Localization of Needle Tip with Color Doppler During Pericardiocentesis: In Vitro Validation and Initial Clinical Application

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This study evaluates a new device that uses color Doppler ultrasonography to enable real-time image guidance of the aspirating needle, which has not been possible until now. The ColorMark device (EchoCath Inc, Princeton, NJ) induces high-frequency, low-amplitude vibrations in the needle to enable localization with color Doppler. We studied this technique in 25 consecutive patients undergoing pericardiocentesis, and in vitro, in a urethane phantom with which the accuracy of color Doppler localization of the needle tip was compared with that obtained by direct measurement. Tip localization was excellent in vitro; errors axial to the ultrasound beam (velocity Doppler –0.13 ± 0.90 mm, power Doppler –0.05 ± 1.7 mm) were less than lateral errors (velocity –0.36 ± 1.8 mm, power –0.02 ± 2.8 mm). In 18 of 25 patients, the needle was identified and guided into the pericardial space with the ColorMark technique, and it allowed successful, uncomplicated drainage of fluid. Initial failures were the result of incorrect settings on the echocardiographic machine and inappropriate combinations of the needle puncture site and imaging window. This study demonstrates a novel color Doppler technique that is highly accurate at localizing a needle tip. The technique is feasible for guiding pericardiocentesis. Further clinical validation of this technique is required. (J Am Soc Echocardiogr 2001;14: 29-37.)

Pericardiocentesis is a challenging procedure that is often required for the rapid removal of even small amounts of fluid in acute cardiac tamponade and for diagnostic purposes when the underlying cause is unknown. In such instances, there may be only a relatively small margin of percutaneously accessible fluid that separates parietal pericardium from visceral pericardium. The safety of pericardiocentesis has improved markedly since it was first described by Schuh[1] in 1840. Reports from large centers where small numbers of experienced operators perform the procedure under echocardiographic guidance have demonstrated an excellent safety record.[1-5] However, in smaller institutions where the procedure is performed less frequently and experienced operators are less available, the success and safety rate of pericardiocentesis may be lower.[6]

Although both fluoroscopy and ultrasonographic guidance are helpful in determining the site and track with which to approach a pericardial effusion, current technology prevents adequate imaging of the needle tip and cardiac structures for the actual puncture and drainage to be guided in real time. A new device has recently been developed that induces vibratory motion in a needle, enabling real-time visualization with the use of color Doppler (ColorMark; EchoCath, Inc, Princeton, NJ). We hypothesized that this technology would allow improved visualization of the aspirating needle during pericardiocentesis. First, we evaluated in vitro its ability to localize a needle tip and the factors affecting accuracy. We subsequently applied this technology in the clinical setting of pericardiocentesis to determine its potential utility and the technical factors for its optimal application.

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Supported in part by Grant NCC9-60, National Aeronautics and Space Administration, Houston, Tex, and from the Mareb Foundation, Jupiter Beach, Fla. G.A. was partially supported by the National Heart Foundation of New Zealand.

0894-7317/2001 $35.00 + 0 27/1/106680

doi:10.1067/mje.2001.106680

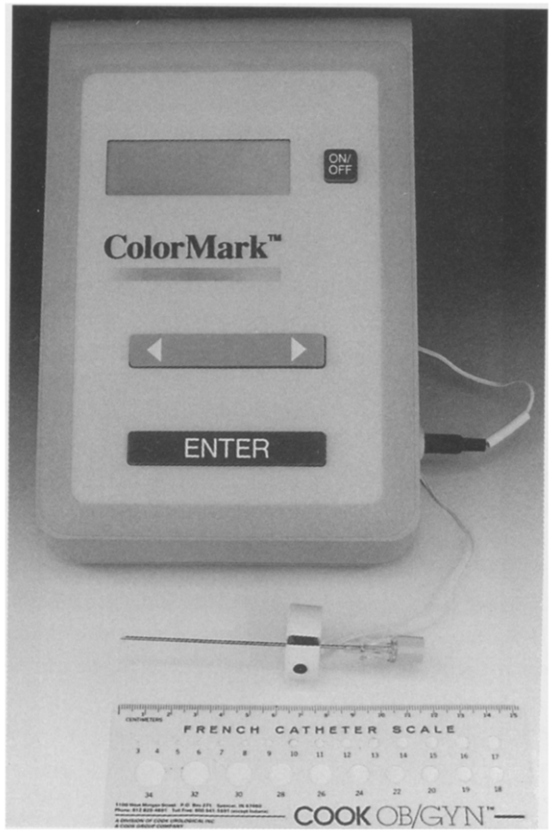

Figure 1 Photograph of ColorMark driver box, piezoelectric clip and 18-g pericardiocentesis needle. The piezoelectric clip attaches near the hub of the needle and converts the electric output from the driver box into mechanical vibrations of the needle. This vibratory motion is of a frequency and amplitude detectable by standard color Doppler ultrasonography.

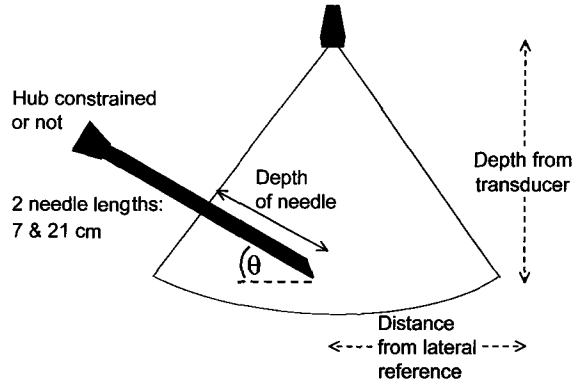

Figure 2 Line drawing of in vitro setup denoting variables that were altered to determine their effect on the accuracy of localization of a needle tip in a urethane phantom. They include the length of the needle, whether the hub was constrained, the depth of the needle in the phantom, and the angle of the needle relative to the ultrasound beam. Accuracy of localization of the ColorMark technique was compared with direct measurement in 2 planes: axial to the ultrasound beam (depth from transducer) and lateral to the beam (distance from lateral reference).

METHODS

Needle-Localization Technology

The ColorMark device induces high-frequency, low-amplitude vibrations in the needle that enable localization with standard color Doppler ultrasonography. A resonant frequency (1000 to 3000 Hz) of the needle is detected by a hand-held battery-operated driver box, the electrical output of which at that frequency is converted into mechanical vibrations by a sterile, disposable piezoelectric element clipped onto the needle shaft approximately 5 mm from the hub (Figure 1). The tip moves more than the base of the needle shaft and therefore can be readily distinguished by Doppler imaging. The system can excite any 14- to 25-gauge needle that is 8 to 25 cm in length, with one clip size for needles of 14 to 20 gauge and a smaller clip for those 20 to 25 gauge. The maximum excursion of the needle tip is only 15 μm, so the vibration is imperceptible to touch, though a soft, high-pitched sound is heard. The peak velocity of the needle tip is obtained by differentiating its equation of motion: $x = A \sin 2\pi ft$, where A is peak tip excursion, f is frequency of vibration, and t is time; velocity (dx/dt) then is given by $2\pi Af \cos 2\pi ft$, ranging from (1000 to 3000) × 2π × 15 μm = 9.4 to 28.3 cm/s for the typical range of vibrational frequencies, well within the display capabilities of commercial echocardiographic instruments. The acceleration of the needle tip, given by the second differential $d^2x/dt^2 = -4\pi^2 Af^2 \sin 2\pi ft$, ranges from 592 to 5326 m/s^2. This results in a variance signal far stronger than that caused by physiologic accelerations (20 m/s^2 in the ascending aorta) or fully developed turbulent flow (15% variation in velocities).

Echocardiography

An ATL HDI 3000 (ATL, Bothell, Wash) ultrasonographic machine with 3 transducers (2- to 3-MHz and 3- to 5-MHz phased-array and 7- to 10-MHz compact linear-array) was used. The Doppler settings were adjusted so that the wall filter was maximal, persistence was zero, and color priority was maximal. Because of the discrete nature of observations in pulsed wave Doppler, careful consideration must be given to the pulse repetition frequency (PRF) used (relative to the vibrational frequency) to maximize the sensitivity for detecting tip motion (see Appendix 1 for theoretical discussion). This optimal PRF is calculated automatically by the driver box from the manually input Doppler frequency of the transducer and is altered on the instrument by changing the Nyquist velocity. Two suitable ranges of Nyquist velocities (corresponding to PRF/Vibratory frequency = 0.65 and 2.0; see Appendix 1) are displayed on the driver box screen. Conventional color velocity Doppler

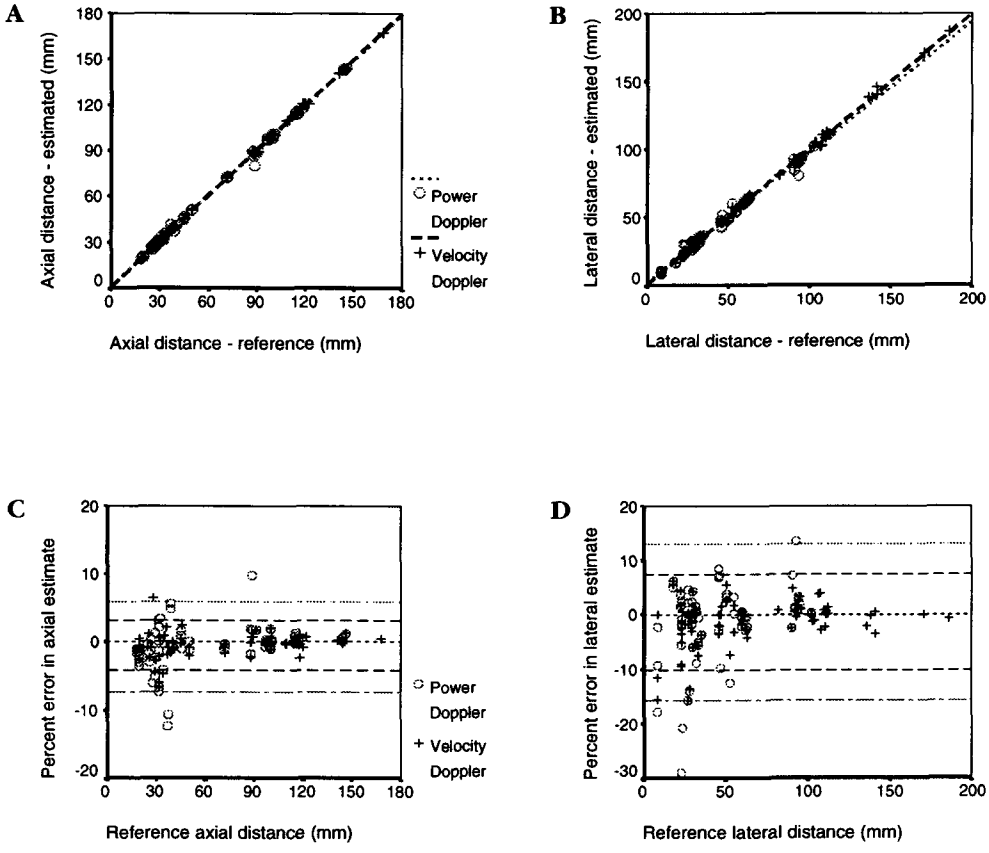

Figure 3 Results of in vitro experiment. ColorMark velocity Doppler localization of a needle tip in a urethane phantom compared with direct measurement. Localization axial (**A**) and lateral (**B**) to the ultrasound beam displayed as correlations and errors displayed by Bland-Altman plot (**C, D**).

was compared with Color Power Angio (CPA; ATL, Bothell, Wash), which displays the power of the returning Doppler signal and is less angle-dependent than the velocity display.

In Vitro Model

A urethane ultrasound phantom (ATS Laboratories, Inc, Bridgeport, Conn) of known dimensions was used. Pericardiocentesis needles (18 g) of two lengths (7 cm, 21 cm) with the ColorMark clip attached were inserted at different depths in the urethane phantom (Figure 2). The reference standard for localization of the needle tip was the position of an air meniscus, which was visualized when the needle was gently injected with air from a syringe,[7] with confirmation also provided geometrically from the known needle length and angle of entry. Localization was determined axial to the ultrasound beam (needle tip to transducer distance) and lateral to the beam (needle tip to a reference marker). The difference in localization (ColorMark - reference) was defined so that overestimation of needle length gave a negative lateral error value, and overestimation of needle distance from the transducer gave a negative axial error value (Figure 2). Needle length, depth in phantom, distance from transducer, angle to ultrasound beam, and presence or absence of hub constraint were all systematically altered to determine their effect on the accuracy of the localization of the needle tip.

Clinical Experience Guiding Pericardiocentesis

We studied 25 consecutive patients who underwent clinically indicated pericardiocentesis. The initial part of the procedure was done in the standard way for our institution by using echocardiography to determine the most appropriate needle puncture site and trajectory. Before passing the needle, the sterile ColorMark clip was clipped onto the needle hub as described above. The lead from the clip was plugged into the nonsterile driver box, which was then activated. The passage of the needle was monitored and guided in real time with use of the ColorMark visualization technology. Once the needle was in the pericardial space, a guidewire was passed, followed by a dilator and a straight 6.7 Fr 60-cm catheter. The effusion was drained through the catheter, which was usually left in overnight. All procedures resulted in successful drainage of pericardial fluid without complication. To evaluate the real-time guidance technology, we defined success when the ColorMark tech-

Table 1 Tip localization in vitro: comparison of Doppler techniques with reference method

Measurement orientation to ultrasound beam	Color Doppler imaging mode	N	Difference in localization (mean ± SD mm [%])	r	P	SEE	Coefficient	Intercept
Axial	Velocity	79	−0.13 ± 0.9 mm (−0.5% ± 1.8%)	0.999	<.0001	0.867	1.005	−0.479
	Power	62	−0.05 ± 1.7 mm (−0.7% ± 3.3%)	0.999	<.0001	1.634	1.011	−0.780
Lateral	Velocity	79	−0.36 ± 1.8 mm (−1.2% ± 4.1%)	0.999	<.0001	1.790	1.003	−0.555
	Power	62	−0.02 ± 2.8 mm (−1.4% ± 7.2%)	0.990	<.0001	2.750	1.030	−1.422

Error in localization (ColorMark − reference) is defined as in Figure 2. Overestimation of needle distance from transducer gives a negative axial error value, and overestimation of needle length gives a negative lateral error value. *SEE*, Standard error of the estimate.

Table 2 Tip localization in vitro: correlation of variables with accuracy of Doppler techniques

	Velocity Doppler		Power Doppler	
	r	P	r	P
Depth of needle shaft in phantom	0.00	NS	0.01	NS
Distance of tip from transducer	0.27	.001	0.1	NS
Needle angle to transducer	0.10	NS	0.14	NS
Needle length	0.16	.04	0.01	NS
Hub constraint	0.10	NS	0.14	NS

Correlations of variables with error (Doppler localization − reference method). *NS*, Not significant.

nique visualized the needle tip in the chest-wall tissues and guided the needle into the pericardial effusion, without complication, in real time throughout the procedure. To determine the utility of this technique for less-experienced operators, the 25 pericardiocenteses were carried out by 18 cardiology fellows-in-training, under supervision of experienced staff cardiologists.

Statistics

For the in vitro model, Pearson correlation coefficients and analysis of agreement were used to examine the relationship between signed errors in localization and individual variables. The repeated-measures analysis of variance, Student *t* test, and chi-square test were used to examine the differences in errors between variables. Logistic regression was used in the clinical study to determine the contribution of different variables to the success of the ColorMark-guided approach to pericardiocentesis. Statistical significance was defined as a 2-tailed *P* value < .05, and all analyses were performed with SPSS Release 7.5 (SPSS Inc, Chicago, Ill) software.

RESULTS

In Vitro Model

Tip localization was excellent by both the Doppler velocity and power methods compared with the reference method (Figure 3, Table 1). Accuracy was better overall for the velocity method compared with the power method ($P = .02$). Accuracy was significantly greater in the axial than in the lateral orientation for color velocity mapping ($P < .0001$), but it was not significantly different for color power mapping ($P = .097$). Table 2 illustrates the correlation between accuracy of localization and factors such as needle length, needle distance from transducer (range 2 to 17 cm), needle angle to beam (range 35° to 145°), depth of needle shaft in phantom (range 8% to 75%), and needle hub constrained versus unconstrained. Axial to the ultrasound beam, absolute errors increased weakly though significantly with distance from the transducer for both velocity Doppler (Pearson correlation: $r = 0.24$; $P = .05$) and power Doppler (Pearson correlation: $r = 0.31$; $P = .01$) techniques. Absolute errors with the velocity Doppler were fewer with the use of the longer needle than with the shorter needle ($P = .04$). Errors did not correlate with the needle insertion depth, needle angle to transducer, or degree of hub constraint.

Reliability and reproducibility. There appeared to be a learning curve, with fewer errors in the last 10 observations (axial −0.3% ± 0.9%; lateral 0.05% ± 2.3%) than in the first 10 (axial −1.8% ± 1.9%, $P = .03$; lateral −3.3% ± 6.2%, $P = .12$). In 10 repeated observations, the difference in errors of color velocity localization between 2 observers was 0.16 ± 0.97 mm (0.4% ± 1.5%, $P = .5$) in the axial plane and −0.98 ± 2.74 mm (−2.3% ± 8.5%, $P = .4$) in the lateral plane.

Clinical Experience

Patient characteristics. Patients were aged 58 ± 14 years. A total of 25 effusions were drained. The causes included postcardiac surgery (17), malignancy (4), postangioplasty or radiofrequency ablation (2), sepsis (1), and the hepatorenal syndrome (1). The percutaneously accessible rim of fluid ranged from 1.0 to 5.3 cm in thickness. In all cases, the primary indication for drainage was hemodynamic compromise as a result of the pericardial effusion.

Procedure. The pericardial effusion was accessed from an apical entry site in 22 procedures and from the subcostal site in 3. Transthoracic imaging was used in all but one patient, in whom transesophageal imaging was employed (with an apical needle puncture site). In 18 of 25 patients, the needle was identified and guided into the pericardial space throughout the procedure with the ColorMark technique. In all these 18 cases, there was successful drainage of fluid and no passage of needle, wire, or catheter into pleural space or cardiac chambers. The advantage of real-time visualization of the needle was apparent in patient 8: the blood-stained fluid initially aspirated from this patient was identified as pleural because the needle tip was seen 2 cm short of the pericardial space. Thus no attempt was made to pass the guidewire, the needle was advanced until it entered the pericardial space, and the pericardial effusion was successfully aspirated. In other patients, real-time visualization resulted in changes of needle puncture site and trajectory (patients 9, 20, and 25).

In the 7 unsuccessful cases, the needle was not identified before entering the pericardial space. One of the unsuccessful cases (patient 3) was a postoperative pericardial effusion, and the needle was not identified at all. The next day, it was confirmed that the catheter was draining the left pleural cavity, and the patient underwent surgical pericardiotomy. The 6 other patients were successfully drained despite lack of visualization of the needle. No other patient required a repeat drainage procedure, and no patient developed infection related to the pericardiocentesis procedure. The reasons for the high initial failure rate were related to (1) incorrect settings on the echocardiographic machine and (2) inappropriate combinations of the needle puncture site and imaging window. One late failure (patient 22) was the result of a huge pericardial effusion that was so close (less than 2 cm) to the skin that it was not possible to visualize the needle before it entered the pericardial effusion. The failure with patient 24 occurred during the training of a new sonographer. The increased ColorMark success rate with experience is illustrated in Figure 4.

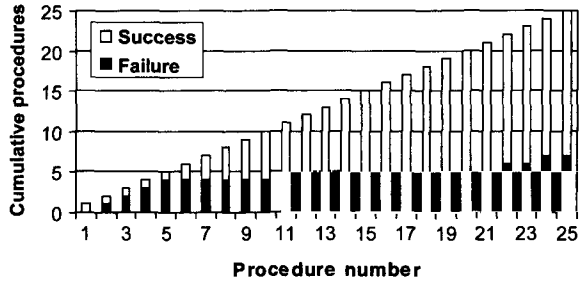

Figure 4 Bar graph of cumulative success of the ColorMark technique for guiding pericardiocentesis. Success: Needle visualized with ColorMark technique before entering pericardial space, and guided into the pericardial effusion without complication. Failure: Needle only visualized after entering pericardial effusion, or not seen at all. Note most ColorMark failures occurred initially, when machine settings and imaging windows were still being optimized.

Predictors of Successful Needle Localization

Logistic regression was performed to determine the probability of ColorMark success associated with procedure number (1 through 25), approach to effusion, experience of operator (first use of ColorMark versus previous use), experience of sonographer (first imaging of ColorMark versus previous experience), effusion origin (postsurgical versus other causes), and width of effusion at puncture site. Only procedure number (P = .014) and approach to effusion (P = .016) were univariate predictors of success. Approach to effusion predicted ColorMark success with a sensitivity of 83% and specificity of 71%. The variables were entered in a forward stepwise fashion into a multiple logistic regression model with the default entry criterion of 0.1 and removal criterion of 0.5. Only these 2 variables were retained in the model, confirming the initial learning curve and the importance of correct combination of puncture site and imaging window. The experience of the operator and sonographer, and the size of the effusion did not influence the likelihood of success.

Echocardiographic Factors Affecting Needle Visualization In Vivo

Initially we used the manufacturer's recommended color Doppler settings, as used for the in vitro validation, but with continued clinical experience, we changed some settings (Appendix 2). We now set the temporal persistence to *medium* (instead of *off*), which gives a more "filled-in" image, and the slow and deliberate passage of the needle does not cause image blurring with this degree of temporal averaging of the color Doppler signal. Confusion can occur with the color Doppler signals from flowing blood within the heart, and from "flash" artifacts caused by cardiac motion. The ColorMark-induced needle-tip motion moves toward and away from the transducer many times each second, resulting in a Doppler signal with a variance 30 to 300 times greater than that of physiologic signals. Use of a color map with variance results in the highly variant ColorMark signal being specifically color-coded (eg, green with ATL HDI Map 6VV), whereas blood is coded mostly red or blue, depending on its direction relative to the transducer. In addition,

we chose the higher Nyquist range displayed on the driver box screen. Typically, this is 69 to 80 cm/s, which is higher than most of the clutter signals from the blood pool. By using these two simple adjustments, the intense, highly variant, high-velocity ColorMark signal is rarely confused with other signals. Excessive color gain is often used with first attempts to locate a needle tip. This is unnecessary because the ColorMark signal is very intense. Too much color gain reduces lateral resolution and increases lower intensity clutter signals. Power imaging was not useful in vivo because of clutter from myocardial coloration. Without a variance feature, these unwanted signals obscure the image of the needle.

Effect of Needle Puncture Site and Imaging Window

Accuracy of localization was not dependent on the incident angle in vitro, but this was not the case in vivo. This was probably the result of the low attenuation properties of the ultrasound phantom material, which allows enough of the weaker scattered echoes to return to the transducer to create an image. However, in the clinical setting we found that if the angle of needle entry was too close to that of the ultrasound beam, an image was difficult to obtain. Therefore it is unnecessary, and indeed undesirable, to select an imaging window close enough to the needle puncture site to require sterile sheathing of the ultrasound probe. Avoiding such proximity also makes the procedure faster and simpler. In addition, the 2-dimensional planar nature of the ultrasound beam needs to be recognized. We found it very difficult to scan far enough anteriorly from the subcostal window to visualize a needle entering from an apical puncture site. In summary, apical punctures are best imaged from a low parasternal window, and subcostal punctures are best guided from either a low parasternal or apical window.

DISCUSSION

In this study, we have demonstrated the accuracy of a new color Doppler technique in visualizing a needle tip in vivo. Furthermore, our initial clinical experience with pericardiocentesis suggests that this novel technique has real utility, especially when the pericardial effusion is small or difficult to access. We found that there was a significant learning curve in the use of this new technique and that the Doppler algorithms and other variables that affect recognition of the needle tip in vivo differ from those of the in vitro experience. However, after the initial learning experience, there were only 2 late failures of the ColorMark needle guidance technique: one occurring during training of a new sonographer and the other caused by proximity of a massive effusion to the chest wall. Clearly in this latter case, real-time guidance is not necessary.

Pericardiocentesis is both a diagnostic and therapeutic procedure that is potentially hazardous because of the risk of puncturing cardiac chambers and vessels, and it is often most difficult in those in whom it is needed most: patients with acute tamponade caused by a rapidly accumulating small effusion. One of the main difficulties in needle pericardiocentesis is that the actual needle puncture is blind because the tip of the needle is difficult to image in real time. Real-time visualization of both needle and cardiac structures may improve procedural safety and has been advocated and even attempted by some authors,[7-12] but it is not possible with conventional echocardiographic and fluoroscopic methods. Analogously, real-time ultrasonographic guidance has been shown to improve the success of cannulation of internal jugular veins with a lower complication rate and in a more timely fashion as compared with an approach that relies solely on anatomic landmarks.[13,14] Fluoroscopy gives a distinct image of the steel needle but does not have enough soft tissue resolution to distinguish pericardium from myocardium. Thus the pericardiocentesis needle is advanced toward the cardiac silhouette without knowledge of whether it represents pericardium or myocardium. Some operators still advocate the use of electrocardiographic monitoring, which detects a current of injury when the needle is advanced into myocardium. However, ideally, the position of the needle tip would be known before it contacts the myocardium.

Conventional 2-dimensional echocardiography is not used in real time in pericardiocentesis because it usually fails to visualize a needle tip within the beam path. The needle is large relative to the ultrasound wavelength and acts as a specular reflector. Most of the ultrasound beam bounces off the highly reflective surface at the incident angle, instead of being scattered back along the beam path to be detected by the transducer. Thus the current technique at most institutions, including our own, is to use ultrasonography to select the needle puncture site and trajectory, but then pass the needle in a blind fashion until fluid is aspirated. If required, fluoroscopy of the wire or an ultrasonic contrast injection of agitated saline via the catheter is used to confirm pericardial placement.

The technology we used to perform real-time echocardiographic guidance involves a novel device that induces vibratory motion in the needle to enhance its visualization in real time with the use of color Doppler. The ColorMark clip induces vibratory motion in the needle, which is greatest at the free

tip. Ultrasound reflected from the moving needle has a frequency shift, which is detected by Doppler instrumentation. This can be displayed as the velocity of the needle (velocity ∝ frequency shift). The high variance of the Doppler signal is more useful than the actual velocity in distinguishing the needle from surrounding tissue. In vitro, we found that the ColorMark system was highly accurate in detecting the needle tip. Axial resolution was superior to lateral resolution, as expected with any ultrasonic technique. The color velocity algorithm was more accurate than the power Doppler algorithm, which displays the amplitude of the returning frequency-shifted signal. In power mode, small increases in gain caused coloration to spread along the track distal to the needle tip. This is because the vibrations are transmitted through the urethane, and the ultrasound beam is reflected from the air-urethane interface. This was not a noticeable problem in vivo because biologic tissue has a high damping tendency; however, the usefulness of the power mode in vivo was hampered by myocardial clutter. Another variables that affected the accuracy of needle tip localization was the length of the needle, which may be because the longer needle is easier to excite. Neither hub constraint nor the incident angle of the ultrasound beam affected accuracy in vitro.

Other studies of ultrasound-guided intravascular interventions have typically involved only a small number of operators who became adept at the technique.[15,16] To determine whether this procedure was simple enough to be widely used by operators of varying experience, we had all pericardiocenteses performed by cardiology fellows-in-training (though always under direct supervision of an experienced staff cardiologist). Because of the differences in experience (for some, their first-ever pericardial tap was a ColorMark-guided procedure), it was not possible to meaningfully compare times of procedures or number of needle passes required (though most taps visualized with ColorMark required only one pass of the needle). In contrast to the in vitro findings, we found the angle of the ultrasound beam to the needle was an important cause of failure to visualize the needle. An exception to the angle dependency of imaging is found with the use of the transesophageal window. Similar to the in vitro phantom, the low attenuation of reflected echoes with the transesophageal approach allows even weak echoes to form an adequate image, even when the needle is parallel to the ultrasound beam. An additional surprising finding from our in vivo experience was the ability to image the guidewire as it was passed through the needle, as it developed its own vibratory motion (Figure 5). This was surprising because the wire would be expected to

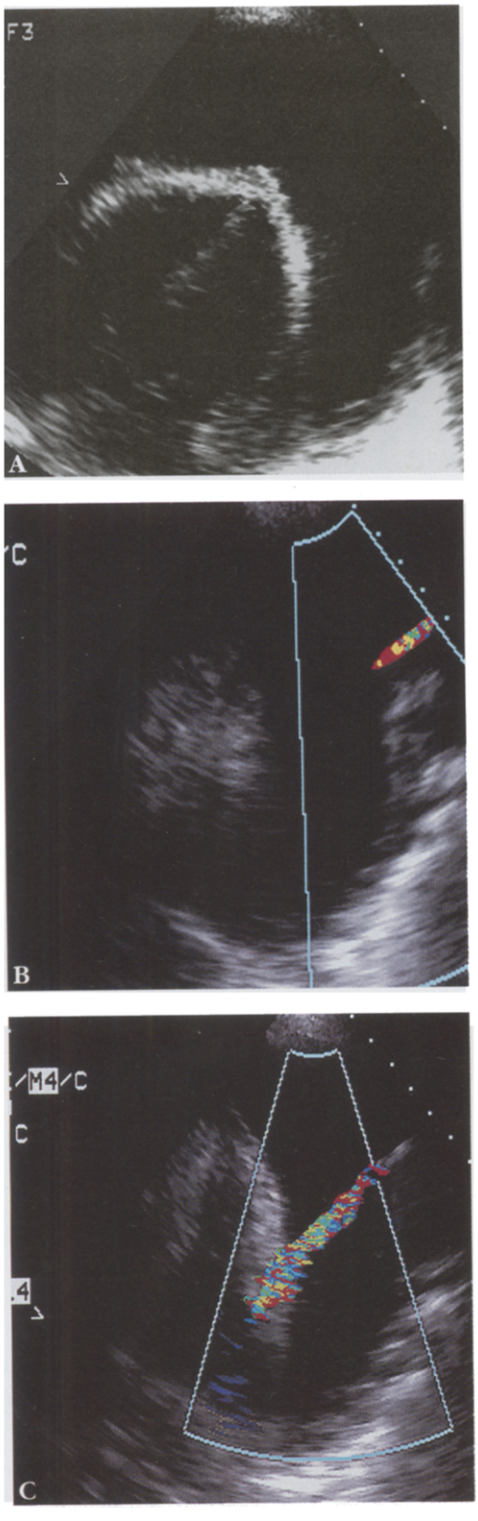

Figure 5 Three still frames from an echocardiogram performed during a ColorMark-guided pericardiocentesis. First frame (**A**) shows a medial apical 4-chamber view with a large pericardial effusion. Second frame (**B**) shows the ColorMark-illuminated needle entering the pericardial effusion from an apical puncture site. Third frame (**C**) shows the ColorMark-illuminated guidewire entering the pericardial effusion.

damp out most vibrations, not resonate with them. This finding proved useful in confirming in real time that the guidewire had passed into a pericardial rather than an intracardiac location.

Conclusions

This study demonstrates a novel color Doppler technique that is highly accurate in the localization of a needle tip. The technique is feasible for guiding pericardiocentesis and may be especially useful in aspirating small or loculated effusions and in distinguishing pleural from pericardial aspirates.

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APPENDIX 1

Analysis of Sensitivity Related to Ratio of ColorMark Vibratory Frequency to Pulsed Repetition Frequency

Color Doppler ultrasonography detects motion by comparing the position of reflectors between consecutive ultrasound pulses. For a vibrating needle such as the ColorMark system, erroneous results can occur if the time between pulses is exactly the same as one vibratory period of the needle. In this case, the needle appears in the same position with every pulse, and like watching a rotating structure with a stroboscope synchronized to the speed of rotation, the needle will be shown as static.

Visualization of the needle is determined by the difference between needle vibratory frequency and the pulse repetition frequency (PRF). The signal obtained from sampling the vibrating needle is, for small ampli-

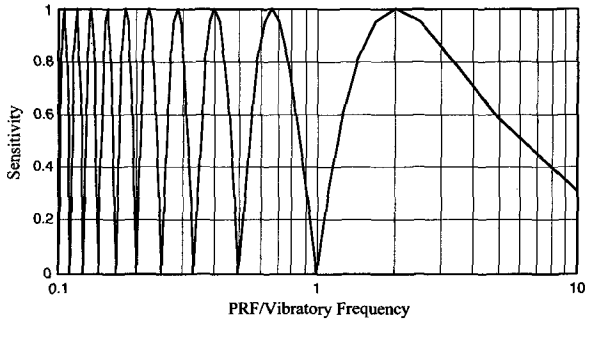

Figure 6 Plot of sensitivity of needle visualization by color Doppler ultrasonography (equal to average needle displacement), plotted against the ratio of pulse repetition frequency *(PRF)* to vibratory frequency. The optimal PRF for observing needle movement, as displayed on the ColorMark driver box, is 0.65 and 2.0 times the needle vibratory frequency. Note the peak at 2.0 is flatter, with greater than 50% sensitivity maintained between ratios of 1.2 to 6.4. This is the preferred operating range of the system and corresponds to a higher Nyquist velocity (typically 69 to 80 cm/s), which minimizes distracting artifacts and blood pool clutter.

tude vibrations of frequency f, equal to the amount of displacement between the two sampling points

$$\Delta = \text{Sin}\ (2\pi ft + \theta) - \text{Sin}\ 2\pi f\left(t + \frac{1}{\text{PRF}}\right) + \theta$$

where 1/PRF is the difference in time between pulses, and θ is defined as the arbitrary starting phase at time $t = 0$.

Time and phase are arbitrary, so the average displacement can be calculated by assuming that the phase of vibration of the needle, $2\pi ft + \theta$, is equally distributed over $0 - 2\pi$. Thus the average displacement is given by:

$$\Delta\text{ave} = \frac{\sum_{n=0}^{M} Sin\frac{n\pi}{M} - Sin\left(\frac{n\pi}{M} + \frac{2\pi f}{\text{PRF}}\right)}{M}$$

where the arbitrary time $t = 0$, and the arbitrary phase is in M increments.

These average displacements (which determine the sensitivity of needle visualization by color Doppler) are calculated and plotted against the ratio of PRF to f (Figure 6).

APPENDIX 2

Optimum settings of echocardiographic machine and ColorMark driver box

Setting	Adjustment	Reason
Color mode*	Velocity	Amplitude (CPA†) setting has too much clutter from myocardial signal.
Color map*	Variance map	High variance from ColorMark image distinguishes it from blood pool signal.
Wall filter*	Maximum	Removes low-velocity, high-amplitude clutter signals from myocardial motion.
Tissue priority*	Off	Pixels with both 2-dimensional and color signals are assigned to color.
Persistence*	Medium	This temporal averaging function makes image appear more "filled in."
Doppler frequency	Input to driver box	The color Doppler frequency is only displayed when color mode is selected. Do not input the 2-dimensional frequency by mistake. The machine uses this to ensure that the Nyquist ranges it displays correspond to an optimum ratio of PRF/vibrating frequency (Nyquist velocity ∝ PRF/transducer frequency). (See Appendix 1.)
Nyquist limit	Higher range displayed on driver box	Broader response curve (see Figure 6 in Appendix 1). Reduces blood pool clutter.
Color gain	Optimize image	Too high causes spread of color into surrounding structures and accentuates reverberation artifacts. The ColorMark signal is very intense compared with other sources of color Doppler signals; therefore high gain settings tend to increase clutter without significantly increasing the ColorMark signal.

PRF, Pulse repetition frequency.
*These settings can be configured as an echocardiographic machine preset and do not need to be adjusted for each procedure.
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