Anesthesiology
59:435–439, 1983

Monitoring Anesthetic Vapor Concentrations Using a Piezoelectric Detector: Evaluation of the Engstrom Emma

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The Engstrom anesthetic gas analyzer (EMMA) was evaluated to determine the reproducibility, response time, gas interference, water vapor dependence, and sensitivity. The analyzer also was evaluated clinically in 20 children undergoing orthopedic surgery. Difference between the analyzer output and anesthetic gas standard (reproducibility) ranged from 0.013 ± 0.008 vol % to 0.018 ± 0.018 vol %. Response times decreased from 710 ms at 5 l·min^{-1} to 149 ms at 30 l·min^{-1}. Nitrous oxide caused an offset of +0.11 ± 0.007 vol %. Water vapor caused positive offsets of 0.25 ± 0.044 vol %, 0.51 ± 0.027 vol %, and 0.80 ± 0.037 vol % at 25°C, 30°C, and 34°C, respectively. The analyzer reproducibly measured dry gas concentrations, but compensation had to be made for water vapor when measuring wet gases. The analyzer's usefulness for end-tidal monitoring was questioned because of its slow response time and its sensitivity to water vapor. (Key words: Monitoring: anesthetic gas, end-tidal, vapor concentration. Equipment: piezoelectric transducer.)

ANESTHETIC VAPOR CONCENTRATION can be measured by infrared absorption, gas chromatography, mass spectroscopy, or elasticity of silicon rubber strips (Narkotest). These analysis techniques have not found wide acceptance clinically because of size, complexity, expense, or instability. Engstrom§ (Bromma, Sweden) has developed a new multigas monitor for anesthesia, trade-named EMMA (fig. 1). This relatively inexpensive in-circuit analyzer measures halogenated anesthetic gases using a piezoelectric quartz crystal.[1–3]¶ We performed laboratory and clinical testing to determine the reproducibility, response time, gas interference, water vapor dependence, and sensitivity of the Engstrom analyzer.

Theory of Operation

A bare quartz crystal in an electrical field will vibrate at a natural resonant frequency.[1,2]¶ If a quartz crystal is coated with a lipophilic layer and exposed to halogenated anesthetic gas, the crystal's natural resonant frequency will decrease in proportion to the partial pressure of the anesthetic gas surrounding the coated crystal.[3] The Engstrom analyzer uses this principle for measurement of in-circuit anesthetic gas concentration. The concentrations of halothane, enflurane, isoflurane, tricloroethylene, or methoxyflurane are displayed in volumes per cent (vol %). The transducer is not specific to each agent.

The front-panel selector switch merely changes the electronic gain of the analyzer, depending upon the agent used. The Engstrom EMMA has a function similar to the familiar Draeger Narkotest; however, the Narkotest depends upon solubility of halothane in silicon rubber strips resulting in a change in tension, whereas the Engstrom gas analyzer depends upon adsorption of halogenated gas onto a lipophilic layer covering a quartz crystal.[4]

Methods and Materials

LABORATORY (IN VITRO) EVALUATION

Reproducibility was measured using a single EMMA analyzer and the four gas standards listed in table 1 (Liquid Carbonic Corporation). Following a 1-h warm-up period, the analyzer was zeroed in a 10 l·min^{-1} oxygen flow and then calibrated with one of the gas standards. The transducer was exposed to the gas standard used for calibration, and after 3 min, a recording was made of the analyzer output on a strip chart recorder (Linear Instruments, Inc.). The analyzer was placed in a 10 l·min^{-1} oxygen flow and zeroed after three min. This procedure was repeated 20 times. The entire procedure with 20 repetitions was repeated for each of the four gas standards.

Response times were measured for dry and wet gases and for water vapor. Response time was measured following a step change in anesthetic gas concentration and was defined as the time taken for the analyzer output to change between 10% and 90% of the step change. Response times were measured using 2% enflurane, 2% halothane, and water vapor at flow rates of 5, 10, and 15 l·min^{-1}.

A three-way solenoid valve (Automatic Switching Co., switching time: 5 ms) placed 15 cm from the transducer was used to generate the step change. One valve inlet was connected through a flow meter (Puritan) to a 35 psi oxygen supply. The other inlet was connected to either a halothane vaporizer (Foregger), enflurane vaporizer

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Received from the Department of Anesthesiology, University of Utah, Salt Lake City, Utah. Accepted for publication March 16, 1983.

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¶ King WH: Using quartz crystals as sorption detectors. Part 1 Res/Dev: 28–33, 1981.

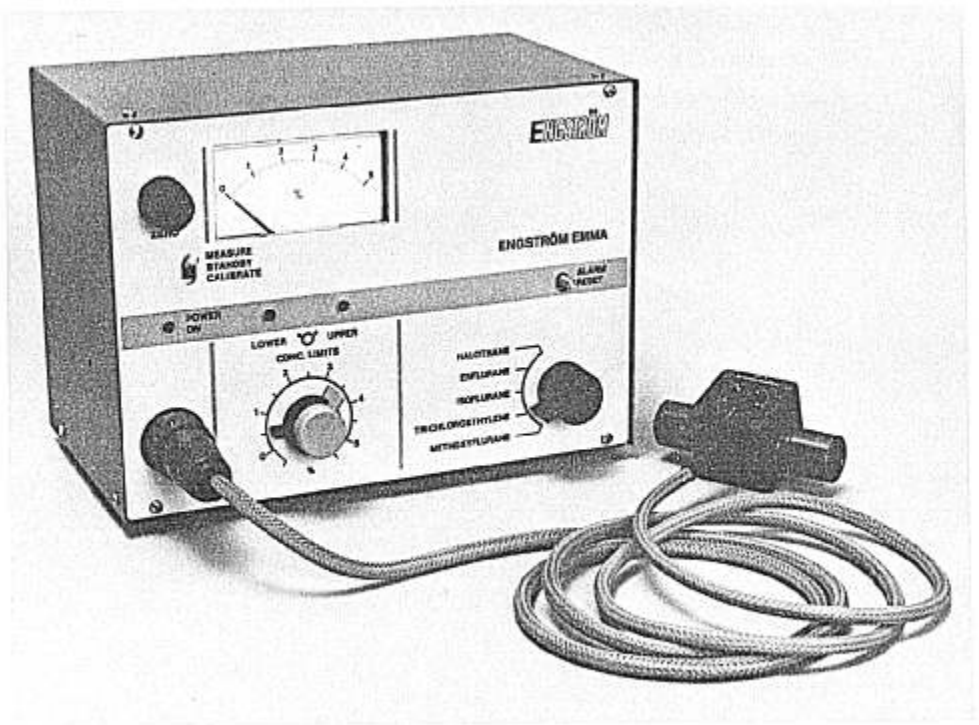

FIG. 1. Engstrom Multigas Monitor for Anesthesia (EMMA) with incircuit transducer.

(Cyprane), or a humidifier (Aquamid) at 25°C. Oxygen at the specified flow rate was used as the carrier gas through the vaporizers or humidifier. The valve switching triggered a storage oscilloscope (Tektronix D13), which displayed the analyzer's response to the step change. Response times were measured from the oscilloscope display.

Twenty step responses were measured for each gas. Dry gases from the vaporizers were introduced into a dry transducer to measure dry gas resonse times. Before measuring wet gas response times, gas from the vaporizer passed through a humidifier for 15 min to allow gas–water equilibrium. Saturated air at 25°C was introduced into the transducer to insure humidification. The measured response time was response to gas concentration change and not humidity change. The response time to a step change in water vapor concentration was measured by switching between dry and wet oxygen. The transducer was dried for 10 min using a 10 $l \cdot min^{-1}$ flow of oxygen before introducing a water vapor step change.

TABLE 1. Anesthetic Gas Standard versus Analyzer Output

Gas Standard (vol %)	Analyzer Output (vol %)	Difference* (vol %)	Error† (% of reading)
2.00 enflurane 98.0 oxygen	2.01 ± 0.025	0.018 ± 0.018	0.9 ± 0.90
1.82 enflurane 39.0 oxygen Balance N_2O	1.84 ± 0.013	0.013 ± 0.008	0.71 ± 0.44
0.75 halothane Balance oxygen	0.761 ± 0.051	0.014 ± 0.013	1.87 ± 1.73
0.981 halothane 39.0 oxygen Balance N_2O	0.994 ± 0.023	0.018 ± 0.015	1.83 ± 1.53

Mean value ± one standard deviation.
* Difference between analyzer output and anesthetic gas standard.
† Error (% of reading) calculated as:

$$\frac{\text{analyzer output-gas standard}}{\text{gas standard}} \times 100.$$

Sensitivity to nitrous oxide, 5% CO_2, air, and nitrogen was measured. After zeroing the analyzer in oxygen, a 5 $l \cdot min^{-1}$ flow of one of the above gases passed through the transducer. After 3 min, the analyzer offset caused by each gas was measured from strip chart recordings with the Engstrom selector switch in the halothane position. The measurement was repeated 16 times for each gas, zeroing with oxygen between each of the 16 measurements.

Water vapor dependence was measured using water-saturated oxygen. A 10 $l \cdot min^{-1}$ oxygen flow passed through an Aquamid humidifier at 25°C, 30°C, or 34°C. Oxygen flow passed directly from the humidifier into the transducer. The flow was continued for 15 min to achieve a steady state temperature before making measurements. The analyzer output was measured from stip chart recordings with the selector switch in the halothane position. Measurements were repeated five times for each temperature. Between measurements the transducer was dried for 15 min using a 10 $l \cdot min^{-1}$ flow of dry oxygen. The water vapor data was analyzed using least-squares linear regression analysis.

The effect of the analyzer's agent selector switch was measured by comparing the analyzer output reading with the selector switch in the halothane position with the

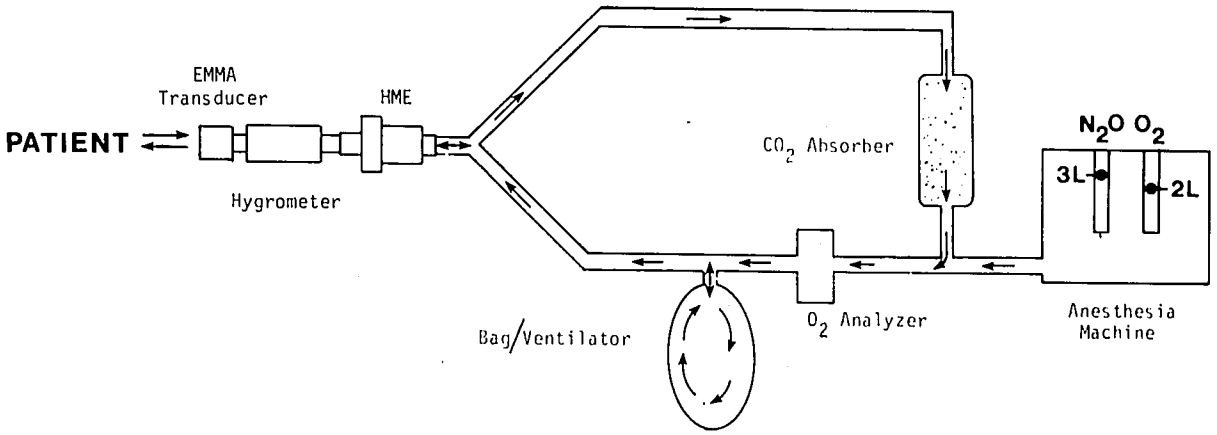

FIG. 2. Clinical test circuit showing orientation of transducer, hygrometer, and heat moisture exchanger within the patient's breathing circuit.

output reading in the enflurane, isoflurane, tricloroethylene, or methoxyflurane position. Various concentrations of enflurane, isoflurane, tricloroethylene, and methoxyflurane were generated by mixing a known flow of oxygen through a copper kettle vaporizer with a 2 $l \cdot min^{-1}$ oxygen flow. When steady state was reached, the analyzer selector switch was changed from the halothane position to the position for the agent being vaporized. The analyzer output was recorded in both positions. Six concentrations were generated for each agent by varying the flow of oxygen through the vaporizer. Linear regression analysis was used for comparing the sensitivity with each agent with the sensitivity to halothane.

CLINICAL MEASUREMENT OF WATER VAPOR SENSITIVITY

The analyzer was used to monitor anesthesia delivery to 20 children (six–16 yr) during orthopedic surgery. Each child's trachea was intubated following iv administration of thiopental and pancuronium. Anesthesia was maintained for approximately 15 min with 60% N_2O–40% O_2. The Engstrom analyzer transducer and in-circuit hygrometer (Hygrodynamics, Inc.) were placed in series (fig. 2). Two thermistors (Mon-a-Therm) were placed within the hygrometer transducer housing to measure gas temperature. The Engstrom analyzer was turned on 1 h before use and zeroed with a 60% N_2O–40% O_2 gas mixture. Fresh soda lime CO_2 absorber was used for each surgical procedure. The Engstrom analyzer offset, gas temperature, and humidity were recorded after approximately 15 min of N_2O–O_2 anesthesia. The data were analyzed using linear regression analysis to show the effect of humidity on analyzer offset. The Student's *t* test was used to compare the slopes for the laboratory bench data and clinical data.

Results

The Engstrom analyzer reproducibly measured dry anesthetic vapor concentration. The average difference between the analyzer reading and known gas standards along with the average error can be seen in table 1.

Response time decreased with increased flow rate (table 2). Response times were similar for halothane and enflurane but increased by approximately 15 ms when wet gases were used. The response time to a step change in water vapor concentration was slower than the response to a change in anesthetic vapor concentration.

The analyzer was sensitive to N_2O. When exposed to 100% N_2O, an output of $+0.11 \pm 0.007$ vol % halothane was seen. Exposure to nitrogen, air, and carbon dioxide resulted in outputs of -0.014 ± 0.003, -0.005 ± 0.002, and $+0.014 \pm 0.004$ vol % halothane, respectively.

The average positive offset caused by water vapor was 0.25 ± 0.044 vol % at 25°C, 0.51 ± 0.027 vol % at 30°C, and 0.80 ± 0.037 vol % at 34°C. This offset can be expressed as a function of the saturated gas temperature:

$$\text{Offset (vol \% halothane)} = 0.061 \times (\text{gas temp °C}) - 1.28$$

with $r^2 = 0.99$ (dashed line in fig. 3).

TABLE 2. Wet and Dry Response Times

Gas	Flow Rate (L/min)	Dry Response Time 10–90% (sec)	Wet Response Time 10–90% (sec)
2% Enflurane	5	0.58 ± 0.02	0.63 ± 0.02
	10	0.25 ± 0.01	0.28 ± 0.02
	15	0.16 ± 0.01	0.18 ± 0.01
2% Halothane	5	0.71 ± 0.07	0.78 ± 0.04
	10	0.26 ± 0.02	0.30 ± 0.01
	15	0.17 ± 0.01	0.18 ± 0.01
	18	0.163 ± 0.003	
	24	0.150 ± 0.005	
	30	0.149 ± 0.009	
Water Vapor 23 mg/L	5		13.2 ± 1.44
	10		7.32 ± 0.34
	15		3.22 ± 0.33

Mean ± one standard deviation.

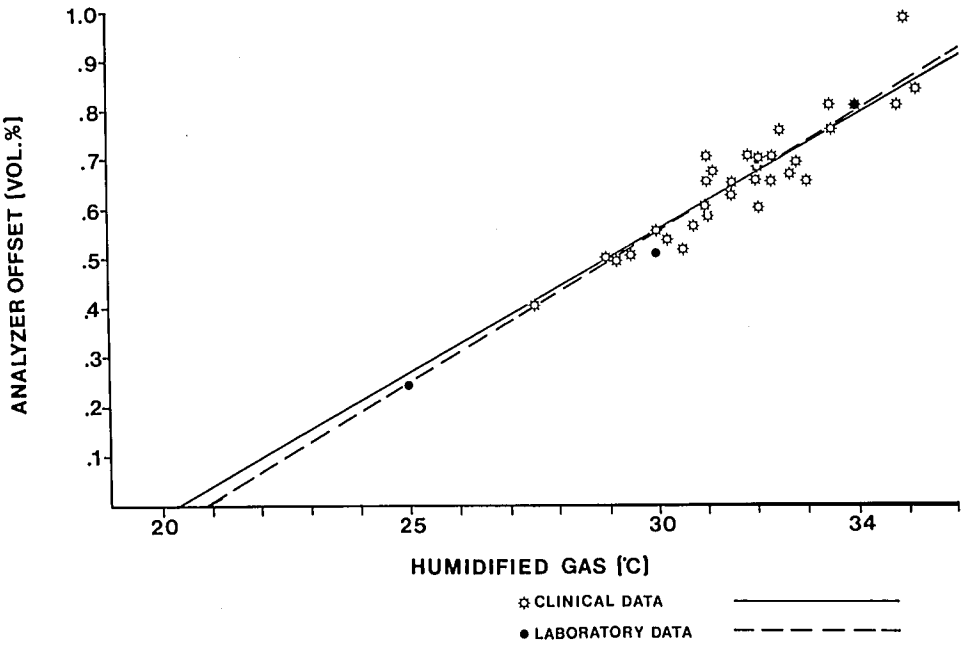

FIG. 3. Scatter-plot showing the analyzer's output in volume % halothane when exposed to water-saturated gas at the temperature shown. The results from laboratory bench testing are shown by the solid dot and dashed linear regression line. Results from clinical testing are shown by the open circles and solid regression line.

The offset measured during clinical use can be expressed as:

Offset (vol % halothane)

$$= 0.057 \times (\text{gas temp } °C) - 1.28$$

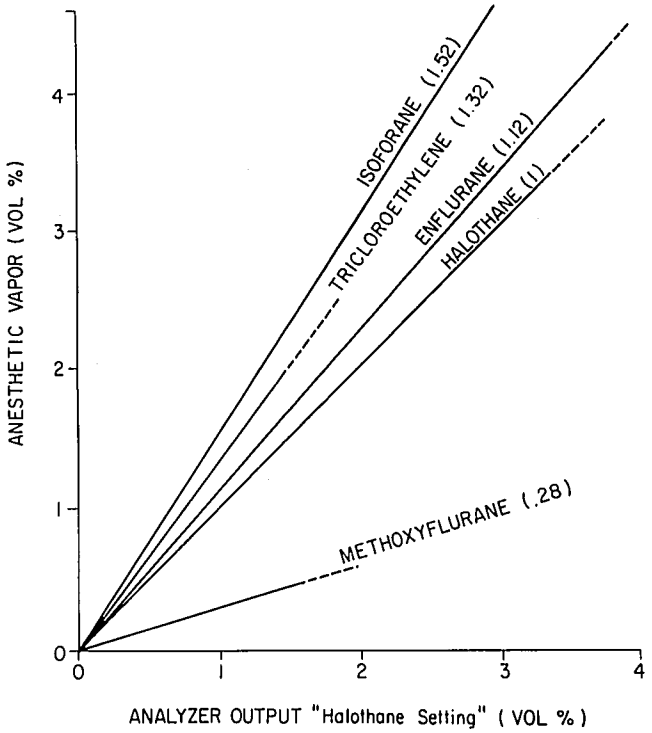

FIG. 4. Effect of the agent selector switch on the output reading. The abscissa shows the analyzer output with the selector switch in the halothane position. The ordinate shows the corresponding analyzer output with the selector switch in the appropriate position for the agent begin vaporized. The number in parentheses is the slope of each line.

with $r^2 = 0.88$ (solid line fig. 3). There was no significant difference between the slopes from the laboratory and clinical measurements ($P = 0.4$). Over the range 25°C–35°C, the water vapor effect can be expressed as the ratio of change in offset over the change in saturated gas temperature: 0.06 vol % halothane/°C.

Sensitivity to common anesthetic agents is shown in fig. 4. The slope of each line defines the change in analyzer gain when the selector switch is turned from halothane to the agent of choice.

The Engstrom EMMA transducer weighs 160 g, has a dead space of 13 ml, resistance to flow of 1 cm H_2O at 1 $l \cdot s^{-1}$.** In our experience the analyzer was not affected by electrosurgical equipment.

Discussion

An anesthetic gas monitor would be useful clinically to monitor the agent vapor concentration delivered by the anesthesia machine, to measure average breathing circuit concentrations, and to measure end-tidal concentrations.[3] The Engstrom analyzer reproducibly measured dry anesthetic vapor concentrations, making it a useful instrument for measuring vaporizer accuracy and anesthesia machine function.

To accurately measure average inspired or average expired anesthetic gas concentrations, the analyzer must be insensitive to other respiratory gases. The Engstrom analyzer was sensitive to N_2O and water vapor. N_2O caused a positive offset of 0.11 vol % halothane in 100% N_2O. Water vapor caused a positive offset of approxi-

** Engstrom EMMA Users Information Manual, Engstrom, Bromma, Sweden.

mately 0.8 vol % halothane when used in saturated air at 34°C. When the analyzer is used clinically, the N_2O and water vapor offsets can be subtracted by turning the zero offset adjustment on the analyzer's front panel. The analyzer then will read correctly if the N_2O concentration and water vapor partial pressure remain constant.

The water vapor offset is caused by adsorption of water on the lipophilic layer covering the quartz crystal. This results in a mass increase with a corresponding shift in the crystal's natural resonant frequency. The transducer is heated to 50° to reduce the water vapor effect. Heating does not solve the problem. Engstrom, therefore, suggests placing a heat moisture exchanger (HME) between the analyzer's transducer and the breathing circuit "Y" piece. According to Engstrom, the Portex Humid-Vent, Terumo Breath-Aid, or Siemens-Elema Servo Humidifiers will reduce the interference due to water vapor by 35%, 35%, and 80% respectively.†† The HME helps stabilize temperature and humidity fluctuation present during inspiration and expiration, but the water vapor offset still must be removed using the analyzer zero adjustment. Our experience with the Siemens HME suggest that in a semiclosed breathing circuit with a fresh gas flow of 5 $1 \cdot min^{-1}$, humidity and temperature equilibrium will be reached in 10 min, after which it is appropriate to zero the offset.

For end-tidal monitoring of anesthetic gases, the analyzer should have a response time of approximately 50 ms.[3] The overall response time of the analyzer can be separated into three phases: phase 1, the wash-in and wash-out of the sample chamber; phase 2, the diffusion of halogenated gas through the boundary layer immediately above the lipophilic substrate; and phase 3, the adsorption of halogenated gas onto the lipophilic layer surrounding the quartz crystal.[3] Because the diffusion and adsorption phases are much faster than the wash-in/wash-out phase, the response time will be limited by wash-in/wash-out at low flow rates. As flow rates increase, the wash-in/wash-out phase will decrease until response time becomes flow independent. It should be possible to find a flow rate above which further increases in flow rate would cause no further decrease in analyzer response time. The response at this flow would represent the analyzer's true response time.

†† Gedeon A, Hamilton K, Kindlund A, Lundstrom I, Mebius C, Haggmark S, Reiz S: A new sensitive method for breath-by-breath monitoring of anaesthetic gases. Anaesthesiology, Proceedings of the 7th World Congress of Anaesthesiologists, Edited by Zindler M, Rugheimer E. Amsterdam-Oxford-Princeton: Excerpta Medica, ICS No. 538, 1980.

As the dry gas flow rate increased from 5 $1 \cdot min^{-1}$ to 30 $1 \cdot min^{-1}$ the response time decreased from 0.71 sec to 0.149 sec (table 2). A response time plateau was reached at 24 $1 \cdot min^{-1}$. Increasing the flow rate to 30 $1 \cdot min^{-1}$ resulted in no significant change in analyzer response time. Because the minimum response time appears to be approximately 150 ms, the analyzer may be acceptable for end-tidal monitoring in adults with normal respiratory rates and the absence of pulmonary disease.

When the analyzer is used for end-tidal monitoring, the changes in water vapor concentration within each breath must be considered.[5,6] If the analyzer offset is zeroed at end-expiration and if the end-tidal water vapor content remains constant throughout the monitoring period, the water vapor effect may be compensated. However, because of the long time constant seen following a step change in water vapor content (3.2 sec at 15 $1 \cdot min^{-1}$), the variation in water vapor content within each breath may cause the end-tidal measurement to be questionable.

In summary, the Engstrom analyzer will reproducibly measure dry anesthetic gas concentrations. Average inspired or average expired breathing circuit concentrations also may be measured accurately when compensation is made for the water vapor offset by properly zeroing the transducer. The analyzer's usefulness for end-tidal monitoring is limited because of its time response and its response to within-breath variations in water vapor concentration. Despite these problems, we believe the Engstrom analyzer fills a present need for monitoring anesthetic gas concentrations during the teaching and administration of anesthesia.

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