Laboratory Evaluation of Pressure Differential-Based Respirable Dust Detector Tube

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Assessment of exposure to occupational dusts is a first step in reducing exposures to harmful dust concentrations. A new type of respirable dust sampler was developed and compared side-by-side to personal gravimetric samplers in the laboratory. The new sampler correlates filter back pressure with mass accumulation to provide mid-shift and end-of-shift determinations of cumulative exposure. The sampler uses a small low flow rate pump to draw dust through a small detector tube that contains a porous urethane foam respirable classification section and glass fiber filter that collects respirable dust.

Six different coal dusts were aerosolized in a laboratory dust chamber and a total of 119 triplicate observations were obtained. For individual coal types, the correlation coefficients were between 0.87 and 0.97. The precision of the two methods was similar, with the percent relative standard deviation of the personal samplers of 12 percent and the new detector method of 14 percent. For all coal types tested the data were best described by a power function where $\Delta P = 1.43\ \text{mass}^{0.85}$, with a correlation coefficient of 0.73. The method becomes more accurate at higher dust loadings such that all laboratory data with mass loadings greater than an equivalent concentration of 2 mg/m^3 fall within +/− 25 percent of the power function. Assessment of the method under field conditions is in progress.

Keywords Respirable Dust, Monitoring, Pressure, Mining

Assessment of personal respirable dust exposure is an important step in eliminating many dust-related occupational illnesses and diseases. Sampling dust levels in mining presents unique challenges because of the variable composition of the dusts and the constantly moving workplace that is a result of the removal of the ore.(1) Currently, dust levels in mining are measured either gravimetrically, using filters and the accumulated dust mass in a given quantity of air,(2) or through the use of instantaneous electronic or direct-reading dust monitors.(3) The filter method takes several weeks to process before results are reported to the mine. This time delay, coupled with the ever-changing and moving workplace of the underground mine environment makes the filter measurement useful only as an historical data point. The results do not provide timely feedback to detect or correct excessively dusty conditions. Electronic dust measurement methods that do provide immediate feedback include photometers, beta gauge, and piezobalances. These devices have helped to understand dust generation patterns in mines and have been very useful research tools. Their use for routine personal monitoring, however, is limited due to their complexity, size, and expense.

The objective of eliminating occupational dust diseases by reducing worker dust exposures can be accomplished in a number of ways. Obviously, the establishment of permissible dust exposure limits is a first step. Adoption of these permissible levels into law and enforcing compliance of these levels has been a mainstay of reducing occupational exposures. Good business practices have also led progressive companies to prevent worker illnesses through worker education and adoption of best-available engineering control technologies.(4) Effective monitoring with immediate feedback of exposure results to workers is another method that has shown benefits at reducing exposures in other occupational settings.(5)

In the *Report of the Secretary of Labor's Advisory Committee on the Elimination of Pneumoconiosis Among Coal Mine Workers*,(6) several recommendations deal with the development of continuous respirable dust monitors to help protect workers' health. In addition, the National Institute for Occupational Safety and Health (NIOSH) *Criteria Document*(7) lists improved sampling devices as a research need pertinent to coal miner respiratory health and prevention of disease. Several approaches are being taken to address these needs. These studies include, but are not limited to, a Machine Mounted Respirable Dust Monitor,(8) light scattering dust monitor response,(9,10) pressure drop evaluation of filter media,(11,12) and other novel techniques. One of the principal goals of each of these efforts has been to identify or develop an instrument that will give short-term or real-time measurements of worker dust exposure. Another concern of the committee's report to the secretary was the issue of how to reduce tampering with reported dust results.

The dust detector tube was developed to provide an inexpensive, short-term measurement of the cumulative personal dust exposure of a worker during a shift. The dust detector tube models itself after the concept of a radiation dosimeter or, more precisely, after the sorbent detector tubes used to measure exposure to various gases. The disposable single-use tube contains a respirable size classifier and the pressure drop filter media and can be assembled for a few dollars per tube.

The correlation between filter back pressure and mass is not new.(13) Recent work by Dobrowski et al. using coal and rock dust mixtures at various humidities demonstrated a linear pressure versus mass response for a specific filter medium.(11) Concurrent work on the use of porous foam as a respirable dust classification medium(14,15) lent itself to the disposable detector tube idea. Combining these elements in an appropriately designed tube can detect respirable mass through the pressure increase across the filter. An inexpensive commercially available low-flow pump with integral pressure transducer pulls dust through the device and onto the filter. These devices are economical and could be worn daily to determine dust exposure.

DESCRIPTION OF DEVICE

The dust dosimeter is analogous to a conventional gas detector tube in that a small, low flow rate pump is used to pull a sample into a small-diameter tube where the dust is sized and deposited onto a filter. A uniform dust mass loading results in a proportional pressure increase across the filter. Any pressure transducer or one integral with the pump can be used to correlate with filter mass. After the detector tube has been used to make a measurement, the tube can be discarded, and a fresh tube used for the next measurement. Dust enters the inlet of the detector tube, illustrated in Figure 1, through a 6.3-mm-diameter by 8-mm-length of polyurethane open-cell foam (Type S, Filtercrest^{TM} from [PCF Foam Corp., Hamilton, Ohio) with a density of 50 pores per inch (ppi). This segment filters out oversized non-respirable particulate and protects the main classifier from plugging with oversize material. The tube narrows to a 4.0-mm-diameter section that contains a 25-mm-length of 90 ppi open-cell urethane foam that collects the non-respirable dust and passes the respirable fraction of the dust.

Dust penetration characteristics of the 90 ppi foam section were compared to the Dorr Oliver 10-mm-diameter nylon cyclone. This comparison was done by first measuring the penetration characteristics of the cyclone and fitting the data into the form of the International Standards Organization (ISO) respirable dust equation(16) with minor modifications. This was done to facilitate the comparison of the foam penetration to that of the cyclone. The nylon cyclone respirable mass fraction (RMF) is defined as:

$$\begin{aligned} \mathrm{RMF} &= [\mathrm{SI}(d)][1 - 0.5\{1 - \mathrm{erf}(-x)\}] \\ \text{where } x &= \frac{l\eta(d/\Gamma)}{l\eta\Sigma}, \text{ and where} \\ \Gamma &= 4.25\ \mu\mathrm{m},\ \Sigma = 1.25, \text{ and the inhalable fraction} \\ \mathrm{SI}(d) &= 0.5(1 + e^{-0.11d}) \end{aligned} \qquad [2]$$

Data from the foam penetration study was found to closely approximate this equation when the flow rate through the tube was 250 ml/min.(17)

The flow path of the classified respirable fraction of the dust now gradually expands in the detector tube to 6.3-mm diameter and travels 55 mm, or about eight tube diameters, to uniformly deposit onto the collection filter. The respirable dust deposits onto an 8-mm-diameter Pallflex Fiberfilm T60A20 fluorocarbon-coated glass fiber filter supported by a porous fiber backup pad. The filter holder was constructed from a compression tube fitting that was bored to 9.53 mm, the same outside diameter as the glass tube. Figure 1 shows the detector tube and the glass tube to filter interface held in place with a flanged, barbed nylon tube fitting compressed onto the backup pad.

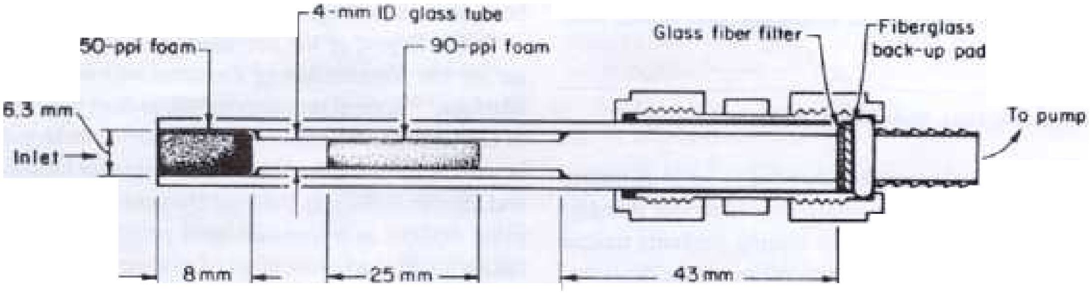

FIGURE 1
Dust detector tube.

A commercially available low flow rate air sampling pump with integral pressure transducer was used to monitor the pressure increase with mass loading. The pump had flow capacity up to 250 ml/min. The battery supplies eight hours of power when run at 200 ml/min at 10 inches water gauge. The combination of this pump with the dust detector tube comprises the new dust dosimeter that was tested.

METHODS AND MATERIALS

A direct comparison between dust concentrations determined by personal gravimetric samplers and the pressure increase of the dust dosimeter was made in a laboratory dust chamber by comparing the means of triplicate measurements of each type of sampling device. The relative standard deviation of each triplicate grouping was also determined. These measurements were then plotted and least squares regression analysis used to determine the correlation equations.

Personal Gravimetric Samplers

Flow-controlled personal sampling pumps operated at a flow rate of 1.7 lpm were used to sample coal dust aerosols from the laboratory aerosol chamber. Dust was classified using 10-mm nylon Dorr-Oliver cyclones and deposited onto standard coal mine sampling cassette filters. Filters were pre- and post-weighed at the Pittsburgh Research Laboratory (PRL) under controlled atmosphere conditions. Filters were prepared without the tamper-resistant backflow valve or the inner stainless steel support wheel. Pump flows were checked weekly with a Gilian Bubble Flow Meter, a primary standard flow measurement device. A total of nine personal samplers were arrayed for each test in groups of three so that each grouping was evenly spaced about the central portion of the chamber at about the same elevation.

Dosimeters

Flow-controlled sampling pumps manufactured by SKC Inc. (Pocket Pump^{TM}) were operated at a flow rate of 0.250 lpm to draw coal dust aerosols into the dust detector tubes. Clean dust detector tubes were prepared with the size-selective foam classifiers and new collection filters. A total of six dust dosimeters were used for each test and divided into groups of three that were arrayed in the test apparatus in an alternating pattern around the central portion of the chamber and at a similar elevation to the personal samplers.

The pump pressure transducer measures the pressure of the entire detector tube, including the two porous foam sections. The contribution to the total pressure from the foams was determined by measuring the pressure restriction of the combined foam sections before and after testing during heavy dust loading conditions. A slant tube manometer was used to measure the pressure at 0.250 lpm. Pressure drop through the interconnecting tubing at this low flow rate was negligible.

Test Aerosols

Six different coal dust aerosols from various sources were used in the study. Coal from the Pittsburgh, Illinois #6, Upper Freeport, Pocahontas, and Beckley A seam, were ground to minus 325 mesh size. One of the Beckley A seam coal samples was doped with a 10 percent by mass Minu-Sil (U.S. Silica Corporation, Berkley Springs, West Virginia) ground silica. Dusts were aerosolized using a TSI fluid bed generator and disbursed in a 1 m^3 aerosol chamber. The aerodynamic size of each coal aerosol was measured with an Anderson 298 Personal Impactor operated at a flow rate of 2 lpm for time periods between 0.75 and 2 hours to obtain optimal stage loadings. Impactor substrates were coated with Dow Corning 316 Silicone Release Spray 24 hours prior to pre-weighing. Substrate weights were measured using procedures similar to the filter weighing. Size distributions were calculated and reported as the mass median aerodynamic diameter (MMAD) and geometric standard deviation(GSD).

Test Procedure

All sampling inlets were arrayed in the central portion of the test chamber facing toward a central point in the chamber. Previous studies of the chamber showed little spatial variability (less than 5%) within the central portion of the chamber. Sampling heads were connected to their respective pumps through short sections of flexible plastic tubing that passed through a bulkhead manifold.

The fluidized bed dust generator was loaded with the coal to be tested and run for a minimum of one hour or until a light-scattering photometer inside the chamber indicated that an equilibrium concentration had been reached. All personal sampling pumps and dosimeter pumps were then started. Initial back pressures from the dosimeter pumps were recorded. At 10-minute intervals the dosimeter pump pressures and the photometer dust concentration were recorded.

At one-hour intervals, groups of three personal sampling pumps were switched off. The mass loadings for each grouping of three personal samplers were averaged and the mean and standard deviation reported. Each test lasted for a total of three hours. The pressure readings of the dosimeter pumps were recorded and the initial pressure subtracted to determine the cumulative pressure increase caused by the dust loading for each time interval. Each group of three dosimeter pumps was averaged for each hour interval and the mean and standard deviation reported.

Each three-hour test yielded six results (two groups of three dosimeters times three gravimetric sampling intervals). This test sequence was repeated at least three times for each of the six coal types tested for a total of 109 observations. An additional 10 observations were made with the Beckley A seam coal to obtain heavier dust loadings by sampling for eight hours. During one test within each coal type, a personal impactor sample was taken after the first hour of the test to determine the MMAD of the aerosol in the chamber.

Analysis

Preliminary data analysis was made by comparing the cumulative dust concentrations as determined by the light-scattering photometer with the cumulative pressures recorded by the

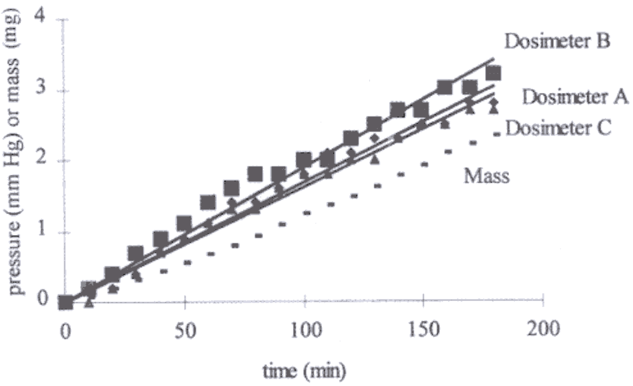

FIGURE 2

Typical individual test showing the precision of three individual dosimeter tubes response to cumulative respirable dust loading.

dosimeter pumps. The photometer readings were normalized to the gravimetric mass for each test at 10-minute intervals by using the average mass from the three-hour personal gravimetric samplers as the correct cumulative mass for that test. This analysis compares the cumulative performance between individual detector tubes. Data was analyzed to calculate the average increase in detector tube pressure of three dosimeters and compared to the average personal gravimetric sampler mass at hourly intervals. The respective relative standard deviations (RSD) were also calculated. Regression analysis used Excel calculation functions to compute power and linear analysis of the dosimeter pressure versus personal gravimetric sampler mass. Error bars were computed based on one standard deviation from the mean.

RESULTS AND DISCUSSION

This testing covered a range of concentration equivalents from about 0.1 to 2 times the MSHA permissible exposure limit (PEL) of 2 mg/m^3.$^{(18)}$ Dust mass loadings for the testing covered a range from 0.23 to 3.42 mg. This is equivalent to an eight-hour concentration range from 0.28 to 4.19 mg/m^3. Not all coal types covered the entire range.

For each test sequence, the cumulative pressure from the dosimeters and the cumulative mass, determined from the gravimetrically corrected light-scattering measurements, were plotted versus time. A typical test result is shown in Figure 2 where the three dosimeters can be seen to follow similar trends. When cumulative pressure is plotted as a polynomial expression, the regression coefficients are better than 0.99. The step like function in the pressure accumulation in the figure is an artifact of the low-precision output from the pump pressure digital transducer. A more precise pressure transducer should help to improve the accuracy and precision. The drift in dust feed to the chamber can also be seen in the slight non-linear cumulative mass data. The comparison between the personal sampling method and the dosimeter method was determined for each coal type. The average mass, measured by personal sampling pumps for one-, two-, and three-hour intervals was plotted against the corresponding average dosimeter pressure increase.

The *x* error bars represent one standard deviation in accuracy of the personal sampler mass measurement and the *y* error bars represent the accuracy of the dust dosimeter pressure measurement. These errors demonstrate the variation in precision of both the reference personal sampling method and the new dust dosimeter. The average RSD of the data presented in Figure 3 is 9.71 percent for the personal samplers and 11.11 percent for the dosimeters. The best fit of the data follows a power function

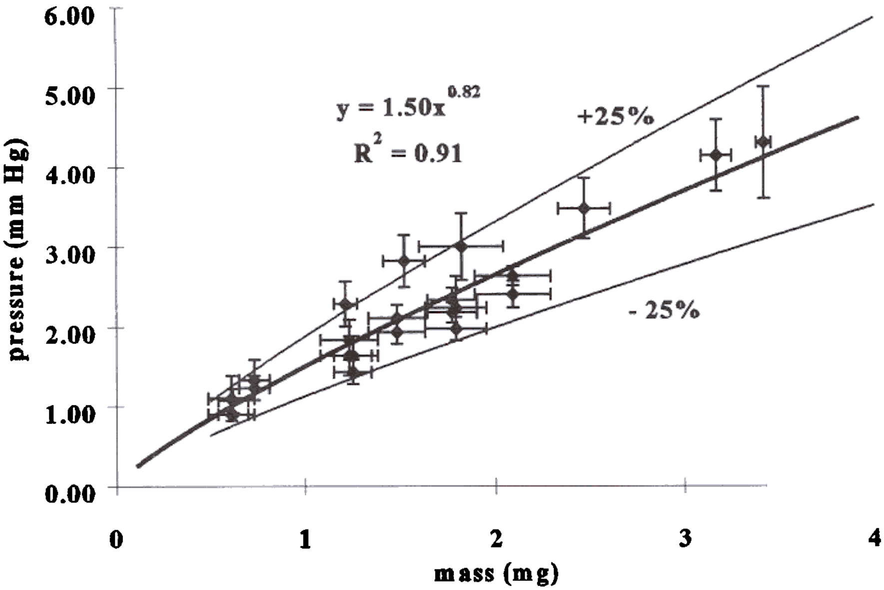

FIGURE 3

Pressure to mass correlation for Beckly A seam coal.

TABLE I
Summary of laboratory correlation data and aerodynamic size distributions

					Size distribution	
Coal type	Power function $y =$	R^2	Personal sampler RSD	Dosimeter RSD	Mass median aerodynamic diameter (μm)	Geometric standard deviation
Beckley A seam	$1.50x^{0.82}$	0.90	9.71	11.11	5.59	2.33
Beckley A seam + silica	$1.74x^{0.69}$	0.87	10.89	10.26	5.19	2.38
Pittsburgh	$0.87x^{0.87}$	0.90	16.37	17.73	4.99	2.31
Illinois #6	$2.10x^{0.60}$	0.94	7.74	9.04	3.62	2.20
Upper freeport	$1.10x^{0.82}$	0.91	13.78	24.79	5.36	2.15
Pocohontas #4	$1.72x^{0.74}$	0.97	12.77	10.81	4.92	2.24
All data	$1.43x^{0.85}$	0.73	11.83	13.96		
(+ 50%)	$2.16x^{0.85}$					
(− 50%)	$0.72x^{0.85}$					
(+ 25%)	$1.80x^{0.85}$					
(− 25%)	$1.08x^{0.85}$					

where y, the differential pressure, $= 1.50x^{0.82}$ where x is the mass. Accuracy of the method may be interpreted through the +/− 25% functions also plotted on the graph.

Data in Table I summarize the results for individual coal types and for all 119 tests. In general, the RSD for personal samplers is lower than the corresponding RSD for the dosimeter. This difference may be reduced by using a more sensitive pressure transducer in the dosimeter pump. Note that for individual coal types a regression coefficient of 0.87 or greater is achieved. However, as can be seen from the power function equations, there remains a range of correlations between pressure and mass from pressure $= 0.87 \times \text{mass}^{0.87}$ to pressure $= 2.10 \times \text{mass}^{0.60}$. This range in response to individual coal types results in a lower regression coefficient for all data.

The effect of the porous foam precollector in series with the pressure measuring filter is minimal. Table II shows the clean and loaded pressures of the combined 50 and 90 ppi foam for the heavily loaded, eight-hour, Beckley A coal tests. Increases in pressure attributable to the foams of 0.14 and 0.18 mm Hg compare to total pressure increases of 4.14 and 4.30 mm Hg increases in the total detector tube. This is less than 4 percent of the total pressure increase for dust loadings, nearly twice the PEL.

The functional relationship between pressure and mass may be dependent on the size of dust being sampled. Dobrowski et al. reported that the different pressure response of various coals was attributable to different sizes of the collected dust, reasoning that smaller-sized dust mechanically restricts air flow at a greater rate than an equivalent mass of larger-sized dust.

Their technique used variable flow rates through a cyclone to alter the size distribution of the collected dust. Thus the dust deposited on the filter was not equivalent to a defined respirable fraction. This study, however, directly compared the respirable mass fraction defined by the cyclone with the respirable mass fraction defined by the porous foam. Thus, similar size fractions were being compared. The MMAD data of the various test aerosols shown in Table I range from 3.6 to 5.6 micrometers. This range of size variability did not appear to correlate with the different functional response between pressure and mass. From an applications viewpoint, the dust dosimeter comparison

TABLE II
Pressure increase of combined 50 and 90 ppi foam attributable to dust loading during heavy loading with Beckley A coal

	Pressure		
Tube no.	Pre loading mm Hg	Post loading mm Hg	Pressure difference mm Hg
1	0.41	0.60	0.19
2	0.45	0.60	0.15
3	0.41	0.56	0.15
4	0.45	0.60	0.15
5	0.41	0.48	0.07
6	0.41	0.56	0.15
Average			0.14
7	0.41	0.63	0.22
8	0.41	0.56	0.15
9	0.37	0.56	0.19
10	0.37	0.56	0.19
11	0.41	0.60	0.19
12	0.45	0.60	0.15
Average			0.18

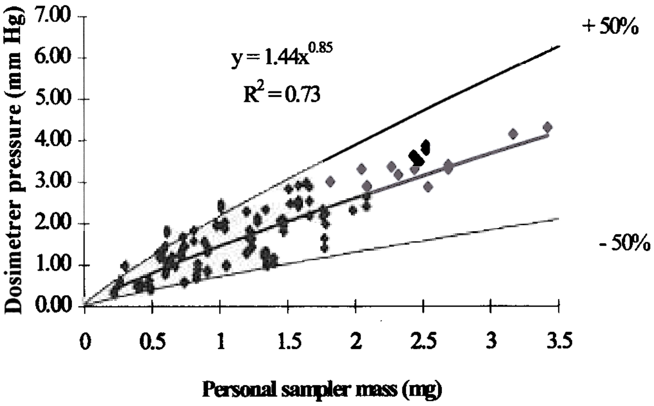

FIGURE 4

Correlation of all laboratory data of pressure with mass.

to personal samplers must work underground where MMADs are expected to be on the order of 7 to 20 micrometers in size, depending on the mining method.(19) Additional field comparisons between personal samplers and dosimeters is underway to answer the question of comparison with typical underground size distributions. For this laboratory work there was no apparent dependence on the functional relationship between pressure and mass attributable to different size distributions.

Despite the variability of individual coal type response, Figure 4 shows that the laboratory response of the dust dosimeter approach provides a qualitative tool to evaluate exposure to a number of respirable coal dusts. As dust concentrations increase, the accuracy of the method improves such that measurements above 1.7 mg (2 mg/m^3) fall within +/− 25% of the laboratory functional curve. Additional research on the variability of coal type of pressure response may help to improve the accuracy of the technique.

The question of accuracy versus cost is pertinent to an overall evaluation of any new respirable dust assessment technique. The low-cost approach of the dosimeter lends itself to an increased number and frequency of samples that can be taken. Furthermore, the cumulative shift personal dust exposure will be immediately available to workers. This can enable quick corrections to procedures or dust controls to immediately reduce dust exposure. Direct availability of the data to the workers may also help to reduce tempering with exposure data. The reduced size, weight, and noise level of the new pumps may also encourage better worker acceptance of the new technique. Even though more accurate methods may be possible, and indeed beneficial for certain applications, that level of accuracy may not be required for routine monitoring of many workplace environments. Improved accuracy may be of less importance when all other benefits are considered.

CONCLUSION

A new respirable dust sampling device has been developed based on the principle of the correlation of pressure restriction of a filter with increasing mass loading. The laboratory comparison of this technique with conventional personal gravimetric sampling showed good correlation for individual coal types and good correlation at higher mass loadings for all coal types. The advantages of this new approach to dust sampling include the immediate availability of the cumulative shift dust exposure, a significant reduction in size of the instrumentation that a person must carry to evaluate their respirable dust exposure, and lower cost per sample. The dust detector tube requires field verification to assure that issues of variable particle size, shape, concentration, humidity, or other environmental factors do not substantially alter the pressure versus mass response.

Protection of workers' respiratory health depends on many factors. Dust assessment tools for engineering control development and compliance determination are available.

Another potentially powerful tool to help improve workers' health may be the empowerment of the worker and management with the timely knowledge of what current dust exposures are routinely occurring. The inexpensive dust detector tube may provide the knowledge that helps workers protect their respiratory health.

DISCLAIMER

References to commercial products are for informational purposes and do not imply endorsement by the Centers for Disease Control and Prevention.

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