Medical Evaluation for Respirator Use

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Medical certification for respirator use should be based on understanding of their respiratory, cardiac, mechanical, psychological, and other effects. Work environmental factors (e.g., level of hazard and work load of the job), respirator characteristics, and personal characteristics of the worker should determine the evaluative procedures used; a three-level scheme is suggested.

Respirators (respiratory personal protective devices) are necessary for worker protection in a contaminated atmosphere when engineering controls are impossible. An effective respiratory protection program has three components: selection of the proper respirator, determination that the employee can work while wearing the respirator, and proper use of the respirators. This report will address selection of the worker who can wear a respirator from the occupational medical perspective, a topic that has received inadequate attention. Although a new respirator rule will be proposed, the current general Occupational Safety and Health Administration (OSHA) regulation (1910.134)[1] merely states in a few lines that there should be determination of appropriate health conditions and "periodic (for instance, annual)" reconsideration. There are, however, general guidelines for the amount of allowable resistance in a respirator and for the permissible rebreathing of carbon dioxide (CO_2) (specified only for self-contained [SCBA] respirators).[2]

A medical certification program should be based on several considerations: the physiologic burdens that a respirator imposes, compensatory mechanisms, effects of disease, screening methods, critical limiting factors, and costs.

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Physiologic Loads Imposed

Respirators produce several important physiologic burdens. The major physiologic effects are those on pulmonary and cardiac function as a consequence of several specific "loads" imposed by the respirator.[3] First, there is resistance to airflow, the "flow resistive load." While this may be present in both inspiration and expiration, it is predominantly an inspiratory load in nonpowered air-purifying respirators. The magnitude of this effect differs considerably from respirator to respirator, and American National Standards Institute (ANSI) recommendations and OSHA regulations provide maximum limits.[2] In addition, there may be a "threshhold" resistance, one that disappears after airflow begins. That is, although pressure must be generated to open a valve, once it is open, there is no effective resistance. This is particularly true of demand-type valves, and it is generally of small significance except when there is a malfunction.

The other major load is "dead space," representing the volume of exhaled air that is rebreathed from the mask with each inspiration. Respirator masks, particularly full-face masks, may be quite large, having volumes equivalent to the internal physiologic dead space.[3,4] However, the total mask volume is not rebreathed with each breath. The rebreathing (dead space) effect requires increased ventilation.

An increased pleural pressure must be generated by the respiratory muscles (diaphragms and chest wall muscles) to overcome the airflow resistance of the respirator. If a respirator has significant expiratory impedance, the pressure in the chest cavity will also be more positive during expiration. During exercise, the peak added pressure has been from 10 to 15 cm of water on the average.[4-6] Increases in the pleural pressure swings have several possible effects. They require increased respiratory work and may produce dyspnea. Furthermore, pleural pressure swings may affect cardiac function by affecting filling of the heart.[7-12]

The net effect of the increased resistance and increased ventilation is a significant increase in the work of breathing. This may be expressed as the integral of pressure times flow over time.[13] In addition to increasing the driving pressure needed to produce any flow rate, respirators also require an increase in the total volume of air breathed in order to overcome the dead-space effect, thus further increasing the total work of breathing. The resistance of a respirator can be comparable with or even greater than the "internal resistance" of the respiratory system (approximately 1.5 cm of water/l/s as determined by plethysmography).[14] In addition to increasing the total work of breathing, respirators also increase the average and peak work rates. The added work may be inspiratory or expiratory or a combination of both, depending on the location of the resistance relative to the valves of the respirator.

Unfortunately, it is difficult to measure directly the total work of breathing since this requires placement of a balloon catheter in the esophagus to estimate pleural pressure. However, the added work may be more easily determined by measuring airflow and mouth pressure, the integral product of which represents the additional work required to overcome the external resistance imposed by the respirator.

Normally the distribution of blood flow within the lung is matched appropriately to distribution of ventilation so that an optimal ventilation-perfusion ratio is maintained in each lung zone.[15] The distribution of blood flow is dependent on gravity and intrathoracic pressure gradients, and the regional distribution of ventilation in the lung depends on flow pattern. Thus, although not empirically verified, it is quite possible that ventilation-perfusion matching may be affected by respirator use.

Physical characteristics of the device itself may be important. A SCBA may weigh more than 30 lb, increasing both the energy demands of the task and the cardiorespiratory demands of any particular job and contributing to back strain and to postural instability. Working in close spaces may be difficult. Mobility is limited when using an airline respirator, which may lead to unusual work postures. Providing an air-tight fit requires bands that may impede lymphatic flow. In addition, field of vision and the clarity of vision may be decreased, and there is interference with the physiology of normal speech. Other physiologic effects include decreased ability to eliminate heat, which becomes particularly important when the clothing worn is impervious to moisture and heat.[16,17]

Anxiety can also produce physiologic stress. If a worker is made anxious by the use of a respirator, catecholamine levels may increase, causing heart rate, blood pressure, and respiratory rate to increase. The mask itself may produce anxiety, and the use of a respirator may signify the presence of "danger." In some workers, the anxiety produced by the respirator may preclude its effective utilization. Morgan[18] has estimated that 10% of workers have psychological problems that affect respirator use.

There have been several reviews[16,19-21] that describe respirator loads.

Compensatory Mechanisms — Faced with added loads due to the respirator, the user may employ several compensatory physiologic mechanisms. First, he may increase the respiratory work. Respiratory work may be expressed as the integral of pressure times volume over time.[6] Any increase in respiratory work is due to both the increase in inspiratory and expiratory effort measured in pressure and the increase in ventilatory volume (to compensate for the mask dead space). Normal subjects tested during progressive exercise with and without respiratory loads in place were easily able to increase their respiratory work (pressure volume product) in going from submaximal to maximal exertion, and were able to increase the peak work rate as well as the average work rate.[6]

With the added inspiratory flow resistance of the respirator, an increase in the inspiratory time will reduce the average pressure, decreasing the work rate of the inspiratory muscles. Increases in both the absolute inspiratory time and the proportion of the respiratory cycle have been demonstrated at several exercise levels.[3,6,22-24] Of course, increasing inspiration leads to a decrease in the expiratory time and can cause dyspnea.[24]

The normal inspiratory and expiratory phases are initiated with high instantaneous flow rates. These early high inspiratory flows, which require marked pressure generation, may be decreased.[6]

Increases in tidal volume or frequency or both will increase ventilation to compensate for the dead-space loading and the increased CO_2 production of exercise.[25-27,5] Increases in tidal volume will be more efficient than increases in frequency, since only that portion of the breath that reaches the gas-exchanging surfaces (the alveolar ventilation) is effective in CO_2 elimination. Even without a respirator, much of a normal breath is "wasted"; for example, the "physiologic" dead space may be about 150 ml of each 500-ml tidal volume. Twelve breaths per minute with a tidal volume of 500 ml would produce 4,200 ml of effective alveolar ventilation. (Normal basal alveolar ventilation is about 4.2 l.) If a mask dead space of 150 ml were added with no compensation, the effective alveolar ventilation would fall to 2,400 ml/min, and the arterial P_{CO_2} would then rise. To maintain the normal alveolar ventilation simply by increasing respiratory frequency would require a respiratory rate of 21/min (for an alveolar ventilation of 4.2 l) with a consequent total minute ventilation of 10.5 l. Alternately, increasing the tidal volume to compensate for the added dead space would require an additional 150 ml per breath (new tidal volume = 650 ml) with a minute ventilation of only 7.8 l (650 ml x 12/min). In actuality, a combination of tidal volume and frequency change occurs to deliver adequate alveolar ventilation. Workers who are unable to increase one or the other will not be able to compensate for the added dead space.

If a higher than normal P_{CO_2} were tolerated by a worker, less alveolar ventilation would be necessary. Elevation of P_{CO_2} is a potent stimulus to respiration and is accompanied by the development of tachypnea and falling arterial pH. While chronic hypercapnea may allow a metabolic compensation, acute hypercapnea, such as would occur with temporary respirator use, would occur too rapidly to allow such metabolic compensation; hence, there would be a large fall in the arterial pH. Therefore, tolerating a higher P_{CO_2} is not a particularly safe compensatory mechanism. However, even normal subjects do increase P_{CO_2} when breathing through very high resistances, but they appear tachypneic and probably dyspneic.[28]

One additional method of adapting is to remove the respirator or to create a leak in the facial seal. Of course, this prevents the respirator from protecting the worker against airborne toxins. However, anecdotal observations and studies such as those of Smith (in cadmium workers)[29] suggest that many workers may choose this method of adaptation.

Effects of Disease

Psychiatric, pulmonary, cardiovascular, and other diseases may interfere with respirator use.

Psychiatric disorders or certain personality traits may prevent safe respirator use.[18] For example, certain phobias may preclude their use, and personality traits may make a worker unreliable in using respirators. Of course, workers who are unable to understand the purpose and proper use of respirators should not be permitted to use them.

Pulmonary disease may be categorized as restrictive disease, obstructive disease, and respiratory control disorders. Obstructive diseases include chronic obstructive lung disease and asthma. Persons suffering from them may have an increase physiologic dead space and characteristically have an increase in airway resistance. In more advanced stages, with their lungs hyperventilated, their inspiratory muscles may be inefficient; the diaphragms are low and flat, and they operate at an inefficient position on their length-tension relationship.[30,31] Individuals with obstructive disease may have dyspnea even in the absence of respirator use. However, many studies of ability to detect and scale added flow resistances suggest that persons with elevated airway resistances may be less "senstitive to" added external resistances.[32-39] These resistances might decrease their dyspnea but could also interfere with their ability to compensate appropriately. Such individuals may also have right-sided heart failure and be sensitive to added pleural pressure swing effects. They may be hypercapneic with exercise or even at rest. A hypercapneic worker will be particularly prone to further, more marked hypercapnea with added loads -- because he has little or no respiratory reserve and has already shown a respiratory control abnormality and because any given decrease in alveolar ventolation causes a more marked elevation in PCO_2 Finally, persons with chronic bronchitis have frequent production of sputum in association with cough. It is not difficult to visualize how a tight mask would be poorly tolerated by a worker with a frequent productive cough.

Restrictive lung disease includes many disorders such as idiopathic pulmonary fibrosis and complicated silicosis. Affected workers have decreased pulmonary compliance (i.e., the lungs are stiff) and they generally have high pleural pressure swings even in the absence of respirator use. They also may be dyspneic, occasionally out of proportion to the apparent abnormalities on simple pulmonary function tests. It would be difficult for them to increase tidal volume because of the decreased pulmonary compliance; typically, patients with restrictive lung disease breathe rapidly and shallowly. They may therefore be particularly prone to adverse effects of respirators.

Respiratory control disorders may be primary (unassociated with other lung disease) or in association with lung disease such as chronic obstructive lung disease. Persons with such disorders do not readily adjust their ventilatory work to the needs because they have lost the normal response to the stimulus of increased arterial PCO_2, hypoxemia, or decreased arterial pH. They may be hypercapneic at rest or may be normal when at rest and while awake. Persons with primary respiratory control disorders may be difficult to detect clinically, may have normal pulmonary function tests (including normal PCO_2), and may require rather sophisticated testing to demonstrate their abnormality.[40-44]

Cardiac disease must also be considered. Angina or arrhythmias may be aggravated if hypoxemia or hypercarbia occurs. Antihypertensive drugs producing postural instability (e.g., guanethidine) may increase the cardiovascular effects of increased pleural pressure swings; fortunately, such drugs are used only on a limited basis. Nonselective β-blocker drugs for angina or hypertension may, in sensitive individuals, increase the airway resistance. Generally, persons who are sensitive (e.g., asthmatics) should not be treated with β-blocker drugs even in the absence of respirator use. The increased respiratory work will require an increase in cardiac output,[31] and persons with certain severe cardiac diseases may have a limited ability to increase cardiac output.

A variety of other medical conditions may interfere with respirator use. The National Institute for Occupational Safety and Health suggests that a perforated typmpanic membrane may make respirator use ineffective.[2] Structural abnormalities (congenital, traumatic, or surgical) of the face may interfere with adquate mask fit. Musculoskeletal disorders may make it difficult to carry a heavy SCBA, and the weight of the respirator may lead to increased cardiac work load.

The Critical Limiting Factors

A medical certification program should be based on the detection of any critical limiting factor that may exist. Several factors may potentially be limiting. These, as well as possible medical evaluative procedures, are shown in Table 1.

Ventilation may be critically limiting. It may not be possible for the worker to achieve sufficient ventilation to compensate for the added dead space. Ventilatory limitation with the added flow resistance due to the respirator may prevent compensation. That is, some workers may be unable to sustain an adequate minute ventilation for more than a short time.[45,46]

Table 1 – Possible Limiting Factors and Means of Evaluation

Limiting Factor	Evaluation
Ventilation	Spirometry
Ventilation with resistance	Spirometry
Hypoxemia	Arterial blood gas analysis
Tidal volume increase	Exercise testing or special spirometry
Expiratory time compression	Measurement of timing
Inspiratory muscle fatique	Electromyogram
Pleural pressure swings	Esophageal balloon
Subjective dyspnea	Observation
Sensitivity to loads	Scaling or threshold methods
Cardiac output	Measurement
Psychological tolerance	Interview
Knowledge	Interview or test

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Development of hypoxemia could limit work using respirators.[47,48] However, there is little evidence to suggest that this is a common primary limitation.

Carbon dioxide excretion may be limited, due to the inability to increase ventilation sufficiently (i.e., some persons may be unable to increase tidal volume and/or rate).

Compression of expiratory time results from prolongation of inspiratory time. Johnson and co-workers,[23,24] in a study of normal volunteers during maximal exhausting exercise, found that expiratory time consistently appeared to predict the point at which subjects could no longer continue. In evaluating submaximal exercise, however, we found considerable reserve in expiratory time compression, suggesting that it is not necessarily the limiting factor under most circumstances.[3,6]

Inspiratory muscle fatique has been recognized increasingly as a concomitant of respiratory failure.[30,31] It can also be produced experimentally with flow resistive loads in healthy subjects; however, the magnitude of these resistance loads is much higher than that of respirators.

Pleural pressure swings may be a limiting factor. Demedts and Anthonisen[49] have shown that each normal person has a particular level of pleural pressure swing that he will toierate. This is probably related to the peak work rate of the respiratory muscles.

The subjective sensation of dyspnea may be limiting. Dyspnea is a poorly understood sensation that has many causes other than simple mechanical factors.[50-52] Pressure swings, both upper airway and intrathoracic, may contribute to dyspnea. Distortion of J receptors may account for dyspnea in persons with pulmonary vascular and interstitial lung disease.[51] Dyspnea may be a consequence of disproportion between work output of the respiratory muscles and ventilation achieved or pressures generated; this is likely to occur in the setting of respiratory loading (i.e., the resistance and additional dead space makes ventilation less efficient). Often the abnormality in pulmonary function can be demonstrated only by evaluation during exercise.

Cardiac output is also a potential limiting factor. With increasing loads, the respiratory muscles take an increasing proportion of the total cardiac output; a worker with cardiovascular disease may be unable to increase total cardiac output adequately.[31]

Psychological tolerance to the respirator or knowledge of its care and use may prove limiting in some individuals.

Certification Program

Identification of workers who cannot safely and effectively use respirators should be based on evaluative procedures that are simple, cost-effective, truly related to ability to use respirators, and preferably "objective." Criteria should not be too stringent (excluding workers unnecessarily) and yet must provide an adequate margin of safety to ensure that no worker is injured. There are many types of respirators, they are used in many different situations, and workers may have a great variety of medical conditions. Clearly, no single system can be appropriate for all situations, and therefore, the choice in any individual case must be based on the three factors —job environment, type of respirator, and characteristics of the individual worker.

A respirator may be used briefly or may be worn throughout the workday; a worker may tolerate it for a short time period but not throughout the day. The job may require minimal physical exertion or heavy physical work with additional stresses such as heat stress. The purpose of the respirator use must be considered — clearly more stringent criteria are necessary for exposures that are immediately dangerous to life and health than for nuisance dust exposure. The frequency of respirator use, however, should not be considered a determinant. Indeed, the case of respirator use for emergency escape only may be particularly dangerous; here, workers will not "self-select" themselves to find new jobs if they tolerate respirators poorly, and they will be using a device with which they may be unfamilar in possible panic situations.

The respirators also differ. Some have considerable inspiratory resistance, while in others this is minimal; similarly, dead space varies considerably from respirator to respirator. Some SCBAs are quite heavy.

Characteristics of the worker must also be considered. Age, previous respirator experience, and physical conditions should determine the evaluation necessary. For example, it is possible to characterize the "risk" of an individual. Persons who have previously experienced difficulty with respirators warrant particularly careful consideration, while previous respirator use at high exertion levels suggests that physiologic or psychological complications are unlikely to occur. Medical conditions may also constitute "risk factors." Any worker with chronic respiratory symptoms or a history of recurrent pulmonary infections needs special attention. Because workers with asthma may vary from day to day, their "risk" must be assessed on a "worst case" basis, considering the most severe episode they might develop while using a respirator. Cardiac disease also constitutes a significant risk factor for the reasons discussed earlier. Psychological assessment (done informally) may also indicate "high-risk" individuals. Ultimately, the determination whether a worker's personal characteristics place him/her at higher than average risk must be made on an individual clinical basis.

Recognizing that several "levels" of evaluation are needed, Table 2 presents a suggested scheme for choosing the level of evaluation based on three factors. Good judgment should always supersede any schema.

A basic component of any program is observation of the worker using the respirator, preferably at an exercise level required by the job. With proper observation, this can provide a great deal of information. At the very least, it can help to identify those workers who require more detailed testing.

The level I evaluation should include at minimum a short questionnaire ("Do you have cardiopulmonary disease? Do you have difficulty using the respirator? Do you know how to use it?"); observation of the worker using the respirator by a trained nurse or industrial hygienist; and measurement of pulse rate, blood pressure, and respiratory rate while working with and without the respirator.

A level II evaluation should include a more detailed questionnaire or interview, a limited examination of the heart and lungs by a physician or appropriately certified nurse practitioner, a spirogram, observation of the worker while using the respirator, and pulse rate, blood pressure,

Table 2 – Choice of Evaluative Level											
	Exertion†			Duration, min			"Risk"‡		Level		
Danger*	H	M	L	0-5	6-30	>30	No	Yes	I	II	III
IDLH	X				X	X	X	X			X
	X			X			X	X		X	
		X				X	X	X			X
		X			X			X			X
		X			X		X			X	
		X	X	X	X		X	X		X	
			X	X	X	X	X	X		X	
			X	X	X			X		X	
			X	X	X	X					X
MOD	X	X				X		X			X
	X	X			X	X	X			X	
	X	X		X			X		X		
	X	X		X				X		X	
			X	X	X		X		X		
			X	X	X			X		X	
			X			X	X	X		X	
SL	X	X			X	X		X		X	
All other cases									X		

* IDLH indicates immediately dangerous to life and health; MOD, toxic atmosphere for extended exposure; SL, slight risk

† H (high) indicates >5 METS; M (moderate, 2-5 METS; L (light), <2 METS

‡ Age >50 or history of heart or lung disease or SCBA or "high" resistance respirator

and respiratory rate measurements taken while exercising with and without the respirator. An electrocardiogram should be performed for those over 40 years of age.

A level III evaluation should also include a more detailed interview and examination by a physician who is familiar with respirators. The peak inspiratory and expiratory pressures that the worker can generate should be measured; this requires only minimal equipment.[53] In addition, a more formal exercise test should be performed. While a standardized laboratory treadmill protocol[54-56] would be optimal, practical considerations preclude this. However, a standardized exercise protocol can be developed for each plant involving a combination of exercise on inclined ground and stairs; comparability between plants can be provided by ensuring that a dozen normal volunteers achieve a pulse rate of 60% of predicted maximal. A worker should complete approximately 10 minutes of exercise without a respirator and then exercise under observation for at least 30 minutes using the respirator. Blood pressure, pulse rate, respiratory rate, and clinical assessment of respirator tolerance should be recorded. In addition, the physician should ascertain by brief interview that there are no psychological contraindications to respirator use.

The criteria for determining fitness need to be defined. Table 2 provides guidelines for the selection of appropriate tests but does not specify what cutoffs should be used or how the individual tests should be combined to yield a final decision. Development of such a set of specific criteria requires a coordinated effort of the occupational health professionals at each work site, integrating information about environmental and medical factors. However, an abnormal test result (e.g., outside the 95% confidence limits defined in a normal population) may define the need to consider a worker's fitness more carefully.

Simple ventilatory measurements alone are unlikely to identify all workers with contraindications to respirator use. Spirometry is of limited sensitivity for detection of restrictive lung disease, respiratory control disorders, problems of endurance, and psychological unsuitability. Spirometric results of asthmatics may vary considerably over time, and therefore testing at one time may not reflect the physiologic state at other times. Performance of routine spirometric tests, particularly the maximal voluntary ventilation (MVV), using the respirator has been suggested,[57] but several questions require further evaluation before implementation. First, the MVV, even without a respirator, is an extremely variable test. Second, there is no clear and direct relationship between a 15-s MVV test and a worker's ability to breathe effectively during a more prolonged work period. Third, the great variety of respirators available makes mechanical linkage to standard spirometers difficult. Fourth, the respiratory pattern during an MVV maneuver is quite different from that during normal work with a respirator.

Those workers who are found to be abnormal or who show subjective or objective difficulty with respirator use should be referred for more specific individualized evaluation. For example, persons with moderate to severe obstructive lung disease should have arterial blood gas analysis to determine if hypercapnea is present. Some workers may require formal exercise testing with measurement of generated pressures as well as metabolic parameters.[6] Current experimental techniques include measurement of load scaling proclivity (which at this time is difficult to perform reliably) and quantitative description of respiratory pattern (which is simple to perform using only a simple spirometer). However, further research is needed to determine if these will be useful in practice.

There have been several additional studies of effects of respirator use,[58-66] but there is as yet no clear means of definitively identifying high-risk workers. More research and practical evaluation are necessary.

In the interim, establishment of a formalized, multilevel scheme such as the one described would help ensure adequate safety for the worker and avoid unnecessary testing.

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Editorial Comment

The evaluation of a worker's ability to wear a respirator is an obviously important responsibility of the occupational physician, and certification that the worker can indeed wear a respirator is an equally important legal responsibility. As Harber has described, the physiologic adaptation by a normal individual to the work load imposed by the respirator is a complicated response. The adaptation required changes as the work load increases. The physician who is asked to evaluate the worker with known heart or lung disease and to determine whether this worker can wear a respirator is faced with a problem for which there is little guidance. Dr. Harber has provided a scheme that considers the hazard of the job, the energy demands of the job, the duration of the task, and the health status of the worker. Each of these factors must be considered individually.

The medical history of the worker can be obtained and physical examination, chest roentgenogram, pulmonary function tests, spirometry, and an electrocardiogram can be performed, Whether all of these tests are normal or not, a history of disease makes a decision difficult. It has been well established that a worker's ability to do a physical job is best determined by observing him doing the job. An identical approach must be used in evaluating ability to wear a respirator. An exercise test should be required, with the energy expenditure (work output) equal to or greater than that of the job assignment. The worker should be observed carefully for dyspnea or other signs of distress, and his pulse rate, respiratory rate, and blood pressure should be noted and recorded. If any abnormalities are detected by the test, the physician can determine whether further study of the worker is indicated or whether he can be permitted to do the job, possibly with some continued observation.

Exercise testing is probably not being done as it should be because it takes time, and because physicians have not had an opportunity to observe the value of such testing. Probably more important, workers, even with cardiopulmonary disease, can do the job because the work load of the job while wearing the respirator is low. Nevertheless, it should be remembered that the asthmatic may appear quite normal by examination and spirogram, but will improve in ventilatory capacity when given a bronchodilator. As Robin has stated in the *Scientific American Medicine,* exercise testing provides valuable information on cardiopulmonary performance, and I add that it cannot be obtained in any other manner.

George Roush, Jr., M.D.

Life Force at the Edge

The most important business of love and friendship is to hold us together as we live on the shifting edge of our differences. Friendship and love are the life force pitted directly against separation and death at the very core of true intimacy. The trembling edge of our separateness — of our potential estrangement — is the site at which friendship reveals its true power and does its work. Friendship draws us out of ourselves, literally forcing us to draw on faith and hope as we close the fault lines that death would claw wide open in our relationships every day. By being friends we not only hold fast to each other, but we strengthen the forces of life, we overcome death on the battleground of everyday mystery. We are not strangers to death if we are friends with life.

— Eugene Kennedy in "On Being a Friend," published by The Continuum Publishing Company, New York, 1982.