[Original Research]

CHEST

Needle Decompression of Tension Pneumothorax with Colorimetric Capnography

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BACKGROUND: The success of needle decompression for tension pneumothorax is variable, and there are no objective measures assessing effective decompression. Colorimetric capnography, which detects carbon dioxide present within the pleural space, may serve as a simple test to assess effective needle decompression.

METHODS: Three swine underwent traumatically induced tension pneumothorax (standard of care, n = 15; standard of care with needle capnography, n = 15). Needle thoracostomy was performed with an 8-cm angiocatheter. Similarly, decompression was performed with the addition of colorimetric capnography. Subjective operator assessment of decompression was recorded and compared with true decompression, using thoracoscopic visualization for both techniques. Areas under receiver operating curves were calculated and pairwise comparison was performed to assess statistical significance ($P < .05$).

RESULTS: The detection of decompression by needle colorimetric capnography was found to be 100% accurate (15 of 15 attempts), when compared with thoracoscopic assessment (true decompression). Furthermore, it accurately detected the lack of tension pneumothorax, that is, the absence of any pathologic/space-occupying lesion, in 100% of cases (10 of 10 attempts). Standard of care needle decompression was detected by operators in 9 of 15 attempts (60%) and was detected in 3 of 10 attempts when tension pneumothorax was not present (30%). True decompression, under direct visualization with thoracoscopy, occurred 15 of 15 times (100%) with capnography, and 12 of 15 times (80%) without capnography. Areas under receiver operating curves were 0.65 for standard of care and 1.0 for needle capnography ($P = .002$).

CONCLUSIONS: Needle decompression with colorimetric capnography provides a rapid, effective, and highly accurate method for eliminating operator bias for tension pneumothorax decompression. This may be useful for the treatment of this life-threatening condition.

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KEY WORDS: needle decompression; needle thoracostomy; pneumothorax; tension; trauma

ABBREVIATIONS: ATLS = Advanced Trauma Life Support; NT = needle thoracostomy

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Trauma is a significant cause of reduced life years and mortality in both military and civilian populations.[1-5] Advanced Trauma Life Support (ATLS) injury assessment and treatment give the highest priority to pathologies that interfere with gas exchange, such as securing definitive airways and relief of tension pneumothorax.[6] Tension physiology is created by space-occupying lesions, specifically a hemothorax or pneumothorax, that generate pressure in a closed space. Increasing volume of the pneumothorax increases intrathoracic pressure relative to cardiac filling pressures in the right atrium, leading to inflow failure, subsequent outflow failure, and eventual cardiopulmonary decompensation and death.

Rapid decompression of tension pneumothorax, via needle thoracostomy (NT), is a putative life-saving maneuver allowing intrathoracic and atmospheric pressure equilibration and partial restoration of cardiac filling. While the technique appears simple, the data regarding the efficacy of needle decompression are controversial. Despite the ongoing debate regarding the standard of care for treatment of tension physiology being immediate needle decompression, little innovation has occurred in this field, outside of the ongoing debate on ideal anatomic location, and length and size of decompression devices.[7-22] Even if all the major variable factors such as chest wall thickness, anatomic location, optimal rigidity of the decompression catheter, and catheter length are accounted for, it remains difficult for field providers to rapidly and objectively confirm therapeutic decompression. Current guidelines (ATLS) recommend that operators use auditory cues (ie, listen for a “gush of air”) and assess for improvements in vital signs and cardiorespiratory function.[6]

Tension pneumothoraces comprise a mixture of respired gases at pressures higher than atmospheric, and arise from air leaks within the respiratory system. Detection and visual recognition of respired gases during decompression constitute a simple method for improving needle thoracostomy. The gaseous composition of the tension pneumothorax is theoretically similar to that of end-respiratory gas, with an increased partial pressure of carbon dioxide when compared with the normal atmosphere, which makes colorimetric capnography an ideal confirmatory test.

We have developed a novel device based on colorimetric capnography to assist providers in rapid and accurate confirmation of needle thoracostomy placement. Immediate confirmation of the success or failure of placement should result in immediate treatment; therefore, this device carries the potential to decrease the rate of mortality in preventable combat mortalities.[1,2]

In this work, we generated and used a swine model of penetrating thoracic trauma to study tension pneumothorax physiology. We hypothesized that by incorporation of colorimetric capnography into the needle thoracostomy decompression device would lead to improved success rates of decompression and earlier detection of success compared with currently used standard of care metrics. We aimed to demonstrate the efficacy and ease of use of needle thoracostomy with colorimetric capnography integration in this large-animal model of tension pneumothorax.

Methods

Device

We employed a custom needle trocar-based device (Fig 1). The device has a side stream chamber for a colorimetric capnography indicator to be exposed to escaping gas. The capnography indication paper was placed in this chamber, distal to a one-way ball valve that prevents air ingress during decompression, but allows free gas egress from the needle. Colorimetric capnography paper was fabricated by generating a solution of distilled water and 0.0065 M sodium carbonate, with an additional equal volume of glycerol added; *m*-cresol purple (Sigma-Aldrich) was added at 0.005% weight per volume of the final solution and dissolved. The final mixture was absorbed on strips of Whatman No. 1 filter paper and dried in warm air provided by a Bunsen burner prior to storage in a desiccated environment. This colorimetric capnography paper is purple (Figs 1A, 1B) in ambient air (0.04% CO_2 by volume), but when exposed to expired air (5% CO_2 by volume) it changes to bright yellow within 3 to 5 s (Figs 1C, 1D).

Subjects

All study procedures were performed in accordance with the National Institutes of Health *Guide for the Care and Use of Laboratory Animals* and approved by the Mayo Clinic Institutional Animal Care and Use Committee. The subject group consisted of three normal healthy domestic swine (30 $\pm$ 5 kg) in the induced tension pneumothorax group and a single animal without induced pneumothorax as a negative control. Areas under receiver operating curves (method described by Hanley and McNeil[23]) were calculated for needle capnography and standard of care, and pairwise comparison was used to assess statistical significance ($P < .05$).

Procedure

Subjects were sequentially anesthetized and orotracheally intubated. Through a lower lateral thoracic incision (eighth intercostal space, anterior axillary line) the pulmonary parenchyma was visualized and sharply injured, using laparoscopic scissors (approximately 4 cm in length, 1 cm in depth). A video thoracoscope was inserted without carbon dioxide insufflation and the chest wall was

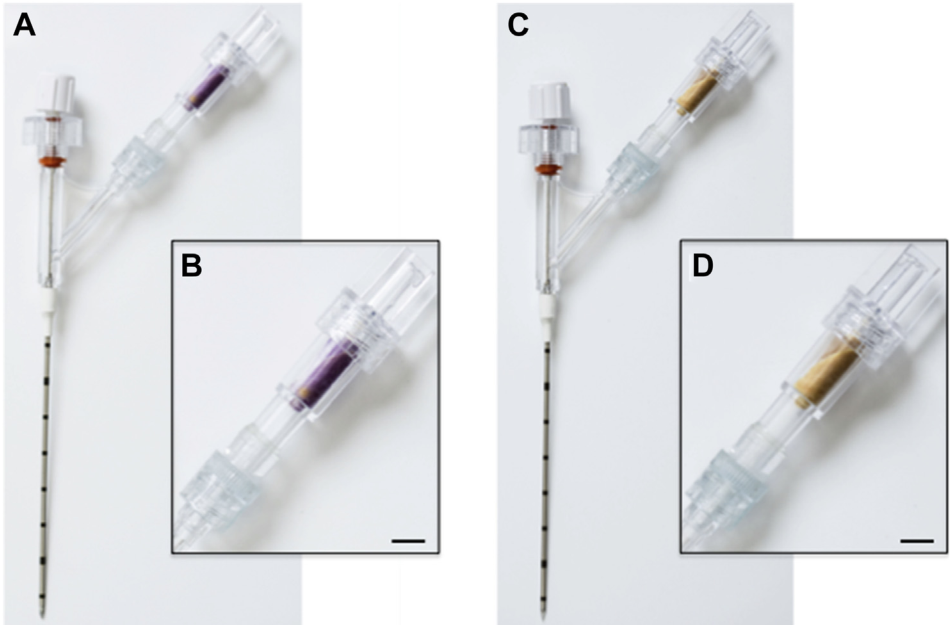

Figure 1 – *A, Overview of needle thoracostomy device with exposure to atmospheric level of carbon dioxide (0.039%); note the purple color of the capnography paper. B, Increased focus on colorimetry portion of the device at atmospheric levels of carbon dioxide. C, After exposure to approximately 5 to 10 mL of 5% carbon dioxide, the color changes to yellow after 5 to 10 s. D, Increased focus on colorimetry portion of the device at 5% exposure to carbon dioxide. Scale bars, 1 cm.*

visualized. Development of tension physiology was monitored on the basis of femoral arterial line pressure and heart rate, and allowed to develop with positive-pressure ventilation (pressure support, 16 cm H_2O; positive end-expiratory pressure, 0 cm H_2O). Once tension pneumothorax developed, based on heart rate (> 140 bpm) and blood pressure (< 90 mm Hg systolic), needle thoracostomy with standard of care (n = 5, each animal) using an 8-cm-long 14-gauge angiocatheter, was performed by either an expert operator (n = 1 animal) or novice operator (n = 2 animals). Similarly, needle decompression was performed with needle capnography. Both decompression procedures, using either technique, were performed at the fourth intercostal space, anterior axillary line (given the lack of anatomical similarities at the second intercostal space at the mid-clavicular line in pigs). Subjective operator assessment of success in placement/active decompression was recorded and compared with the actual success/failure of placement as observed by thoracoscopic visualization with both techniques. The needle operator was blinded to thoracoscopic visualization. One animal was used as a negative control, without pneumothorax, with 20 decompressions (n = 10, standard of care; n = 10, with needle capnography). External video capture was performed with a HERO4 camera (GoPro).

Results

Thirty needle decompressions were performed (n = 15, standard of care; n = 15, with needle capnography) on three independent animals with tension pneumothorax. Overall, needle capnography decompressions were detected in 15 of 15 attempts (100% success rate). Standard of care needle decompressions were detected by operators 9 of 15 times (60% success rate). Actual decompression, under direct visualization by thoracoscopy, occurred 15 of 15 times (100% success rate) with capnography (Fig 2), and 12 of 15 times (80%) without capnography.

Operator Experience Outcome Assessment

In the expert decompression series (1 animal: n = 5, with standard of care; n = 5, with needle capnography), actual decompression occurred five of five times using standard of care, as assessed by video thoracoscopy. However, decompression was detected by the operator only four of five times. In the judgment of the operator, the successful attempts were based on normalization of heart rate and blood pressure in four of five attempts (80%). An audible "gush of air" was heard in one of five decompressions (20%).

In the novice decompression series (2 swine: n = 10, with standard of care; n = 10, with needle capnography) actual decompression occurred 7 of 10 times using standard of care, as assessed by video thoracoscopy. Failures were attributed to off-axis (nonperpendicular) insertions. Decompression was subjectively judged to have occurred 5 of 10 times (50%), using standard of

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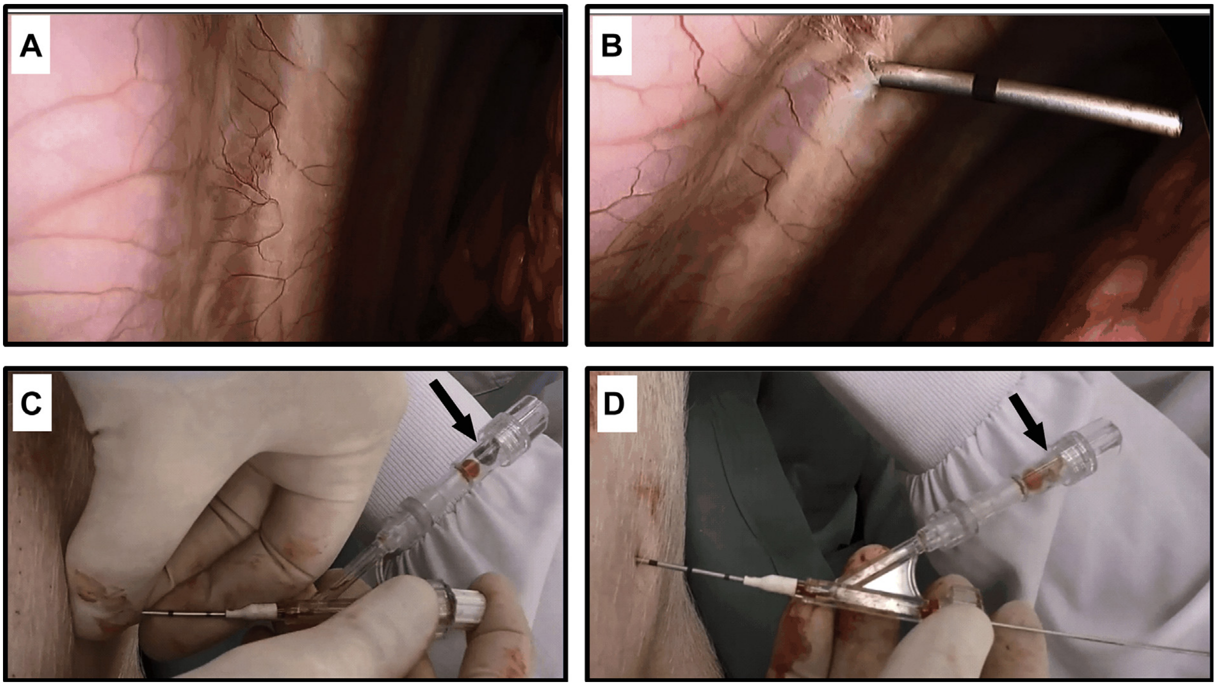

Figure 2 – *A, Video thoracoscopic view of the thoracic cavity and chest wall with presence of tension pneumothorax. B, Needle thoracostomy placement, with decompression of tension pneumothorax confirmed by visualization with a video thoracoscope. C, External view of needle thoracostomy placement, with capnography paper (arrow) exposed to atmospheric carbon dioxide before penetration through the thoracic wall, decompressing the tension pneumothorax. D, External view after decompression of tension pneumothorax. Capnography paper undergoes colorimetric change (arrow) within 5 to 10 s of decompression and entry into the thoracic cavity.*

care. The confirmation in these cases was based on an audible "gush of air" in one of five attempts (20%) and a slight "bubbling" at the cannula site in the other four of five attempts (80%).

In the negative control animal, with no pneumothorax, no decompression was detected in 10 of 10 attempts (100%) when using needle capnography and in 7 of 10 attempts (70%) when using standard of care.

Rate of Change of Detector and Statistical Analysis

For both operators, using the capnography adjunct with the same size and caliber of needle for decompression, the color change was visible within 3 to 5 s (Fig 2) and noted by the operators before reversal in heart rate and blood pressure changes (Video 1). If the needle was off axis the operator was able to quickly assess incorrect placement and reposition the device, resulting in overall success in 10 of 10 attempts.

Areas under the receiver operating curves[24] (Fig 3) were 0.65 for standard of care and 1.0 for needle capnography ($P = .002$).

Discussion

On the battlefield, tension physiology of the chest causes preventable deaths.[1,2] To our knowledge, no simple and effective adjunct is available for immediate confirmation of tension pneumothorax decompression. Gases within the thoracic cavity that lead to tension pneumothoraces are either leaked from the lung

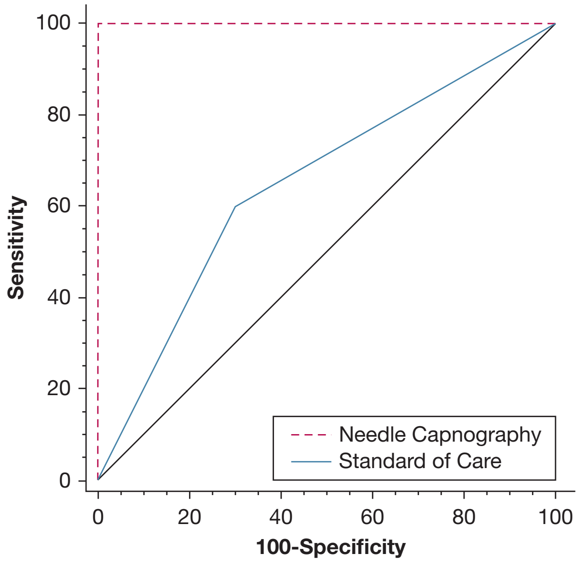

Figure 3 – *Areas under the receiver operating curves, comparing needle capnography decompression with standard of care decompression. The area under the receiver operating curve for needle capnography decompression was 1.0, and 0.65 for standard of care decompression. Pairwise comparison for difference: P = .002.*

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parenchyma itself or are in gaseous communication with the lung tissue. Using our custom needle trocar-based device with colorimetric capnography, we have demonstrated in a swine model of tension pneumothorax, after chest trauma, that the use of capnography to detect respiratory gas efflux can eliminate operator subjectivity and results in more reliable decompression outcomes.

When performed properly, tension pneumothorax decompression can be life-saving. However, the procedure is controversial and has high failure rates[13,20]; furthermore, there is no method to judge its effectiveness in the field except by subjective operator assessment. The settings in which needle decompression are performed are austere, loud, and often stressful. A visual device and method to remove operator subjectivity in treatment would, in the field, be significantly more useful than an audible "gush of air" for assessment of decompression success.[6] This audible gush of air is highly subjective, most often due to its rare occurrence, and is less likely to occur with larger gauge decompression needles. Furthermore, the difficulty in determining that this sound has occurred in a loud, stressful, militarized environment is to be appreciated.

Previous work has assessed the effect on safe needle placement of such variables as chest wall thickness at various locations,[21] as well as differences in efficacy of increasing needle lengths.[20] However, no study has assessed the clinical efficacy of an adjunct for decompression that is simple, reproducible, portable, and generalizable to the broad treatment of trauma patients. In this study, the addition of visual color change confirmation by capnography for intrathoracic needle placement drastically alters the paradigm for operator ease and potential reduction of NT failure. The technology we describe here has been well validated for endotracheal tube intubation and has been proven effective as a reliable adjunct for definitive airway control; it is currently the standard of care for confirmation of endotracheal intubation.[24-26]

The ideal device for a needle adjunct would allow providers of variable technical and medical knowledge (soldiers, medics, paramedics, trauma surgeons, intensivists, emergency medicine providers, and pulmonologists) to perform needle thoracostomy in such a manner that they can easily and directly receive real-time confirmation that successful or unsuccessful decompression has occurred. Importantly, the method presented here is simple enough that novice field providers (eg, nonmedically trained soldiers) may be easily educated regarding its use and significance. As visual confirmation results in more objective NT efficacy, this methodology could potentially decrease rates of mortality in nearly one-third of preventable battlefield combat casualties and likely have similar applicability in civilian trauma systems. Furthermore, this simplification of the procedure indicates tension decompression success before vital sign changes are clinically detectable. This new technology could effectively rule out tension physiology as a cause of death in patients and allow providers to target therapy to the treatment of other potential causes of death.

Advances in the recognition, diagnosis, and treatment of tension pneumothoraces are urgently needed. Visual color change confirmation of correct NT insertion and field confirmation of the diagnosis as well as the most effective treatment will permit military and civilian health care providers increasingly to perform a more targeted resuscitation of patients in extremis. To our knowledge, there is no other clinical methodology for rapid determination of NT efficacy in the field other than anecdotal reports of techniques based on intravenous lines connected to the NT and saline to replicate water seals to visualize gaseous bubbling. Improvements in simple life-saving maneuvers, while untested in humans and active trauma scenarios, have significant potential to improve needle decompression reliability, and potentially to reduce rates of mortality associated with tension pneumothorax.

Here we show that this model successfully recapitulates tension pneumothorax based on traumatic etiology, fidelity of the animal model, and, most importantly, physiologic parameters without resorting to instillation of carbon dioxide gas.[10,22,27]

There are several limitations to this study. This experiment involved a swine model of acute thoracic trauma that results in a tension pneumothorax. In this chest trauma model, there are anatomical differences compared with humans. Notably, chest wall thickness is markedly smaller in swine than in people, particularly at the second interspace mid-clavicular line and the fourth interspace anterior axillary line. In particular, the second interspace was not used secondary to anatomic differences in the pig (quadruped, narrow chest, and extremely cranial second intercostal space). Our purpose in this study was not to compare chest wall thickness or placement location, which is why the same length of needle, and the same caliber, were used as well as the same anatomical locations. The novice operator was

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intended to simulate a person in the field, such as a military enlisted person who may have to perform the procedure and determine, with little or no training, whether the treatment was effective. The expert operator was intended to demonstrate standard subjective decompression rates, using all vital sign parameters. Such vital sign measurements are not available in the field, and their absence would likely lead to worse subjective assessments even by an expert operator. A further limitation is an absence of simulation of the “sucking chest wound” (open pneumothorax) causing a tension pneumothorax. This was not performed because of an inability to standardize the size of the wound and conditions of an open pneumothorax, and the relative rarity of the condition (approximately 1%).[1]

Conclusion

In a porcine tension pneumothorax model after penetrating thoracic trauma, visual confirmation of NT insertion on the basis of colorimetric capnography outperforms the blind subjective assessment standard of care method. Implementation of this simple adjunct is likely to have implications for treatment of injured military and civilian patients with tension pneumothorax.

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Additional information: The Video can be found in the Multimedia section of the online article.

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