PREGLED MOGUĆNOSTI ISTOVREMENOG VENTILIRANJA VIŠE BOLESNIKA JEDNIM VENTILATOROM – KRITIČKI OSVRT

Kriza izazvana pandemijom virusa COVID-19, te velikim brojem mogućih bolesnika koji će trebati ventilatore, osvježila je prethodna razmišljanja kako riješiti taj problem. Krize u prošlosti dovele su do razmišljanja o situaciji u kojoj bi bilo puno više bolesnika koji zahtijevaju ventilatorsku potporu nego li raspoloživih ventilatora. Objavljeno je nekoliko radova u kojima su prikazane sheme kako to učiniti. SVI TI RADOVI SU EKSPERIMENTALNI I NISU PROVEDENI NA LJUDIMA, VEĆ SIMULACIJOM POMOĆU BALONA.

Zadnji rad koji se proširio internetom, a prenijeli su ga i neke utjecajne novine, https://www.dailymail.co.uk/news/article-8136299/Doctors-turns-one-ventilator-nine-genius-DIY-mechanics.html govori o mogućnosti istovremenog ventiliranja DEVET bolesnika jednim ventilatorom!? https://www.upworthy.com/canadian-doctors-brilliant-evil-genius-hack-turns-one-ventilator-into-nine

U navedenim člancima NIGDJE NEMA SHEME kako to učiniti, već je autor na svom Twitter profilu ”prikvačio” tuđi video uradak s Youtube-a, koji prikazuje kako spojiti četiri bolesnika na jedan ventilator.

https://www.youtube.com/watch?v=uClq978oohY

Ovaj video uradak zasnovan je na članku: **Neyman G, Irvin CB. A single ventilator for multiple simulated patients to meet disaster surge. *Acad Emerge Med* 2006:13 (11);1246 – 1249**

https://onlinelibrary.wiley.com/doi/pdf/10.1197/j.aem.2006.05.009

Glavni nedostatak ovog rada jest u tome što je analizirano samo jedno, početno mjerenje, ne vodeći računa o promjenama tijekom trajanja ventiliranja.

Neusporedivo bolja analiza takve mogućnosti objavljena je u članku: Branson RD, Blakeman **TC, Robinson BRH et Johannigman JA. Use of a single ventilator to support 4 patients: Laboratory evaluation of a limited concept. *Respiratory Care* 2012:57(3);399 – 403**

http://rc.rcjournal.com/content/57/3/399

U zaključku autori navode sljedeće:

Na modelu pluća, evaluacija primjene jednog ventilatora kojim bi se omogućila ventilacijska potpora za četiri osobe, rezultati ukazuju da navedena tehnika ima bitne prepreke u provođenju. U ovom trenutku ta se tehnika mora izbjegavati, budući da je potencijalno štetna zbog neželjenih komplikacija.

Razlog je vrlo jasan: **Ne postoji više bolesnika s ARDS-om, koji bi imali identične ili vrlo slične karakteristike stupnja bolesti i plućne popustljivosti.**

U navedenom članku, autori upućuju na jedinu do sada objavljenu analizu mogućnosti ventiliranja (samo) dva bolesnika jednim ventilatorom, a koje bi, u krajnjoj nužnosti, bilo moguće primijeniti. Radi se o radu iz 1994. godine:
Sommer DD, Fisher JA, Ramcharan V, Marshall S, Vidic DM. Improvised automatic lung ventilation for unanticipated emergencies. *Crit Care Med* 1994;22(5):705–709.

Bit njihovog pristupa jest konstrukcija dva neovisna ventilacijska kruga priključena na jedan ventilator.
Navedeni rad je u prilogu.

CRITICAL CARE MEDICINE
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Vol. 22, No. 4
Printed in U.S.A.

— *Apparatus and Techniques*

Improvised automatic lung ventilation for unanticipated emergencies

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Objectives: **To design an improvised circuit that can be used to extend the capability of a single ventilator to ventilate two or more patients and that can be assembled from readily available parts in times of unanticipated emergency.**

Design: **Research and development, followed by technical analysis and evaluation.**

Setting: **Biomedical laboratory.**

Measurements and Main Results: **We describe two circuits that can be assembled from readily available inexpensive components to function as improvised ventilators. One circuit requires only a central mushroom valve driver and an additional source of fresh gas for each patient. The other circuit is configured as a number of secondary circuits in parallel, connected to a single ventilator. We constructed and tested the circuits using mechanical lung simulators. The secondary circuit configuration was more efficient in terms of fresh gas usage, but was more complex regarding operation and troubleshooting.**

Conclusions: **These two improvised circuits can extend the capability of a standard volume-cycled ventilator to provide automatic ventilation of the lungs in times of disaster. (Crit Care Med 1994; 22:705–709)**

KEY WORDS: **respiration, artificial; ventilators, mechanical; oxygenation; positive end-expiratory pressure; pulmonary emergencies; apparatus and instruments; positive-pressure respiration; critical illness**

An issue of medical importance was raised during the Persian Gulf War of 1990 to 1991. Iraq's neighbors had to deal with the threat of the use of nerve gas against civilian and military populations. Regardless of the considerable civil defense measures instituted in response to the threat, a successful attack would burden the medical facilities with large numbers of awake, paralyzed, but otherwise healthy patients. It is unlikely that civilian hospitals equipped for peacetime operation would have an adequate number of ventilators in reserve to handle these patients (1). In more general terms, the need for multiplying ventilator capacity can occur in many places throughout the world as a result of war, massive industrial accidents, and natural disasters.

This article describes an improvised method of providing controlled automatic ventilation for patient numbers in excess of the number of ventilators that are available. We describe two systems that are easy to assemble, inexpensive, and show promise of effectiveness. Each system we describe is controlled by a single ventilator, and is capable of ventilating several patients with individualized tidal volumes, airway pressures, FIO_2, and positive end-expiratory pressures (PEEP). The PEEP capability of the driving ventilator is maintained. Cross-infection is avoided by isolated patient circuits.

We assembled and tested two systems using mechanical lung simulators. Institutional Review Board approval was not required. In both systems the tidal volume was generated by controlling the expiratory port of the patient circuit with a mushroom valve driven by a ventilator. In one system, the inspired volume was generated by flow directly from the fresh gas source. In the other system, the inspired volume consisted of a combination of fresh gas flow and gas displaced by the controlling ventilator.

MATERIALS AND METHODS

Fresh Gas Flow and Mushroom Valve System. This configuration consists of a T-piece with a mushroom

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We thank Mr. Richard Smith for assembling the ventilator system and for his helpful and critical comments.

0090-3493/94/2204-0705$03.00/0

valve on the expiratory port (Fig. 1). The required components for fresh gas flow and the mushroom valve system are: a mushroom valve, fresh gas flow source, high-pressure relief valve (pop-off valve), and low-pressure alarm. To minimize rebreathing, the fresh gas flow must be introduced as close as possible to the patient's endotracheal tube. In addition, the circuit should contain an alarm for airway pressure loss, and a pressure-relief valve (pop-off valve) to reduce the risk of barotrauma. A PEEP valve can be added to the expiratory port of any patient circuit, and thus individual PEEP can be optimized for each patient (2, 3). The ventilator's PEEP valve can also be engaged, but the same amount of PEEP will be applied to each patient.

Analysis of System. The advantages of this system are that it is inexpensive and easy to assemble, use, and trouble shoot. The number of patients that can be ventilated with this system is determined by the capacity of the ventilator to drive the mushroom valves and the availability of fresh gas sources. Its major disadvantage is its inefficient use of fresh gas flow. During the expiratory phase, the fresh gas flow is vented and thus wasted. For example, considering an inspiratory time of 2 secs, and a tidal volume of 500 mL at 12 breaths/min, a fresh gas flow of 15 L/min is required, of which only 6 L is used to ventilate the patient.

Secondary Circuit System. Fresh gas flowing during the expiratory phase of ventilation stays within the secondary circuit and makes up part of the inspired volume. In this instance, the required fresh gas flow would be equal to the minute ventilation.

Assembly. Figure 2 is a schematic diagram of two secondary circuits attached to one ventilator. Table 1 lists the components required to double the ventilator capacity using this system. The ventilator should ideally be a volume- or pressure-cycled ventilator, using a mushroom valve on the expiratory port. The ventilator circuit is attached to each secondary circuit.

Secondary Circuit. The "box" should be transparent to allow visualization of the bag. It should have two ports, one port attached to the ventilator circuit, and the other port attached to the bag inside the "box"

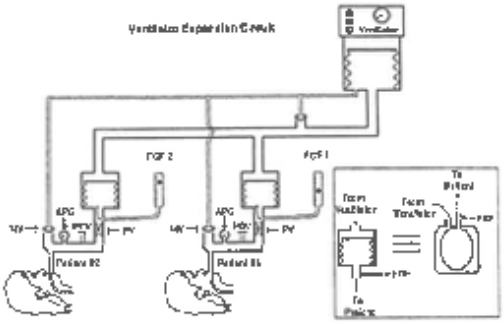

Figure 2. A schematic of the secondary circuit ventilator. Each secondary circuit is T-pieced to a volume-cycled ventilator circuit. The ventilator's mushroom valves are configured in parallel to the primary ventilator circuit and each secondary circuit. The "bag in box" is diagrammatically simplified as a bellows. *MV*, mushroom valve; *APG*, airway pressure gauge; *POV*, "pop-off" valve; *PV*, positive end-expiratory pressure valve; *FGF*, fresh gas flow.

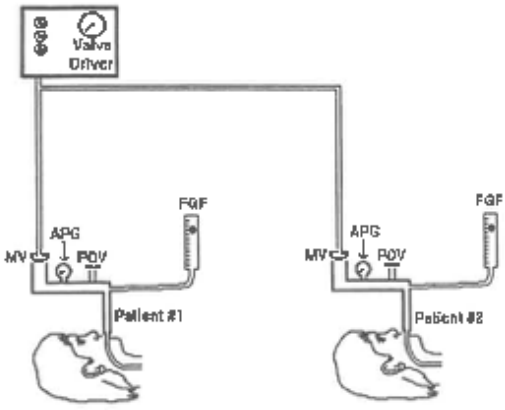

Figure 1. Fresh gas flow and mushroom valve ventilator showing a T-piece configuration. The fresh gas flow should enter the circuit as close as possible to the patient to avoid rebreathing. *MV*, mushroom valve; *APG*, airway pressure gauge; *POV*, "pop-off" valve; *FGF*, fresh gas flow.

Table 1. Apparatus for secondary circuit system required to double ventilatory capacity

"Bag in Box"
Two "boxes" e.g., 4-L suction bottles
Two 3-L bags
Two in-line spring-loaded PEEP valves
Mushroom Valves and Connectors
Two mushroom valves
1/8" ID tubing (4 m)
Two 4-mm "Y" connectors
Circuit Tubing and Connectors
Two 15-mm ID "T" connectors
Two nebulizer "T" connectors (as FGF inlet)
Two oxygen tubes
Four straight connectors
Nine meters of 22-mm corrugated aerosol tubing
Safety Monitors
Two aneroid manometers
Two pressure-relief valves (pop-off valves)
Two low-pressure alarm monitors

PEEP, positive end-expiratory pressure; ID, inner diameter; FGF, fresh gas flow.

(Fig. 2). The fresh gas flow and an in-line spring-loaded PEEP valve are attached to the port containing the bag. (Ball-on-ring type valves are gravity dependent and may fail if tipped.) The purpose of this PEEP valve is to allow the bag to fill during expiration and to provide a variable stepping down of the pressure from the primary ventilator circuit to the patient circuit. The remainder of the patient circuit should contain an aneroid pressure gauge and pressure-relief valve (pop-off valve). The patient expiratory port is controlled by a mushroom valve attached in parallel with the ventilator mushroom valve. A low-pressure alarm system is highly recommended for each secondary circuit.

We assembled the secondary circuit system from components in storage in our respiratory therapy department (Fig. 3) and tested it on mechanical lung simulators (Medishield, Harlow-Essex, UK). For our "box," we used a 4-L suction bottle (Gomco 01-90-3105, Chemetron Medical Products, Buffalo, NY), which had an airtight rubber seal cap containing two 15-mm inner diameter ports. One port had a plastic tube extending into the bottle, where we attached a 3-L anesthetic bag. To this port, we attached a 15- to 22-mm connector with oxygen stem (0001405, Airlife U/Adaptif™ straight adapter, Baxter Edwards Critical-Care, Valencia, CA) and a spring-loaded PEEP valve (900, Vital Signs, Totowa, NJ; or BD 06362, Bird, Palm Springs, CA). The rest of the circuit contained an aneroid pressure gauge (Bird), a pressure-relief valve (Bird), and a mushroom valve (000583, Puritan-Bennet, Pickering, ON, Canada).

Analysis of System. At fresh gas flow equal to minute ventilation, the ventilator's tidal volume capacity limits the cumulative tidal volume output of the secondary circuits. Since the volume of fresh gas flowing during inspiration is added to the volume displaced from each secondary circuit, the individual tidal volume can be supplemented by increasing fresh gas flow above minute ventilation. In this way, additional secondary circuits can be attached without decreasing tidal volume in the interdependent circuits.

Suggested Method of Operation. Patients are selected for the interdependent system and the fresh gas flow is set for each secondary circuit at approximately the intended minute ventilation of each patient (70 to 80 mL/kg). The tidal volume setting on the ventilator is set equal to the intended combined tidal volumes of the patients. The ventilation frequency is set at 10 to 12 breaths/min with an inspiratory/expiratory ratio ranging from 1:2 to 1:4. The secondary circuits are attached to the patient's endotracheal tubes. The ventilator's tidal volume setting is adjusted such that the airway pressure in the primary and all secondary circuits provides the patient who has the lower chest compliance with an adequate tidal volume (4). The patient with the higher chest compliance may temporarily be getting a higher than intended tidal volume. This increased tidal volume is reduced by empirically increasing the resistance through this patient's secondary circuit PEEP valve and thus reducing his/her peak airway pressure. This circumstance will also cause gas from the ventilator to redistribute toward the companion secondary circuit and effectively increase the tidal volume of the patient with the lower chest compliance. Tidal volumes and minute ventilation can be further adjusted by altering the fresh gas flow. A PEEP valve can be added to the expiratory port of any secondary circuit, and thus, individual PEEP can be optimized for each patient (2, 3). The ventilator's PEEP valve can also be engaged but the same amount of PEEP will apply to each patient on an interdependent secondary circuit. To minimize the effects of dynamic changes in respiratory resistance and compliance in parallel secondary circuits, we recommend that patients with the most stable pulmonary compliance be grouped together on these circuits. Heat and moisture exchangers can be added to the patient-circuit interface to provide humidification.

Monitoring. Patients can be visually monitored by observing chest movement, as well as other clinical signs (5). Bag motion and airway pressures in the secondary circuits are also useful monitors. The primary and secondary circuit should be equipped with low- and high-pressure alarms. An expiratory monitor attached to the patient's secondary circuit will reflect the patient expiratory volumes as in a normal ventilator, as long as the fresh gas flow is less than or equal to minute ventilation. Ideally, the patient should be monitored for oxygen saturation and end-tidal P_{CO_2}.

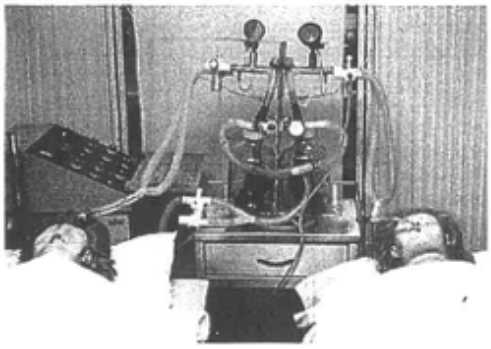

Figure 3. A photograph of the secondary circuit ventilator we assembled in our hospital from components readily available in the respiratory therapy department. The patients are manikins.

Blood gas measurements can be performed as necessary.

In the event of a power or gas source failure, the patients must be disconnected from the circuits and ventilated manually, as is the practice when standard ventilators are used.

Trouble-Shooting. A system malfunction is normally detected by an aberrant filling and emptying motion of one or more of the bags in the secondary circuits. The patients affected should be disconnected from the circuit, ventilated manually with a self-inflating bag, and the circuit attached to a rubber anesthesia bag until the problem is identified. Malfunctions are classified according to one of the following three conditions: a) primary circuit malfunction; b) mismatched fresh gas flow; c) secondary circuit malfunction.

Trouble-shooting consists of differentiating between these three conditions. In a primary circuit malfunction, all patients and bags are affected simultaneously. Problems that appear to be affecting predominantly one patient reflect a fresh gas flow mismatched to minute ventilation, or a malfunction in any interdependent secondary circuit. The adequacy of fresh gas

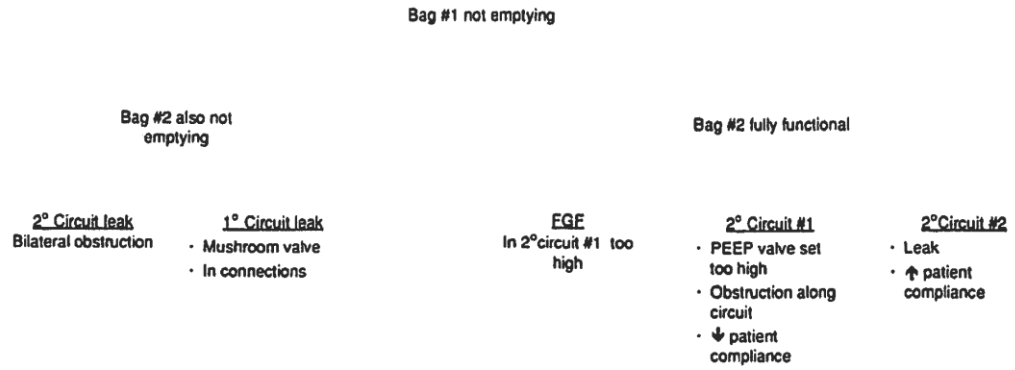

Figure 4. Chart for trouble-shooting when the bag in the secondary circuit on the index patient (*Bag #1*) is not emptying. *FGF*, fresh gas flow; *PEEP*, positive end-expiratory pressure.

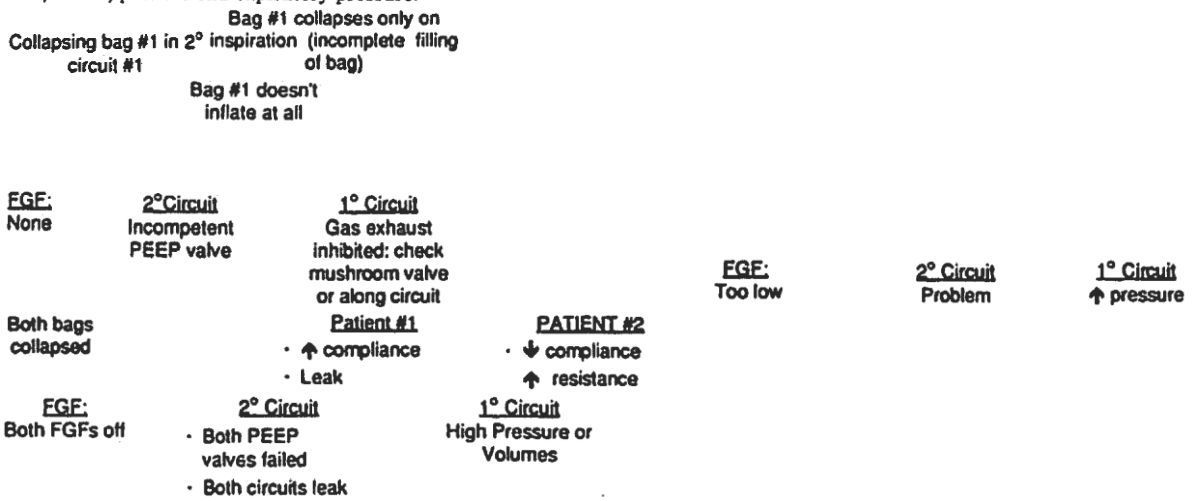

Figure 5. Chart for trouble-shooting when the bag in the secondary circuit on the index patient (*Bag #1*) is collapsing inappropriately. *FGF*, fresh gas flow; *PEEP*, positive end-expiratory pressure.

flow in the circuit appearing to malfunction is checked first, then each interdependent secondary circuit is examined for leaks or obstruction. Figures 4 and 5 outline the steps for trouble-shooting a sample secondary circuit system consisting of two secondary circuits (Fig. 2).

DISCUSSION

Positive-pressure ventilatory support has been known since antiquity (6–8). Its application has been limited by, among other things, the development of the technology of ready airway access, that is, endotracheal intubation (9).

Negative-pressure ventilators were developed at the turn of the 20th century. The Drinker "iron lung" gained widespread acceptance for the management of polio patients after a demonstration of its clinical efficacy in 1928 (10, 11). Nevertheless, the epidemic nature of the disease (polio) frequently resulted in numbers of paralyzed patients exceeding the number of negative-pressure ventilators available (7, 11, 12). This circumstance led to the development of negative-pressure chambers that were able to hold two and even four patients (11).

Technological improvements in endotracheal tubes responded to the need to provide positive-pressure ventilation during anesthesia for patients with open chests and for those patients paralyzed with curare (13). In January 1953, Lassen (12) described the use of endotracheal intubation and hand-delivered positive-pressure ventilation for polio victims as "therapeutic improvisations...when the one tank ventilator and six cuirass respirators proved wholly insufficient when the epidemic developed into a major catastrophe."

The development of positive-pressure ventilators followed. They have evolved into expensive, complex machines designed to provide ventilatory support for patients with lung disease (13–15). In one respect, we have come full circle. Positive-pressure machines have replaced negative-pressure machines, but their supply is once again limited to satisfying ongoing requirements (1) and there are no provisions for an unanticipated large increase in demand other than one-to-one manual ventilation as described by Lassen (12).

In this article, we describe a simple, easily recruited source of automated, intermittent, positive-pressure ventilation that was obtained by extending the capabilities of a ventilator, to ventilating more than one patient.

REFERENCES

1. Robinson A, Shapira Y, Hendler I, et al: Improvement of hospital preparedness for mass casualties of chemical warfare in the aftermath of the gulf war. Abstract #22. Proceedings of the Eighth World Congress on Emergency and Disaster Medicine, 1993, Stockholm, Sweden
2. Suter PM, Fairley HB, Isenberg MD: Optimum end-expiratory airway pressure in patients with acute pulmonary failure. *N Engl J Med* 1975; 292:284–289
3. Tenaillon A, Labrousse J, Gateau O, et al: Optimal positive end-expiratory pressure and static lung compliance. *N Engl J Med* 1979; 299:774–775
4. Hylkema BS, Beekmeyer-Degenhart P, Gravink RG, et al: Lung mechanical profiles in acute respiratory failure: Diagnostic and prognostic value of compliance at different tidal volumes. *Crit Care Med* 1985; 13:637–640
5. Gilston A: Facial signs of respiratory distress after cardiothoracic surgery. *Anaesthesia* 1976; 31:385–397
6. Rosen Z, Davidson JT: Respiratory resuscitation in ancient Hebrew sources. *Anesth Analg* 1972; 51:502–505
7. Soemerson SJ, Sicilia MR: Historical perspectives on the development and use of mechanical ventilation. *Journal of the American Association of Nurse Anesthetists* 1992; 60:83–91
8. March ET: History of mechanical ventilation. *In*: Clinical Applications of Ventilatory Support. Kirby RR, Banner MJ, Downs JB (Eds). New York, Churchill Livingstone, 1990, pp 1–61
9. Mushin WW, Rendell-Baker L, Thompson PW, et al: Automatic Ventilation of the Lungs. Third Edition. London, Blackwell Scientific Publications, 1980, pp 184–249
10. Drinker P, Shaw L: An apparatus for the prolonged administration of artificial respiration. *J Clin Invest* 1929; 7:229–247
11. Drinker PA, McKhann CF: The iron lung. First practical means of respiratory support. *JAMA* 1986; 255:1476–1480
12. Lassen HCA: A preliminary report on the 1952 epidemic of poliomyelitis in Copenhagen with special reference to the treatment of acute respiratory insufficiency. *Lancet* 1953; 1:37–41
13. Lee JA, Atkinson RS (Eds): A Synopsis of Anaesthesia. Tracheal Intubation. Seventh Edition. Bristol, UK, J Wright, 1973, pp 222–244
14. Barbarash RA, Smith LA, Godwin JE, et al: Mechanical ventilation. *DICP, The Annals of Pharmacotherapy* 1990; 24:968–970
15. Pereis IL: Thirty years of mechanical ventilation. Changing implication. *Arch Intern Med* 1988; 148:745–749