner tissues spread apart through cutting manipulation [9, 10]. Although voxel-based models [11, 12] provide volumetric representation, they cannot support real-time deformation of soft tissues.

In order to simulate volumetric soft tissue cutting interactively, Bielser and Gross [13] employ a tetrahedral subdivision scheme. Tetrahedral subdivision is useful to define cut surfaces and valid mesh modification. At present, more detailed subdivision algorithms [14, 15] are proposed. In order to represent real-time physical behavior during cutting soft tissue, particle-based models (mass-spring models) [16–19] are normally applied for performing interactive update rates while handling mesh modification. In case of applying particle-based models, however, simulation accuracy is a key problem for realistic surgery simulation. This problem is mostly due to computational properties of particle systems that are sensitive to their own topology. To perform accurate simulation, the virtual object has to consist of fine and detailed mesh, and proper parameter setting of elements is also required. However, increase of elements (or calculation cost) becomes a serious drawback to interactive simulation, and therefore providing accurate deformation of incision is currently one of the significant research issues.

On the other hand, a finite element method (FEM) [4,20,21] is known as the computationally most accurate model to simulate biomechanical behavior of elastic soft tissues. Although FEM-based simulation provides accurate and stable deformation, it takes large cost in calculation. To perform real-time interaction with a volumetric deformable object, a condensation technique [20] is proposed. However, this approach requires pre-computation, which is incompatible with topological change in cutting simulation. Several models [22, 23] also enable interactive cutting based on finite element formulation, the quantitative validation is not confirmed, and further adaptation is needed for practical planning use.

From this viewpoint, forgoing methods cannot be applied directly to estimate surgical fields. Also, such practical applications that enable planning of surgical approach are not proposed or developed. To improve applicability of both current models and computer-assisted planning, this paper presents an integrated simulation framework, and aims to develop virtual reality-based strategic planning system.

Physics-based simulation of constructing surgical view

In order to simulate construction of surgical fields, we focus on a series of surgical procedures: Cutting and deformation of incision, and extract the following functions that should be provided by the planning system.

- Interactive performance on detailed models
- Complete subdivision of tetrahedral mesh
- Fast remodeling of stiffness matrix
- FEM-based deformation of incision in real time

To satisfy these requirements on standard PCs, this paper gives an adaptive physics-based framework to simulate surgical procedures in constructing surgical fields. Figure 1 illustrates outline of the methods. The framework has two

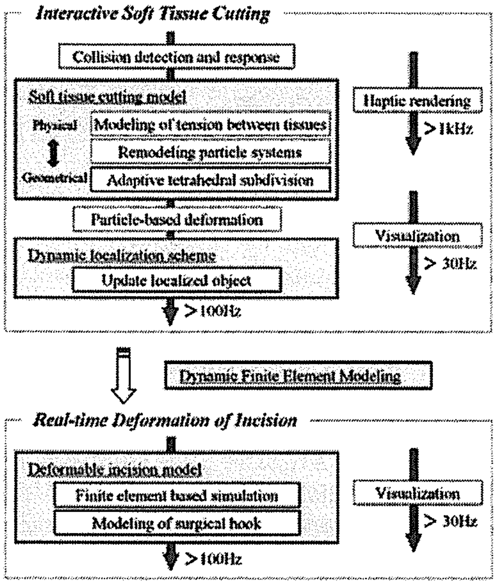


Fig. 1 Adaptive physics-based simulation framework

simulation parts: Interactive soft tissue cutting and real-time deformation of incision.

The interactive cutting part provides efficient and stable computation, and can be applied to large dataset that have huge elements. A particle-based model and a fast computational structure are employed to perform interactive simulation. Also, modeling of stiffness matrix using a complete tetrahedral subdivision scheme enable finite element-based deformation after mesh modification. This adaptation of the models aims to perform both interactive performance and simulation accuracy suitable for each surgical procedure.

Adaptive tetrahedral subdivision

In order to create cut surfaces for visualizing volumetric incision on virtual anatomical models, new edges and polygons are needed. However, complex description [13–15] is required to inherit topology of tetrahedral objects, and radical increase of the elements becomes a serious drawback to interactive simulation. For this issue, this paper presents adaptive tetrahedral subdivision that describes complete and minimized mesh modification.

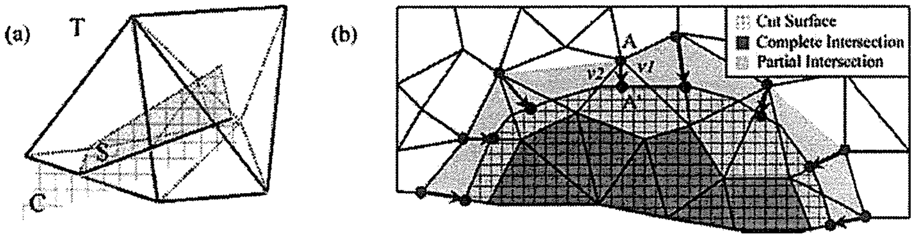
For concrete description of the methods, we assume a situation that a virtual scalpel cuts into a 3D virtual body that is composed of tetrahedral mesh. Movement of the virtual scalpel defines a clipping plane C, which clips a cut surface S from tetrahedral objects T. Figure 2(a) illustrates the relationship between these three elements. Note that incomplete intersection appears at some tetrahedra because C is given as a partial plane by cutting manipulation. This incomplete intersection is shown at the rightmost tetrahedron of T in Fig. 2(a). For this situation, we define the cut surface S by removing incomplete intersection instead of handling complex patterns [14, 15] of the whole intersection. Definite solution that removes incomplete intersection is illustrated in Fig. 2(b), which represents movement of vertices on the clipping plane C. For example, the vertex A is updated to the vertex A' on the boundary B of the clipped area C. The movement vector of the vertex is given as an average of edge vectors (v1, v2) that intersect at B. All adjacent vertices outside of the area C are moved and replaced on its boundary B.

The cut surface S can be simply represented as combination of the two intersection patterns in Fig. 3. Some edges are inserted into the object to define complete subdivision for finite element modeling. The generated surface S provides volumetric incision. In order to describe small deformation of incision while cutting tissues, a remodeling scheme of the particle-based system [24, 25] is applied to all edges that are clipped by C. The scheme represents internal tension: Biomechanical characteristics of soft tissues including skins, fats, muscles, and organs.

Implementation of the methods is simple because complex description of subdivision patterns is not required. Moreover, this approach provides more efficient solution that reduces growth rates of vertices than that proposed in foregoing works [13–15].

Due to the fact that increase of elements grows up calculation cost, large-scale simulation that handles all elements of virtual bodies cannot produce interactive performance. To solve this problem, J. Berkeley *et al.* reduced calculation cost and achieved valid solution using localization of simulation area [26]. However, since the method aims to provide static localization in the stage of pre-processing, it must not be applied to global and dynamic manipulation directly. We

Fig. 2 Definition of cut surface (C: clipping plane, S: cut surface, T: tetrahedral object): (a) Intersection between a clipping plane and tetrahedra, (b) movement of vertices on the clipping plane



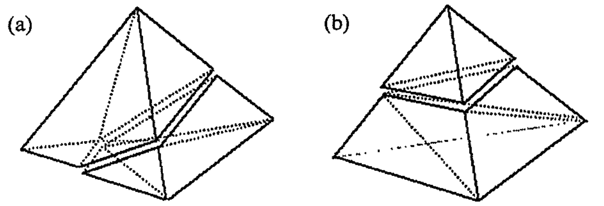


Fig. 3 Minimal tetrahedral subdivision: (a) Four-edge intersection and (b) three-edge intersection

improve the method, and produce an advanced approach to perform dynamic localization.

Figure 4 shows an image of the proposed dynamic localization. Since physical interference in actual tissue cutting does not influence on large area, it is reasonable to assume that only a part of vertices around the contacted point are affected by physics-based simulation. The fixed vertices allow not only controlling calculation cost but also keeping the physical system stable.

To concrete this scheme computationally, a hierarchy of elements is constructed using adjacent information. In the pre-processing stage, a class structure is developed to manage a 3D anatomical object that consists of primitive elements: Vertices, edges, polygons, and tetrahedra. All edges, polygons, and tetrahedra have pointers of their component vertices, and hold relational information such as adjacent, parent and child elements. This class structure makes it easy to access and to search topologically related elements and computational cost in constructing hierarchy of elements can be efficiently reduced.

Figure 5 illustrates a mechanism of dynamic localization using the hierarchy of vertices. The root node of the tree is dynamically updated to the nearest vertex around a tip of the virtual scalpel. When collision between the scalpel and the tissue is detected, the nearest surface vertex in Fig. 4 is assigned as a root vertex, and its children are configured as adjacent vertices. Note that the hierarchy is reconstructed partially using stored relational information between elements. The depth *d* or the number of vertices *n* briefly manage the level of localization. For example in Fig. 5, the number of free vertices is 10. When the hierarchical structure is constructed, fixed status is initially given to all vertices and then 10 vertices are freed by breadth-first search. Thus, using the number of vertex as a threshold of localization, the lower vertices in the tree are fixed and the upper vertices are allowed to move for deformation. This procedure is processed per one simulation cycle and allows users to adjust simulation accuracy and interactive performance.

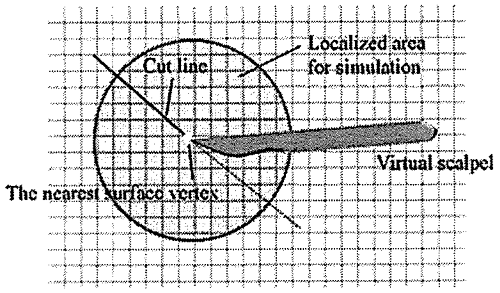


Fig. 4 Outline of dynamic localization

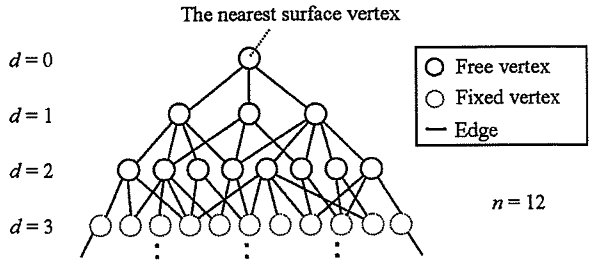


Fig. 5 Localization of calculation using hierarchical structure of elements

FEM-based deformation of incision

Next, this section presents a modeling scheme that enables finite element-based simulation after cutting manipulation.

As described above, we applied a particle-based model to achieve interactive performance in cutting simulation. However, the particle system does not allow accurate modeling of elastic properties. In this situation, finite element method based on linear elasticity theory is useful. Although pre-processed finite element model can optimize calculation cost, condensation techniques [20] have been incompatible with cutting simulation because it requires time-consuming manual pre-processing.

For providing FEM-based deformation in real time even after topology modification, the proposed scheme aims to switch the particle-based model to the linear finite element model [20] automatically as a background process. This process constructs a condensed inverse matrix by the following procedures.

1. The modeling area is defined around incision by integrating whole area localized by dynamic localization in Fig. 4.
2. All tetrahedra in the modeling area form a localized elastic object, and all vertices outside the area are fixed.
3. The inverse stiffness matrix of the localized object is calculated automatically from assigned elastic parameters (Young's modulus and Poisson's ratio).
4. Parallel CPU workstations with a shared memory efficiently support the proposed scheme (Fig. 6). A first CPU continues calculation of particle-based deformation for interactive and valid estimation, while a second CPU is processing the modeling algorithms. Once the inverse stiffness matrix is constructed, finite element-based

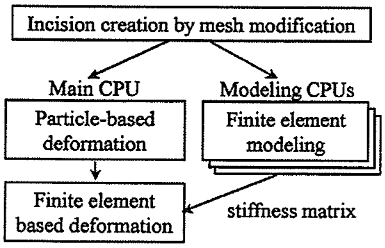


Fig. 6 Dynamic finite element modeling

simulation is given. If other CPUs calculate larger matrices, more accurate simulation can be performed after each process is over. To perform seamless switch of the two models completely, proper parameters should be assigned to the particle system based on finite element formulation. However, in this case, strict parameter setting is not essential because deformation of incision is still small just after cutting manipulation.

A virtual hook model

In real surgery, a surgical hook is used to open incision for setting up surgical fields. To simulate such physical behavior, we give a virtual hook model and perform FEM-based deformation of incision. Interaction between the surgical hook and the incision is simplified as point-based interaction between several control points and the virtual body. Figure 7 illustrates the virtual hook model using two control points per one hook. The direction for opening incision is defined as a normal of the cutting vector.

This approach enables widespread deformation in real time as well as simulates valid physical interaction between virtual bodies and surgical hooks. Increasing the number of control points provides accurate simulation results instead of requiring large calculation cost. The optimized number of control points is determined under the condition that the system maintains over 30 Hz refresh rate.

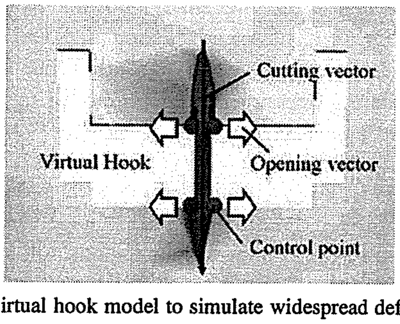


Fig. 7 A virtual hook model to simulate widespread deformation of incision

Hybrid virtual body

For supporting strategic planning of soft tissue surgery, VR-based preoperative rehearsal system requires both interactive simulation and high-quality visualization of soft tissues. Although a voxel-based representation (Fig. 8(a)) is currently used for diagnosis or preoperative planning, it is incompatible with physics-based soft tissue simulation. So far, most studies adopted model surfaces because of achieving interactive performance. Although surfaces are compact and easy to render, surface representation lacks internal information. In addition, large number of surfaces are required to visualize complex 3D geometry of anatomical structures (e.g., myocardium and blood vessels etc.). Also, strict volume segmentation and surface reconstruction from medical images are time-consuming tasks.

In order to provide interactive simulation while visualizing key features like coronary, this study proposes an efficient hybrid approach to construct virtual bodies. Figure 8(b and c) illustrates a hybrid virtual model which is composed of both tetrahedral mesh and voxels. Because this paper handles physics-based simulation on the body, tetrahedral mesh is used to represent a breast part and other inner tissues consist of voxels. This adaptation is useful to establish both interactive simulation and high-quality volume rendering of tissue status. Note that this hybrid approach does not require high-cost manual segmentation because the breast part is easily extracted from CT/MRI dataset.

Evaluation and results

This chapter examines functions and availability of the proposed methods for preoperative strategic planning. Several experiments were given by applying clinical dataset measured from CT.

System configuration

The overall methods were integrated into the interactive simulation framework, and a strategic planning system was constructed. The simulation framework was installed on a standard PC (CPU: Pentium 4 Dual 2.4G Hz, Memory: 1024 MB, Graphic Card: nVidia Quadro4 900 XGL and OS: Windows XP). Force feedback during cutting manipulation is simply provided based on the haptic rendering scheme [27] through a PHANToM (Sensable Technologies). Surgical plans or incision are also given on virtual bodies directly by mouse manipulation based on the 3D input method [28]. The simulation results strictly fulfill interactive refresh rate, 30 Hz for visual feedback and 1000 Hz for haptic feedback.

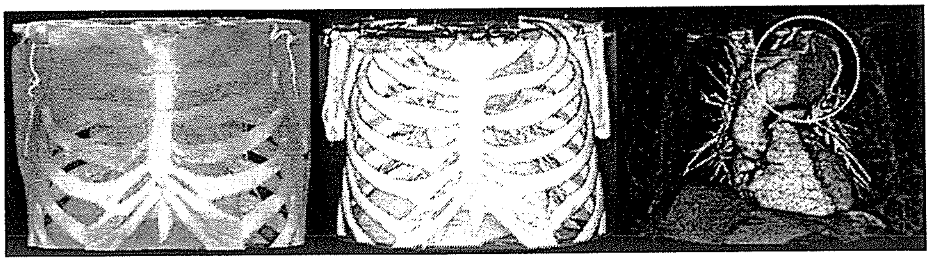


Fig. 8 (a) Voxel-based model and (b and c) hybrid model mixing mesh and voxel for enabling both real-time computation and high-quality visualization

Quality and performance of interactive cutting

This section demonstrates quality and performance of the methods. Clinical CT images (256^3 voxels) in an aneurysm case were adopted. We constructed the hybrid virtual body from CT voxels using modeling software Amira 3.1 (Mercury Inc.). Firstly, we eliminated 3D lung region by filtering lung voxels based on CT value. Then, the chest wall was semi-automatically extracted by cutting out 3D heart region based on region growing algorithms and manual paint tools. After the labeling stage, 3D surfaces of a chest wall were created, and then divided into finite tetrahedra. The reconstructed virtual chest object has 17,582 vertices, 100,807 edges, 19,964 polygons, and 73,279 tetrahedra. The internal voxels were obtained by subtracting the chest wall part from the entire body voxels. Also, bone was extracted based on CT value from chest wall voxels. This process takes approximately 10 min. Thus, since the geometry of the chest wall is not complex, the hybrid virtual body is simply constructed.

Figure 8 shows the constructed hybrid model and compares it with an ordinary volume rendering result of entire voxels. Bone and internal structure like the heart and the blood vessels are voxel models and chest wall is composed by tetrahedral mesh (see Fig. 8(b) and (c)). This hybrid virtual body performs both physics-based simulation and visualization of the target organs and tissues like aneurysm, coronary and internal artery. The 3D positional relationship is the key information for planning surgical approach.

Interactive cutting and simulated volumetric cut on the chest wall mesh are demonstrated in Fig. 9. A bright part of the chest wall near the virtual scalpel represents the localized area where physical simulation is applied. In this case, the localization depth was set as 4. The area dynamically moves to follow the tip of the virtual scalpel. Intersected tetrahedra by the scalpel are subdivided, and deformed incision is represented by relaxation of internal tension [24, 25] between elements. Figure 10 shows some examples of cuts with different tension. In this case, average calculation time per one frame was 2.3 ms.

To clear the performance of mesh modification techniques, average increase of elements after cutting manipulation are compared between some models. Table 1 shows increase of elements and subdivision patterns required for implementation. Model 1 is generalized subdivision. This model gives static subdivision per tetrahedron and yields lots of new tetrahedra. Models 2 [13] and 3 [15] handle several subdivision patterns and reduce creation of new elements. Model 4 is the proposed adaptive tetrahedral subdivision. Compared to other existing models, the increase of elements is restrained and only two patterns like in Fig. 3 are taken into consideration. Thus, the proposed subdivision scheme moderates increase of calculation time in addition to enabling simple implementation.

Finite element-based deformation of incision

Although the particle-based model efficiently simulates small deformation and intuitive visual appearance during cutting manipulation, it does not assure accurate deformation results based on continuous elastic theory. In order to perform valid estimation of the surgical field, our main strategy is to use FEM-based simulation for estimating deformation of incision.

In order to use the two simulation models compatibly, modeling time (e.g., matrix calculation time) and update time per deformation are essential. Calculation time for finite element modeling depends on the number of target vertices in localized area near the incision. In Fig. 9, 462 vertices

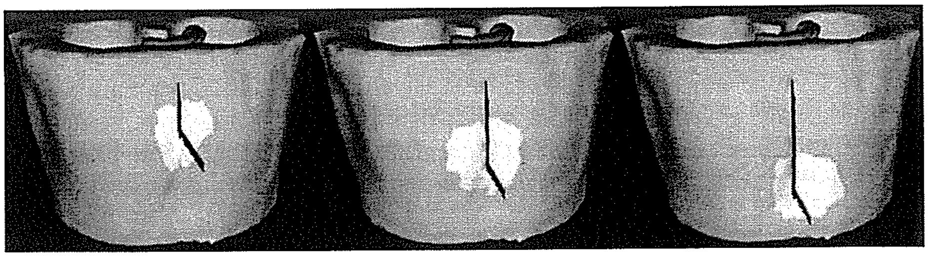


Fig. 9 Interactive soft tissue cutting on virtual chest wall (1, 2, and 3 s)

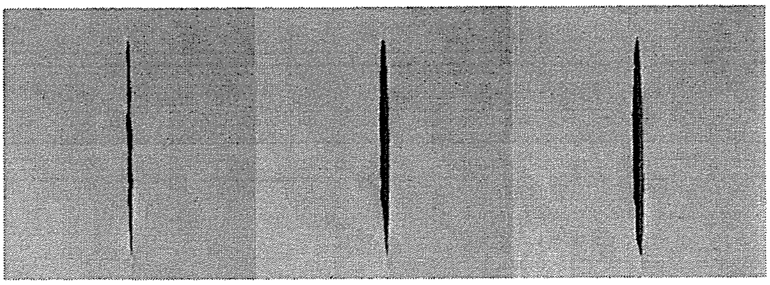


Fig. 10. Example of simulated incision in case of 2, 4, and 6% tension

around incision become the modeling targets and 8.4 s is required for constructing the stiffness matrix. The localization scheme reduces modeling cost and gives valid estimation based on physical characteristics of soft tissues. This approach allows the user to input the incision interactively and to simulate accurate FEM-based deformation after several seconds.

Next, we confirm quality and performance of FEM-based deformation of incision using the proposed virtual hook model with four or eight control points. As shown in Fig. 11, deformed incision depends on the number of control points. In case of (b), smooth incision is provided. However, even in the eight control point case, the shape of incision seems not to follow the hook shape. Since the control points become boundary condition to the FEM model, the deformation results are influenced by their placement on the model. Although more accurate simulation results are obtained using a detailed hook model, increase of control points becomes drawback to real-time deformation. In case of Fig. 11, the calculation time per one frame was 1.91 and 7.54 ms, respectively. Because large incision is estimated to be at most 40 cm in surgery, this quality and performance are valid for specific planning use.

Clinical trial

Thirdly, field trials were given with four cardiovascular surgeons using the developed system and clinical CT dataset. Figure 12 illustrates a hybrid virtual body reconstructed from an aortic arch aneurysm case. The chest wall consists of tetrahedral mesh and other parts like bone, aorta, and heart are voxels. 2D CT images were first presented to the surgeons. The surgeons discussed the best approach by the conventional way used in the current preoperative planning. Three standard approaches: Median incision approach, intercostal incision approach, and distal incision approach were considered. Consequently, two surgeons selected median incision approach and the other surgeons selected intercostal approach.

Table 1 Comparison of mesh modification techniques

	Increase of elements (Average)	Subdivision pattern
Model 1 (General)	16	1
Model 2	8.6	5
Model 3	5.6	11
Model 4 (Adaptive)	4.8	2

To support discussion for these two approaches, the developed planning system was used. The surgeons rehearsed procedures in approaching the target aneurysm region. Cutting line was given on the 3D virtual patient model and incision was opened interactively. Figure 12(a) illustrates the planned median incision and the estimated surgical field. The simulation results show that median incision approach is easy to palpate aortic arch around the aneurysm for grasping sclerosis status. However, a part of distal aneurysm cannot be observed. Thus, the surgeons confirmed several key points that require careful treatment in surgery. Figure 12(b) shows the intercostal incision approach and the estimated surgical field. Although this approach enables surgeons to recognize whole shape of aneurysm, it also suggests a possibility of removing the costal. The surgeons compared the two approaches using simulation results and determined intercostal incision approach is better based on the relationship of the aneurism region and the surgical field.

We also gave another experiment, which is totally virtual preoperative planning of minimally invasive direct coronary artery bypass grafting (MIDCAB). Surgeons gave

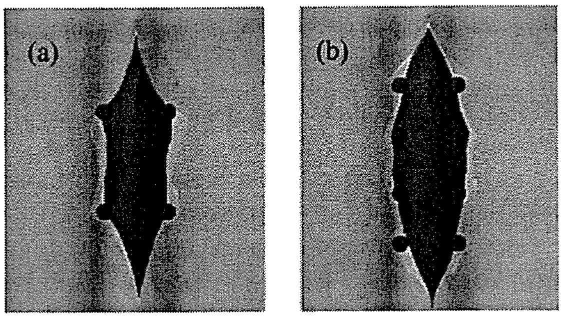


Fig. 11 Deformation of incision using four and eight control points

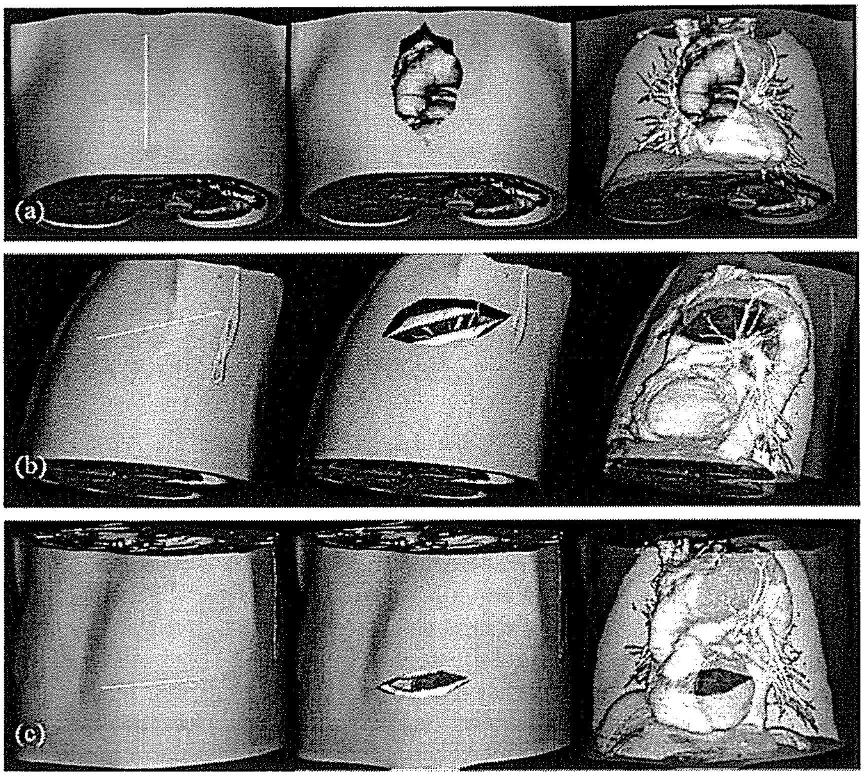


Fig. 12 Results of strategic approach planning of aorta aneurysm surgery. (a) Rehearsing midline incision approach and estimated surgical field. Aneurysm is partly observed. (b) Intercostal incision approach. Aneurysm is grasped without bone. (c) Surgical approach selected in virtual MIDCAB planning. Anastomotic point is located at the center of surgical field

cutting lines for approaching the region and the target point where an internal artery is connected was visualized on the 3D patient model. Four different approaches were proposed (Fig. 12(c)). The surgeons carefully observed relationship of the target point and incision and selected one best approach. The target point of the selected approach is located in the center of the surgical field. The surgeons used this factor to determine the best approach and adjusted incision by rotating or enlarging the virtual body. These results show the reconstructed surgical field is efficient to discuss fine adjustment of incision in minimally invasive surgery.

Characteristic evaluation

Finally, characteristic evaluation was given based on the results of the field trials. Each surgeon marked one to five points to six questions on a questionnaire. The first three questions: 3D shape, location, and quality of the simulated surgical field are selected as functional requirements for strategic planning. Planning effect, crisis recognition, and overall necessity are also examined in order to evaluate availability of the total system.

The averages of the points are designated in Fig. 13. The results assure that the simulated images of the system are sufficient to grasp 3D shape and location of the organs in the surgical filed. However, as a result of discussion with the surgeons, they require more detailed image of other minute organs and tissues such as coronaries and nerves. From this viewpoint, they commented the increase of overall applicability of the system required to improve visual quality of anatomical information.

Discussion

The result of evaluation demonstrates that the developed system simulates procedures for setting up surgical fields and efficiently supports planning of surgical approach. On the other hand, several issues on the system are also revealed.

In this paper, uniform value is used for elastic parameters (e.g., springs and their tension) of the model. For improving reality of interactive cutting, detailed parameter setting is required considering topology of the mesh. However, resetting all parameters of particle systems is time-consuming task and is not always necessary because deformation of incision is still small during cutting manipulation. After cutting operation, accurate deformation of incision is provided based on finite element formulation.

Although the developed framework employs a linear finite element model for performing accurate simulation results, deformation of incision by surgical hooks become large especially in open surgery. In this case, the linear elastic model

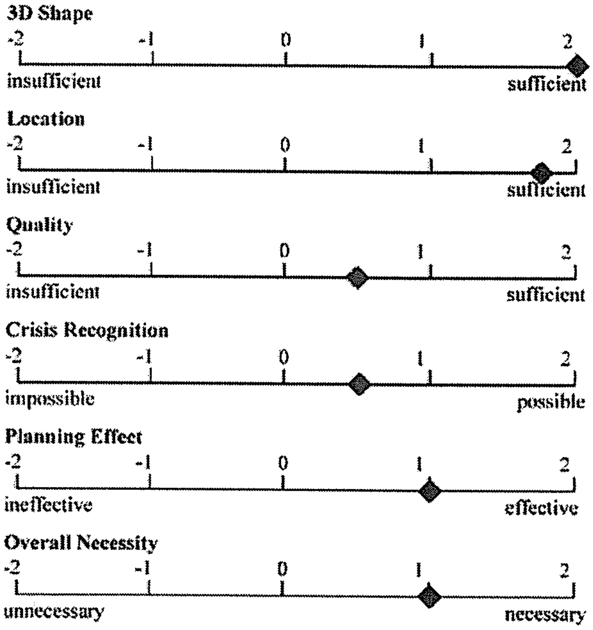


Fig. 13 Characteristic evaluation of the strategic planning system

is not sufficient due to non-linear anisotropic characteristics of soft tissues. In order to simulate such physical behavior, several methods [29] have been reported.

Regarding functions of the planning system, several procedures (e.g., ablation) in setting up surgical fields are skipped. This assumption is effective under the condition that the target organ does not change its position drastically like in minimally invasive surgery or in some cases of thoracic surgery. To improve applicability of the system, influence of both organ–organ interaction and ablation process should be handled.

Consequently, our future direction is to improve quality and performance of the physics-based framework and to examine validation of the system through clinical trials.

Conclusion

This paper first proposes an adaptive physics-based framework that simulates both interactive cutting and accurate deformation on reconstructed virtual bodies.

The framework modifies tetrahedral mesh via cutting manipulation, and then constructs stiffness matrix required for finite element-based simulation. This adaptive subdivision is simple for implementation and efficiently reduces increase of elements. In addition, the fast computation scheme provides valid solution for simulating widespread soft tissue cutting interactively.

A deformable incision model using a virtual hook enables widespread deformation in real time, and simulates construction of estimated surgical field. Improving simulation quality using online finite element modeling is effective to achieve realistic estimation of intra-operative physical behavior for preoperative planning.

Using the proposed methods, we developed a strategic planning system that supports decision of surgical approach, and applied measured clinical dataset of an aortic aneurysm case. Some experiments and usability tests made it clear that the system contributes to grasping 3D shape and location of the target organs. These results confirm that the developed system efficiently supports detailed planning of patient-specific surgical approaches.

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Transferring Bioelasticity Knowledge through Haptic Interaction

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This study establishes a practical environment for transferring knowledge on bioelasticity between expert and trainee medical practitioners. Through haptic interaction with a deformable virtual anatomical model, experts set the model's elasticity conditions by simulating a surgical procedure. Trainees experience the elasticity by attempting the same surgical manipulation.

Knowledge of soft-tissue bioelasticity is essential to medical practitioners in making a successful diagnosis and skillfully carrying out surgical procedures, such as palpation or handling surgical tools. Intraoperative palpation, for example, lets clinical medical practitioners determine the medical status of the body's organs, so it's essential that practitioners understand soft tissue's physical characteristics. Currently, general bioelasticity training is conducted in a "learn by doing" approach during daily medical work. This approach, the traditional style of clinical education, offers few chances for practice in clinical fields. Consequently, it's difficult for students to gain systematic experience in dealing with a wide variety of diseases or rare cases.

In this article, we describe how we constructed haptic media to represent the specific physical behavior of a beating aorta for instructing intraoperative palpation in cardiovascular surgery. We analyze the results of a communication sequence during a user study that involved skilled cardiovascular surgeons and students who trained on haptic interaction using our virtual, deformable models. The study tested this method's effectiveness in communicating both key elasticity properties and the means of manipulation required to master palpation. It's difficult to determine an aorta's bioelasticity, especially in cases such as sclerosis. Therefore, both the approach we created and the quantified knowledge gained during our study will be useful indices for the future development of haptically valid anatomical models.

We chose this area to investigate because currently, there's no training environment provided for intraoperative palpation despite its being a basic technique that all cardiovascular surgeons need to master. Another reason is that the aorta palpation procedure is simple and is performed with a simple push of a finger. Because current force-feedback devices, such as SensAble Technologies' Phantom (http://www.sensable.com), ably support the push operation, the only additional requirement for creating a realistic interaction environment is a valid physics-based aorta model.

Background: Surgical training methods

Virtual reality (VR)-based surgical simulators[1-7] have emerged as possible practical environments for residents to attempt repetitive training in surgical procedures. Physics-based models have been developed for simulating visual and haptic feedback of virtual organ manipulation.[8-15] Recent studies report that simulator-based training helps improve the results of actual surgery.[16,17]

Some of these haptic simulators, targeted specifically at palpation training, are designed to support bioelasticity knowledge acquisition.[4,5] In fact, we too have developed palpation simulators,[6,7] which concentrate on modeling beating behavior and organ–organ interaction in human bodies. In general, these simulators require more accurate haptic displays than the training simulators used in tool manipulation, such as suturing.[2,3,13]

More work, however, remains to be done to advance palpation simulators so they can be used effectively in training. The main obstacle lies in developing valid anatomical models because of the difficulty in accurately specifying organs' elasticity. Output from simulations varies accord-

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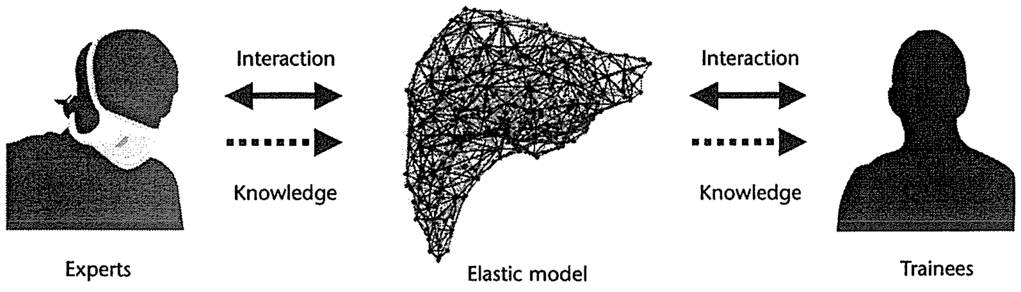

Figure 1. Basic concept. Elastic models support communication between experts and trainees as deformable media. Experts transfer their elasticity knowledge onto the models and trainees study the elastic behavior through haptic interaction.

ing to physical parameters and the complexity of the virtual organs that are being manipulated. Techniques for modeling patient-specific elasticity haven't yet been established; consequently, it's difficult to create accurate models for diseased organs. In addition, the effectiveness of training using haptic simulators must be further evaluated so that researchers can understand and improve simulator performance.

On the other hand, instruction by skilled medical practitioners has traditionally played a large role in the education of patient-specific elasticity. In practical situations, experts sometimes communicate images that are difficult for residents to conceptualize by referring to similar, known elastic objects. This approach is an accepted method of teaching, but verbal communication alone, without hands-on experience, isn't sufficient for effectively transferring knowledge on tissue elasticity. Therefore, an optimized education process requires a combined approach using both simulation and skilled instruction. If an expert's knowledge on bioelasticity could be efficiently transferred to trainees via a computer-assisted environment, trainees would learn key elasticity skills, including those needed for disease and rare-case scenarios.

Researchers have made some headway in developing haptic communication between experts and trainees. Haptic teaching systems developed in other fields focus mainly on tool manipulation[18,19] and are used to teach trajectory and applied force, especially in the field of handwriting. Satoshi Saga and colleagues[19] have proposed a haptic video system, which replays the force history acquired from an expert's manipulation. These approaches support the instruction of tool manipulation rather than provide a simulation environment where objects are manipulated. In manipulating elastic objects, such as during a surgical procedure, a surgeon feels reaction force other than that resulting from the tool's position. Consequently, a surgeon's education in physical behavior of elastic objects must include both haptic interaction and physical modeling of the object under manipulation.

In our study, we aimed to establish a communication support environment for transferring knowledge on bioelasticity using virtual anatomical models. Figure 1 shows the basic concept. We propose an interactive system that lets skilled medical staff instruct residents or medical students in organ bioelasticity by haptic interaction with the models. In our deformable media approach, virtual models are used to transfer elastic information from experts to trainees. The elastic information is stored quantitatively as part of the model's physical parameters. In a simple process, experts set up the model according to their experience, and trainees learn how to perceive the elastic information by attempting surgical procedures on the same model.

Supporting communication on bioelasticity

Medical practitioners generally learn objects' elasticity through attempting to recognize their physical behavior by conducting haptic interaction maneuvers, such as direct hand manipulation or varying the manner of contact. Practitioners also learn bioelasticity properties associated with specific diseases by touching and manipulating tumors in daily medical work.

Basic principles

To advance current training methods and techniques, practitioners require a platform on which medical procedures can be practiced. This platform—haptic media—should serve to let experts share their knowledge and trainees conduct self-study in the virtual space. Here, we outline the basic design, and the two primary tasks, of our proposed environment:

1. *Expert sets virtual model elasticity.* Experts simulate medical procedures on the virtual