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ScienceDirect

Journal of Electrocardiology 47 (2014) 788–793

JOURNAL OF Electrocardiology

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Sensitivity of CIPS-computed PVC location to measurement errors in ECG electrode position: the need for the 3D Camera

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Abstract

Background: The Cardiac Isochrone Positioning System (CIPS) is a non-invasive method able to localize the origins of PVCs, VT and WPW from the 12 lead ECG. The CIPS model integrates a standard 12-lead ECG with an MRI derived model of the heart, lungs, and torso in order to compute the precise electrical origin of a PVC from within the myocardium. To make these calculations, CIPS uses virtually represented ECG electrode positions. These virtual electrode positions, however, are currently assumed to represent the standard 12 lead positions in the model without taking into account the actual, anatomical locations on a patient. The degree of error introduced into the CIPS model by movement of the virtual electrodes is unknown. Therefore, we conducted a model-based study to determine the sensitivity of CIPS to changes in its virtually represented ECG electrode positions.

Methods: Previously, CIPS was tested on 9 patients undergoing PVC ablation, producing a precise myocardial PVC location for each patient. These initial results were used as controls in two different simulation experiments. The first moved all virtual precordial leads in CIPS simultaneously up and down to recalculate a PVC origin. The second moved each virtual precordial lead individually, using 8 points on multiple concentric circles of increasing radius to recalculate a PVC origin. The distance of the newly calculated PVC origin from the control origin was used as a metric.

Results: Moving either all electrodes simultaneously or each V1-6 precordial electrode independently resulted in non-linear and unpredictable shifts of the CIPS-computed PVC origin. Simultaneously moving all V1-6 precordial electrodes by 10 mm increments produced a shift in CIPS-computed PVC origin between 0 and 62 mm. Independently moving an electrode, a shift of more than 10 mm resulted in an unpredictable CIPS-computed PVC origin relocation between 0 and 40 mm. The effect of moving the virtual electrodes on CIPS modeling more pronounced the closer the virtual electrode was positioned to the actual PVC origin.

Conclusions: Slight changes in the virtual positions of the V1-6 precordial electrodes produce marked, non-linear and unpredictable shifts in the CIPS-computed PVC origin. Thus, any variation in the physical ECG electrode placement on a patient can result in significant error within the CIPS model. These large errors would make CIPS useless and underscore the need for accurate, patient specific measurement of electrode position relative to the patient specific torso geometries. A potential solution to this problem could be the introduction of a 3D camera to incorporate accurate measurement of physical electrode placement into the CIPS model.

Since the 3D camera software integrates the 3D imaged position of the electrode with the MRI derived torso model, it is conveniently incorporated in the next generation CIPS software to decrease the errors in modeled location of the electrodes. Thus, the 3D camera will be the IIIrd component of the CIPS to increase its accuracy in PVC, VT, and WPW localization.

Keywords: CIPS; 3D camera; ECG electrodes; Quantitative PVC localization

Introduction

Using the standard 12-lead ECG, electrophysiologists routinely localize PVCs and stable and focal VT qualitatively in a descriptive format to regions of the myocardium [1–4]. Our goal has been to automate and quantitate this

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http://dx.doi.org/10.1016/j.jelectrocard.2014.08.005

0022-0736/

process to improve its accuracy. In order to accomplish this, we first developed a computer program that produced depolarization isochrones from the standard 12-lead ECG [5,6]. This program, entitled Cardiac Isochrone Positioning System (CIPS), mathematically models the translation of the electrical signal from the electrodes on the chest to isochrones on a modeled heart surface. A cardiac MRI of the individual patient was necessary to reconstruct the patient specific anatomy of the torso, lungs, blood cavities, valves and the myocardium within the model.

Our first goal was to use CIPS to localize the PVC origin to expedite catheter ablation. CIPS has the capability to localize the PVC to the endocardium, epicardium, or mid-myocardium [6,7]. In our recently published study [6], CIPS correctly localized 5 of 7 PVCs to the exact area of the successful ablation site. The CIPS-computed PVC location for the remaining 2 cases was close, but alternated between the anterior and posterior RVOT. When we applied CIPS to new retrospective cases, however, the CIPS model produced errors in the range of 50% of the long axis chamber length. One difference noted between the previous 7 patient cases and the new retrospective cases was the careful attention to accurate placement of ECG electrode placement on these first patients. In the new retrospective cases, the electro-anatomical mapping technician had put on the electro-anatomical mapping patches first preventing the EP technician to put the ECG electrodes in the standard 12 lead ECG positions. This helped generate a hypothesis: errors between the physical electrode placement on patients is and the location of the virtually positioned electrode on the CIPS torso model by would result in significant error in the CIPS-computed PVC origin.

The following computer-model study was designed to test the effect of electrode measurement errors by moving the virtual electrodes within the CIPS model.

Methods

The Cardiac Isochrone Positioning System method

The Cardiac Isochrone Positioning System (CIPS) is a non-invasive method that positions simulated cardiac isochrones such that the resulting simulated ECG matches the original measured 12 lead ECG.

To convert the 12 lead ECG into isochrones, CIPS merges data from two different sources:

1) The 12 lead ECG from which a single PVC is selected.
2) The Magnetic Resonance Imaging (MRI) from which DICOM data is used to create patient specific heart, lung and torso triangulated geometries.

The heart, lung and torso geometries were created by custom software [8]. This software morphs existing normal heart, lungs and torso models to match the boundaries of the heart, lungs and torso on the MRI images. To integrate the numbered intercostal spaces of the ribcage in the created torso model, the intercostal spaces were manually localized from the MRI of the patient. From these intercostal spaces the spatial V1-6 electrode positions on the torso model were determined. These positions are referred to as the *V1-6 electrode* positions.

The Boundary element method used the triangulated heart, lung and torso geometries to compute a patient specific transfer matrix (**A**) that takes into account the proximity effect, spatial orientation of the electrodes and the volume conductor effects. The **A**-matrix relates the modeled cardiac activity (**S**) by means of the equivalent double layer (EDL) [9,10] to the ECG at the electrodes:

$$ECG = A \cdot S \tag{1}$$

Using the Cardiac Isochrone Positioning System to localize the PVC origin has been described in detail in van Dam et al. [5,11]. Briefly, the fastest route algorithm [12] determines the origin of the PVC by correlating the ECGs simulated from the activation sequences originating from every node of the triangulated ventricular model. The ECG with the highest correlation between measured and simulated ECG is selected as the rough estimate of the cardiac isochrones. The resulting ECG waveforms roughly match the measured ECG because of the errors made in modeling the cardiac activation. Consequently the rough estimate is fine-tuned by changing the locations of the isochrones such that simulated and measured ECG match. The origin of the PVC can be derived from the resulting cardiac isochrones on the cardiac anatomy.

The standard 12-lead ECGs were recorded during the ablation procedure from which a representative PVC of the clinical ECG waveforms was selected. Fiducial points, i.e. onset and end QRS, were manually determined. Subsequently, the PVC was baseline corrected between two successive QRS onsets.

Sensitivity analysis

In the CIPS model, a reference standard was defined as the traditionally placed standard 12-lead ECG electrode positions. These positions were used to compute a reference PVC location. Subsequently, the V1-6 precordial electrodes were virtually moved over the torso surface while using the same baseline ECG and MRI input. Two experiments of V1-6 precordial electrodes movement were tested:

1) All V1-6 precordial electrodes were virtually moved over the MRI derived torso model simultaneously and equally in either the cranial or the caudal directions in increments of 10 mm (Fig. 1a)
2) Each V1-6 precordial electrode was virtually moved individually in 8 number of concentric circles, each increased by 5 mm in radius. For each circle, 8 different positions were used along its circumference at 45 degree increments (Fig. 1b).

For each electrode configuration CIPS computed a new PVC location. The distance between the *standard V1-6* electrode PVC origin and each of the moved electrode(s) PVC origin was computed. With reference to the *standard*

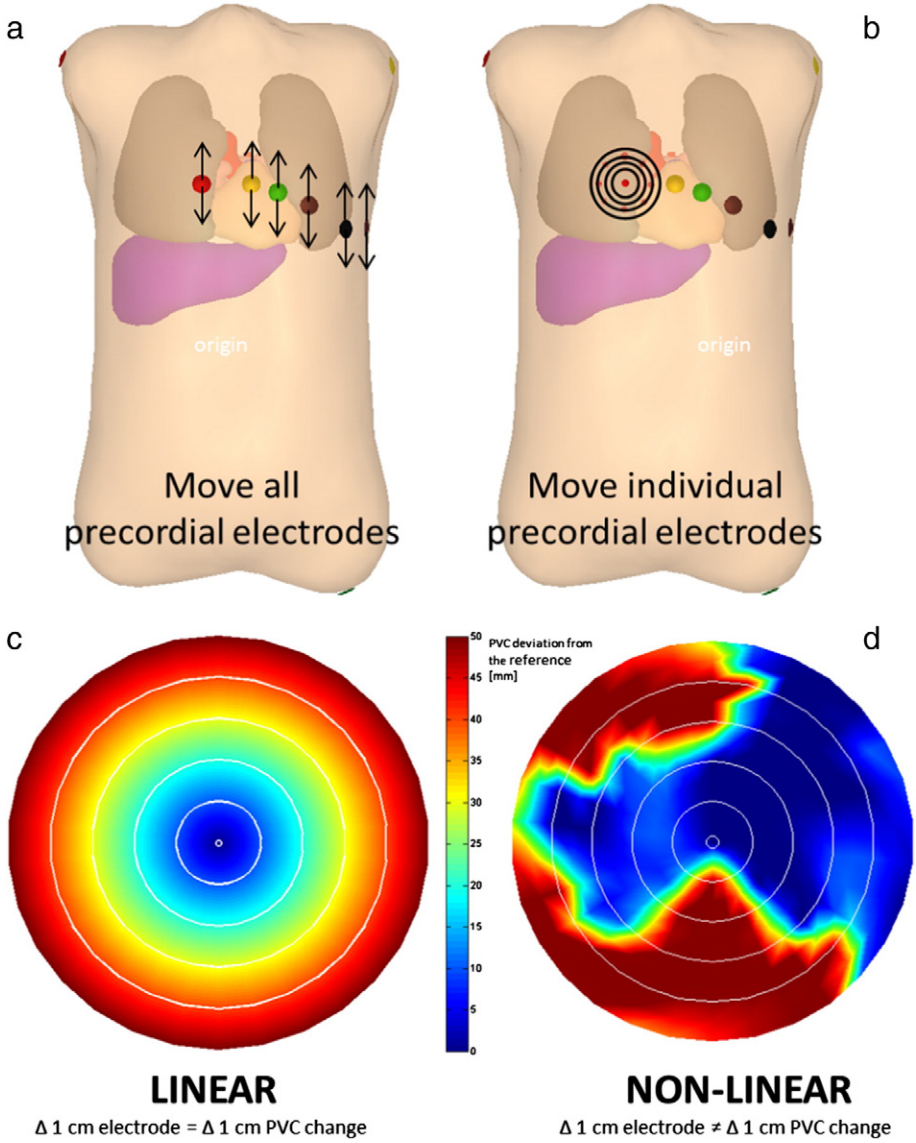

Fig. 1. a) Movement of the electrodes for experiment 1. The V1-6 precordial electrodes are virtually moved in cranial and caudal direction as indicated by the arrows. b) Movement of the individual V1-6 precordial electrodes for experiment 2. The virtual movement of the individual electrode V1 at 5 mm circumferential increments and at 45° angle increments is shown. c) A linear relationship between electrode movement over the torso model results in as in a similar PVC shift as shown in this concentric color map. d) For a non-linear relationship the deviation in PVC location from the reference shows such a non-linear, unpredictable pattern (see also Fig. 2b V3).

V1-6 electrode PVC location, the change in PVC location was used as a measure for the sensitivity of CIPS to errors in the modeled electrode positions.

Table 1
Patient characteristics, gender, age and PVC ablation site.

Patient	Gender	Age	Location ablation site
1	F	39	LV Superior Septum
2	M	31	RVOT Septal
3	M	36	Mid left endocardial lateral wall
4	F	46	RVOT endocardial anterior
5	M	15	RVOT mid septal
6	M	51	RVOT antero-superior septal
7	F	50	RVOT antero-superior free wall (endocardial)
8	M	42	RVOT epicardial
9	M	28	Mid left endocardial superior lateral wall

Table 2
The changes in the PVC origin as determined by CIPS for different vertical shifts of all V1-6 precordial electrodes for all 9 patients, min, max and mean ± standard deviation. The shift: + = cranial, − = caudal.

V1-6 precordial electrodes movement [mm]	Changes in PVC origin [mm]		
	min	max	Mean ± standard deviation
−40	10	51	28 ± 15
−30	0	49	23 ± 17
−20	6	49	23 ± 20
−10	0	36	17 ± 28
0	0	0	0
10	0	49	9 ± 18
20	5	49	17 ± 16
30	0	62	20 ± 19
40	5	35	17 ± 8

Results

Nine patients underwent electrophysiological mapping and ablation of symptomatic PVCs (Table 1, van Dam et al. [6]). In the first simulation experiment, virtually moving all V1-6 precordial electrodes up and down simultaneously in small intervals resulted in large shifts of the PVC locations (Table 2). A simultaneous movement of 10 mm V1-6 precordial electrodes resulted in a marked 0 to 49 mm shift of the CIPS-computed PVC (Table 2). The relationship between the electrode movement and shifts in the computed PVC was unpredictable for the individual patient.

In the second simulation experiment, each individual electrode was moved circumferentially around each reference standard V1-6 precordial electrode (Fig. 1b). The results for each V1-6 precordial electrode shift is shown for 3 patients (Fig. 2), in which blue means no change in PVC, and dark red represents a shift of 40 mm or more. The results of this experiment show that the effect of the single electrode movement is both unpredictable and non-linear. A linear relationship would have been found when the amount of the virtual electrode movement resulted in a similar shift of the CIPS-computed PVC origin (Fig. 1c). An example of the actual non-linear relationship between virtual electrode movement and CIPS-computed PVC location is shown in

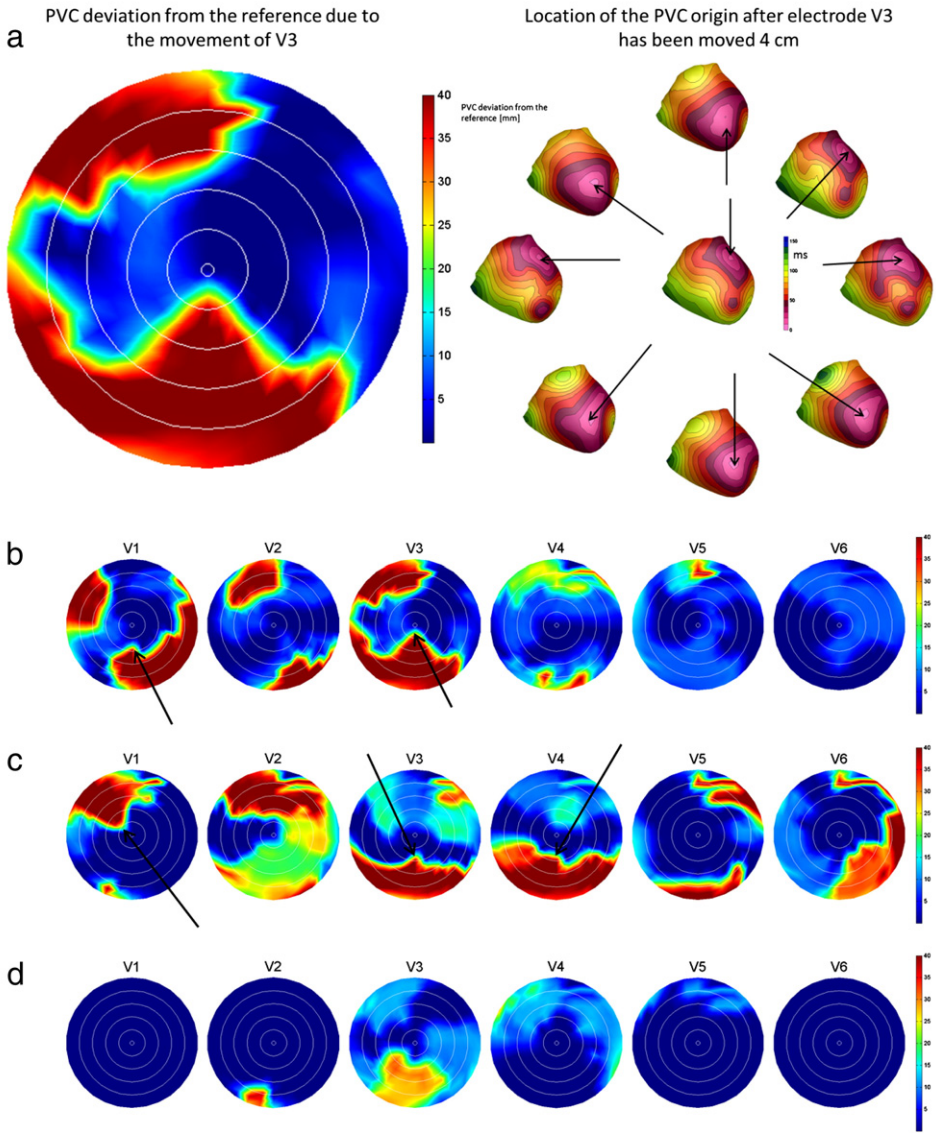

Fig. 2. The movement of a single ECG electrode can result in a non-linear and unpredictable shift of the PVC origin as determined by the cardiac Isochrone positioning system. Panel a & b) The results for patient 8. The black arrows in panel b, c, and, d point at electrode movements of less than 20 mm that result in shifts of more than 40 mm shift in the PVC origin. In panel a) the center represents the standard lead position of lead V3 (blue). Moving away from that center causes the PVC to shift unpredictable (red) as the shift is not the same in all directions. The shift in PVC localization can also be viewed for this patient in panel, indicated by the arrows b). The reference activation isochrone computed by CIPS are shown in the center. The other 8 ventricular isochrones around it show the situation for a displacement of 40 mm if V3 at each 45°. Note that V3 is also one of the leads closest to the PVC origin. c) The results for patient 5, again here the PVC locations vary most for the electrodes closest to the PVC origin. d) The results for patient 9, here the PVC origin was located on the left lateral wall, i.e. relative far away for all electrodes of the 12 lead ECG. A limited sensitivity for an electrode shift was found for V3. For the other electrodes the electrodes placement does not seem to influence result very much.

Fig. 1d. For some electrode movements no change in PVC is shown (Fig. 2d), whereas for others a movement of 20 mm in V1-V3 results in a PVC shift as much as 40 mm, indicated by black arrows in Fig. 2). For the latter two cases, the ablation site was relatively close to the precordial leads V1-3.

In summary, in both the first and second experiments the electrode movements produced a non-linear and unpredictable effect on CIPS localization of the PVC origin.

Discussion

The Cardiac Isochrone positioning system (CIPS) is able to locate PVC origins from the standard 12 lead ECG [6]. This modeling study shows that CIPS is sensitive to errors in the measured electrodes placements; small errors in electrode positions resulted in unpredictable and non-linear shifts of the CIPS-computed PVC location (Table 2 and Fig. 2). To reduce the CIPS-computed PVC localization error we have added a 3rd important module to the CIPS software: a 3D camera with the ability to incorporate the spatial location of the ECG electrodes with the patient specific MR/CT derived torso model.

We conducted two separate experiments: the first by moving all virtual electrodes simultaneously either cranially or caudally (Fig. 1a) and the second by individually moving each virtually electrode multiple times around multiple concentric circles (Fig. 1b). The first experiment demonstrated unpredictable shifts in CIPS ability to accurate localize a PVC origin. In that 50% of cases resulted in a shift of less than 20 mm, the remaining 50% resulted in larger and unpredictable shifts in the CIPS results (Table 2). The second experiment also resulted in unpredictable and non-linear shifts in CIPS results. These experiments demonstrated that CIPS is most sensitive to virtual electrode position changes in which the electrode is in close proximity to the PVC origin. This is best observed in Fig. 2b-d, where the localization error in the new CIPS-computed PVC origin is larger when the electrodes are closest to the initial CIPS-computed PVC origin.

Both experiments emphasize the importance that electrode position has on CIPS results, and thus they highlight the need for CIPS to incorporate electrode position into its calculations to obtain accurate results. Simply estimating the standard 12 lead electrode position on patients is prone to errors, considering that external anatomical landmarks such as the ribs and sternum are not modeled within CIPS. Also, even small lead misplacement [13–16], which occurs frequently, could greatly alter CIPS accuracy (Fig. 2).

A potential vehicle to link the actual anatomical ECG electrode positions on patients with their virtually represented positions used in CIPS could be a 3D camera. The 3D-camera and developed PKINECT software can accurately measure the spatial position of the electrodes on the chest wall. The information obtained from this 3D camera could then be incorporated into the CIPS to accurately place the virtual electrodes used by the program.

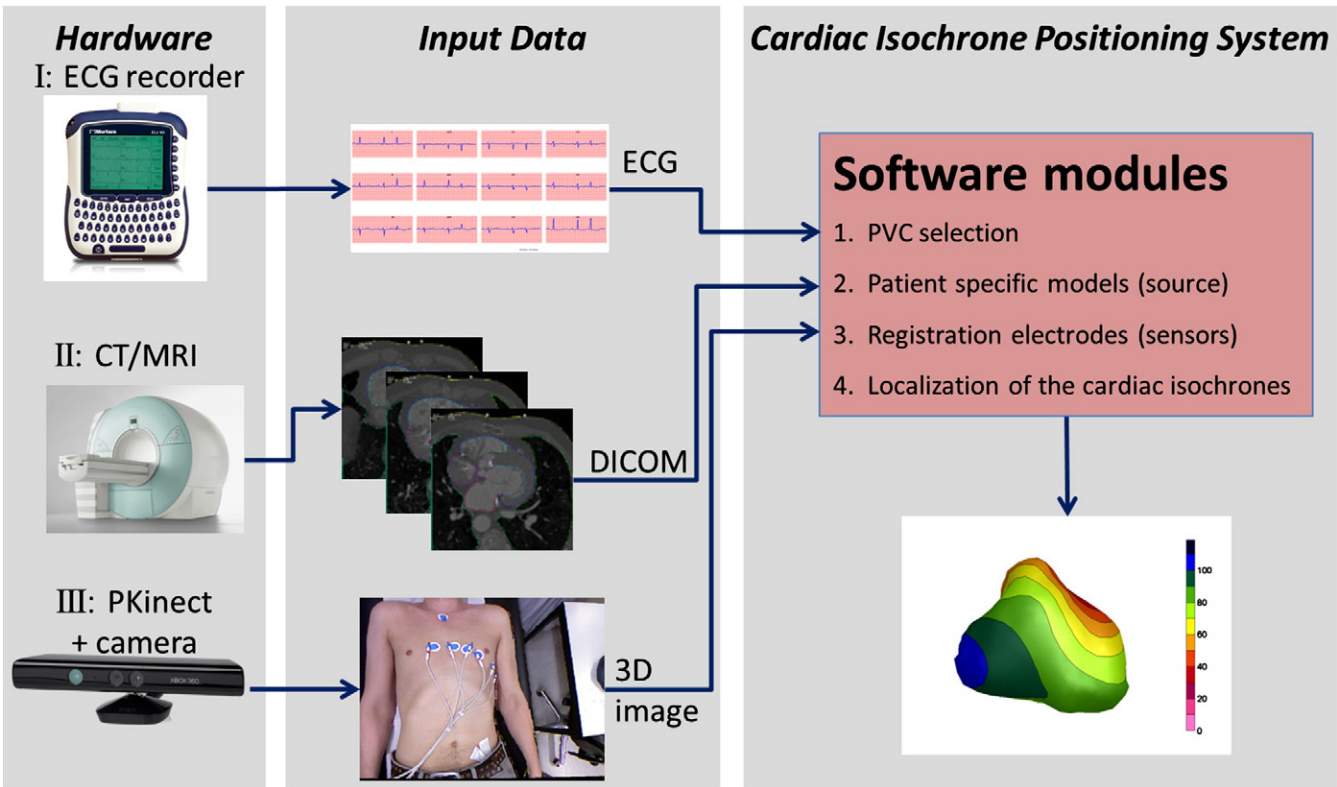

Fig. 3. The overview of the Cardiac Isochrone Positioning System (CIPS) modules and input data. CIPS requires 3 different types of input data: I) the ECG, II) the MR/CT data and III) the 3D camera image. The 3D imaged obtained by the Kinect® camera and custom made *PKinect* software is the required to enable the localization of the electrode positions on the chest wall. The CIPS software module integrates this data to compute the PVC origin.

How does the 3D camera work to localize the ECG electrodes accurately?

The KINECT 3D camera is incorporated into the new CIPS software (Fig. 3, III). This camera combines a regular photo with the 3D position information obtained from an infrared light-sensor, giving every photo pixel an x, y, and z coordinate. With these precise coordinates, a 3D, quantified image can be accurately constructed. The spatial resolution of the KINECT® camera is excellent, ranging from 1-2 mm for the usual distance from target of 50-80 cm [17]. It could be easily incorporated into the processing of CIPS in order to closely represent the actual electrode placement on a patient in CIPS virtual model (Fig. 3, III).

Conclusions

This computer-simulation study shows that the CIPS localization of PVC origins is highly sensitive to virtual electrode movement within the computer model. Up until now, CIPS was placing its virtual electrodes in an assumed standard 12 lead position without knowledge of the actual electrode placement on the patient. Incorporation of a 3D camera to ascertain the actual electrode placement on patients and subsequently incorporate this information into the CIPS model has the potential to greatly increase the accuracy of CIPS-computed PVC localization. Addition of the 3D camera as a new module completes the CIPS triad: the 12 lead ECG, the modeling of the patient anatomy through MR/CT, and the localization of the ECG electrodes with the 3D camera (Fig. 3).

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