Bel W3 tobacco plants. The injury estimates for beans involve only one sensitive leaf, whereas the tobacco data represent the average estimates of five leaves, some of which were not at maximum sensitivity.

The literature contains reports of varying threshold concentrations producing plant injury (*4*). In these reports humidity records are usually not included. Variability may be due to differences in atmospheric humidity at the time of plant conditioning and exposure, and humidity records should be included with each study. Toxicant injury to apple fruit at lenticels in which humidity was found to have no influence has been reported (*5*). This is understandable since the lenticels on mature apples are permanently open. Irrigation (sprinkling) is also reported to increase plant response (weather fleck) to ozone (*6*). While no explanation for this response is given, it is clear that irrigation would greatly affect humidity around the sprinkled plants, thus increasing susceptibility to ozone. In addition the marked effect of humidity on stomatal apertures should influence plant response to all pollutants. This may explain the greater sensitivity (*7*) to ozone injury obtained with plants grown in the eastern United States as compared with those grown in the Southwest.

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Pulmonary Gas Transport Time: Larynx to Alveolus

Abstract. *The transport time of gas from the larynx to pulmonary alveolar capillary blood was directly measured by injecting a bolus of carbon monoxide into the inspired airstream of dogs and photoelectrically monitoring the formation of carboxyhemoglobin in the capillaries on the surface of the lung. The rapidity of transit (0.3 second) implies that gas transport during inspiration is facilitated by an interaction between bulk flow and diffusion.*

It is currently accepted that inspired gas moves from the nose to alveolar surfaces by combinations of turbulent and laminar flow in the large airways (bulk flow where movement is caused by pressure gradients) and finally by still gas diffusion (where gas transfer is caused by concentration gradients only) near the alveoli. Because of the anatomical complexity of the bronchial tree, the undetermined interactions of the diffusion and bulk flow, and the unknown transit times for inspired gas to reach the alveoli, realistic modeling in any detail of normal gas transport mechanisms and their disruption by disease has been virtually impossible. We now present results of a technique that measures pulmonary gas transport time.

Spectrograms of reduced and oxyhemoglobin (HbO_2) have identical absorption coefficients at a wavelength of 805 nm, whereas carboxyhemoglobin (HbCO) has a significantly lower absorption at that wavelength (*1*). Thus a photodetector observing blood at 805 nm is insensitive to changes in the level of HbO_2, but is very sensitive to the concentration of HbCO. This principle has been used to measure transit time of gas from larynx to alveolus. A bolus of carbon monoxide is injected into the inspired airstream, and the formation of HbCO in the capillaries on the surface of the lung is photoelectrically monitored.

Mongrel dogs (23 to 30 kg), anesthetized by intravenous injection of sodium pentobarbital (30 mg/kg), are tracheotomized and then artificially ventilated (by intermittent positive pressure breathing) throughout the procedure. A transparent thoracic window is implanted in place of a resected portion of the eighth rib (*2*). A box from which light is excluded containing an RCA-925 phototube is attached to the external surface of the window such that the photocathode is directed toward the surface of the lung. Illumination appropriately filtered to 805 nm from a General Electric-EJV quartz halide lamp is directed through the box onto the surface of the lung under the window. The phototube output is recorded by an Electronics for Medicine DR-8 oscillograph at an amplification sufficient to produce full-screen deflections at the peak of HbCO formation (Fig. 1a). Under our experimental conditions there is approximately a 1 percent increase in reflected light at the peak of the response.

A spring-driven 10-ml syringe is loaded with CO (100 percent). A signal at a predetermined phase of respiration from the DR-8 trigger channel electrically releases the spring which drives the CO rapidly (35 msec) into the base of a T-tube connected to the tracheal cannula at a point equivalent to the larynx. The base of the T-tube, having a dead space of 4.5 ml, reduces the amount of CO which enters the inspired airstream as a bolus to 5.5 ml. The point of injection is demonstrated by a rapid deflection in the signal from a pneumotograph connected to the respiratory side of the T-tube. The animals are respired by a Harvard piston respirator (model 607D) in which piston speeds during inspiration and expiration can be varied independently. Tidal volume has been held constant at 350 ml for all experiments.

We have studied two variables. First, the length of time for a complete inspiration is varied to cover either 0.60 second (designated fast inspiration) or 0.98 second (designated slow inspiration). The inspiratory flows closely approximate the positive half of a sine wave with peak flows of 45.3 liter/min and 25.4 liter/min for fast and slow inspiration, respectively. Second, the CO was injected either before the beginning of inspiration (designated negative injection time) or when inspiratory flows reach half of their maximum rate (designated positive injection time). Transport times for negative injection times are measured from the beginning of inspiration; measurements are made from the point of CO injection for

Table 1. Effect of inspired air velocity on pulmonary gas transport times (seconds). Abbreviations are: FI, fast inspiration; SI, slow inspiration; T+, positive injection time; T−, negative injection time; S.D., standard deviation.

	FI T+	FI T−	SI T+	SI T−	FI T+	SI T+	FI T−	SI T−
				Dog 194				
Mean	0.351	0.556	0.535	0.541	0.350	0.535	0.556	0.541
S.D.	0.055	0.099	0.059	0.098	0.055	0.059	0.099	0.098
P	< .0005		< .60		< .0005		< .60	
				Dog 195				
Mean	0.392	0.524	0.577	0.651	0.392	0.577	0.526	0.651
S.D.	0.069	0.121	0.067	0.070	0.069	0.067	0.121	0.070
P	< .005		< .05		< .0005		< .025	
				*Dog 196**				
Mean	0.309	0.354	0.401	0.510	0.309	0.401	0.354	0.510
S.D.	0.008	0.044	0.049	0.024	0.008	0.049	0.044	0.024
P	< .005		< .0005		< .0005		< .0005	

* Animal 196 was transiently hyperinflated to overcome atelectasis. This is a possible cause of the more rapid transport times.

positive injection times. These variations provided a variety of inspiratory flow rates; an average of 11 measurements were made at each flow rate on each of three dogs.

The data for all dogs have been combined in Fig. 1b. The fastest times are found during the fast inspirations with positive injection times (mean time 0.36 second, with individual times as low as 0.30 second). The longest transport times are measured during slow inspiration with negative injection times (mean times 0.56 second, with individual times as long as 0.70 second). Transport times (Table 1) clearly decrease as inspired air velocity increases ($P < .05$). Positive injection times are critical because flow changes rapidly during inspiration; but transit times are unaffected by the length of time that the CO is injected before inspiration.

That the phototube detects the formation of HbCO alone has been confirmed on samples of Hb, HbO_2, and HbCO in vitro. In addition, there is no deflection in the signal when 10 ml of air is injected in place of CO. The animals' arterial oxygen saturation drops 3 to 5 percent over the course of the studies, but there is no evidence that the accumulation of HbCO affects the measurements of transport time because the transport times at the beginning and end of the studies are identical (CO injected during fast inspiration and positive time in both cases).

Because the 5.5-ml bolus of CO is diluted by 350 ml of inspired air and then further diluted by the total lung volume (3400, 3800, and 3900 ml in our animals), it is probable that the phototube does not detect the initial HbCO formed. However, the point read as initial formation of HbCO is less than 1 percent of the peak deflection.

To our knowledge these are the first measurements of pulmonary gas transport times in vivo. It should be emphasized that the transport times were measured from the larynx to the surface of the right lower lobe. An alveolus at an average distance from the mouth probably would receive inspired gas in shorter times than those reported here (*3*).

In order to determine the mechanisms of gas transport it will be necessary to use constant inspiratory velocities and take into account the precise anatomy of the canine airways. Based on the data and calculations of Ross (*3*), Rauwerda (*4*), and Thews (*5*), however, we can make a conservatively small estimate of transport time of 0.8 second for gas transfer by bulk flow in large airways and by still gas diffusion near the alveolus. The transit times we measured were much less than this estimate and therefore imply that gas transport is facilitated by interaction of bulk flow and diffusion, quite possibly in a way similar to that shown by Taylor (*6*).

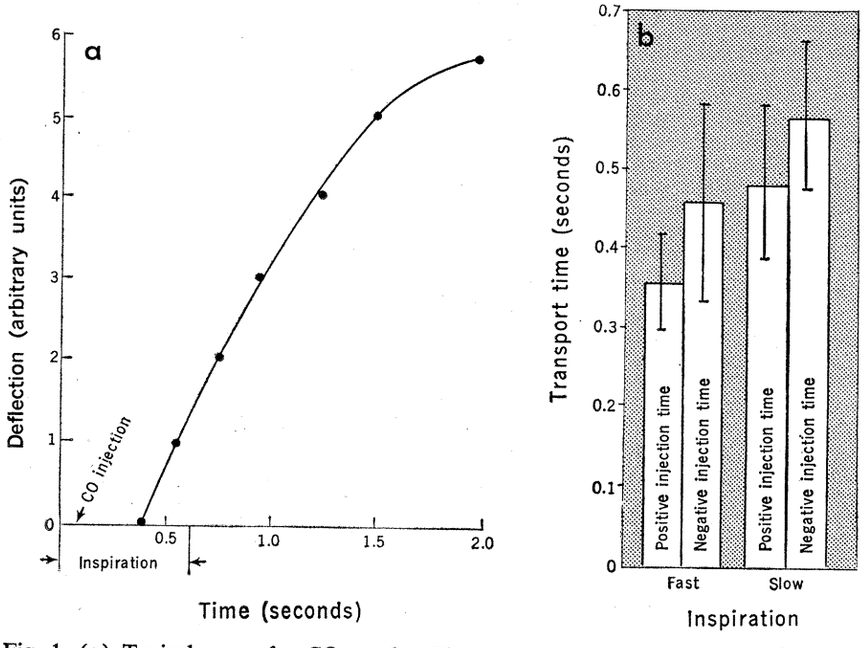

Fig. 1. (a) Typical curve for CO uptake. The sharp departure from base line makes initial formation of HbCO simple to determine. (b) Gas transport times for all animals. Transport times decreased with increased inspiratory flows. Vertical bars are 1 S.D.

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