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CLINICAL APPLICATIONS OF CAPNOGRAPHY AMONG MECHANICALLY VENTILATED CHILDREN

By

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ABSTRACT

Background: Capnography provides insight into the management of many emergencies. It reflects the factors affecting perfusion and metabolism, and it is used for continuous monitoring of mechanically-ventilated patients. **Objectives:** To investigate the correlation between the partial pressure of end tidal carbon dioxide ($PetCO_2$) and arterial blood carbon dioxide ($PaCO_2$), and to investigate the accuracy of the change of capnographic curve in diagnosis of special pathological situations. **Patients and Methods:** A total of 100 patients (1 day to 15 years), mechanically-ventilated due to various clinical causes were monitored by PetCO2, and arterial blood gas (ABG) concomitant with assessment of PetCO2. **Results:** Significant correlation was found between $PaCO_2$ and $PetCO_2$, and abnormal $PaCO_2$-$PetCO_2$ gradient was found to be correlated well with the duration of mechanical ventilation. Various $PetCO_2$ waveforms were recorded. **Conclusion:** Capnography should be used for monitoring of critically ill patients and for confirmation of endotracheal intubation. It should be applied during cardio pulmonary resuscitation (CPR) and to monitor the quality of CPR. It is used to monitor the integrity of patient ventilator interface, identification of ventilated patients in need for additional sedation or neuromuscular blockage, and readjustment of ventilator parameters.

Key words: Capnography, $PaCO_2$, $PetCO_2$.

INTRODUCTION

Carbon dioxide (CO_2) is the most abundant gas produced by the human body. The accumulation of CO_2 is the primary drive to breathe and a primary motivation for mechanically ventilated patients. Monitoring the CO_2 level during respiration (capnography) is noninvasive, easy to do, and relatively inexpensive. The capnogram is a graphical representation of the level of exhaled CO_2, and it reflects both physiologic and anatomical changes, e.g. tube kinking or obstruction.

The expiratory capnogram is a technique that provides qualitative information on the waveform patterns associated with mechanical ventilation and quantitative estimation of arterial $PaCO_2$ as well as the calculation of the PaCO2-PetCO2 gradient **(Blanch et al., 2006)**. End-tidal CO2 monitoring is also useful in identifying apnea and bronchospasm in non-intubated children undergoing procedural sedation **(Soto et al., 2004)**, and in assessing the degree of metabolic acidosis in various pediatric populations **(Agus, 2006)**.

There are three technologies currently available for CO2 monitoring: colorimetric devices, cable connected mainstream, side stream, and self-contained mainstream. This last category is the newest entry in the armamentarium of available devices. Mainstream or side stream devices can either display CO2 as a digital readout (capnometer) or as a waveform (capnograph). Colorimetric devices detect and present a range of PetCO2 in a qualitative format rather than as a specific number. They display color changes indicative of the presence of CO2. This type of device has a pH-sensitive chemical indicator visible through a clear dome that turns from purple to yellow when attached to a correctly intubated patient, indicating that CO2 is in the expired breath and the tube is therefore in the trachea **(Godden, 2011)**.

The present work aimed to investigate the correlation between $PetCO_2$ and $PaCO_2$ with calculation of $PaCO_2$-$PetCO_2$ gradient, among intubated patients admitted to the pediatric and neonatal intensive care units, and to investigate the accuracy of the change of capnographic curve in diagnosis of special pathological situations, and its reliability in adjustment of ventilator parameters.

PATIENTS AND METHODS

This study was carried out on 100 mechanically-ventilated pediatric and neonatal patients admitted due to various causes. Their ages ranged between one day up to 15 years. This study was carried out in the Pediatric and Neonatal Intensive Care Unit of Al-Hussein University Hospital during the period from May 2014 to July 2016.

Inclusion Criteria: Patients between day one and 15 years old, mechanically-ventilated due to various clinical causes admitted at the Pediatric and Neonatal Intensive Care Unit of Al-Hussein University Hospital.

Exclusion Criteria:

1. Patients with cardiac diseases.
2. Patients with chronic pulmonary diseases.
3. Patients with metabolic abnormalities that affect CO_2 liberation, e.g. refractory shock, end stage diseases, and patients with multi-organ dysfunction.

All patients were subjected to the following (after approval of the parents by a written consent):

A) Clinically:

1. Full history-taking with especial emphasis on the history of recurrent hospital admissions and medical history.
22. Thorough clinical examination including assessment of respiratory system, cardiovascular system, review of other body systems, and a base-line oxygen saturation using a pulse oximeter.
3. Monitoring of $PetCO_2$ using main stream capnography, performed at the first day of mechanical ventilation.

B) Laboratory investigations and imaging (as needed for each case). The followings were done:

- CBC, CRP, RBS, electrolytes, LFTs and KFTs.
- Chest radiograph.
- Abdominal ultrasonography.
- Echocardiography.
- CT and/or MRI.
- ABG, to be measured concomitant with assessment of $PetCO_2$ via mainstream capnography.

Statistical Methods:

Normality of numerical data distribution was examined using the D'Agostino-Pearson test. Non-normally distributed numerical variables were presented as quartiles and intergroup differences were compared using the Mann-Whitney test (for two-group comparison).

- Categorical variables were presented as number and percentage. Correlations were tested using the Spearman rank correlation.
- P-value <0.05 was considered statistically significant.

RESULTS

The demographic distribution of the study population (patients characteristics), showed that neonates were 84 cases, whereas infants and children were 16 cases **(Table 1)**.

Table (1): Demographic Distribution of the Study Population (Patients Characteristics).

Age category	Variables / Count	Mean	SD	Median	Minimum	Maximum	Ratio
Neonates (n=84 [84%])	Gestational age (weeks)	34	3	34	28	38	
	Post natal age (days)	6	6	4	1	37	
	Weight (kg)	2.1	0.8	2	0.9	5.5	
	Gender (M/F)						55/29
Infants and Children (n=16 [16%])	Post natal age (months)	29	37	14	3	120	
	Weight (kg)	11.4	6.4	9.5	3.5	27	
	Gender (M/F)						8/8

Correlation between PaCO2 and PetCO2 among the study population revealed that there was high statistical significant correlation between PaCO2 and PetCO2 **(Fig. 1)**.

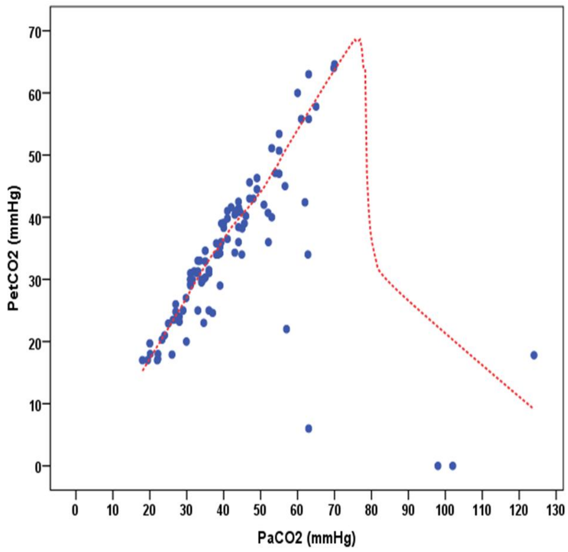

Figure (1): Correlation between PaCO2 and PetCO2 among the study population.

Various capnographic waveforms were obtained by capnogram **(Table 2)**, we recorded 18 different waveform patterns.

Table (2): Frequency of Various Capnographic Waveforms

Capnographic curve / Count	Number	Percent
Normal capnogram	23	23.0
Baseline capnogram (cardiac arrest)	1	1.0
Biphasic wave	10	10.0
Circuit leak	1	1.0
CPR capnographic waves	5	5.0
Curare cleft	4	4.0
Esophageal intubation	1	1.0
Expiratory valve malfunction	6	6.0
Gradual decrease in $PetCO_2$	1	1.0
Hyperventilation	3	3.0
Hypoventilation	7	7.0
Iceberg capnogram	1	1.0
Multiple rebreathing waves	9	9.0
Prolonged plateau	1	1.0
Ripple effect	4	4.0
Shark fin appearance	16	16.0
Signature capnogram	5	5.0
Terminal upswing of phase 3	2	2.0

The normal capnogram consisted of 4 phases: phase 1 in which expiration of air from the anatomical dead space, phase 2 corresponded to expiration of alveolar air mixed with air from the dead space, phase 3 occurred due to expiration of purely alveolar air which eventually formed a plateau in the capnograph, representing the maximum PetCO2, and phase 4 in which the person inspired again, creating the swift down stroke on the capnogram, and the cycle repeated **(Fig. 2)**.

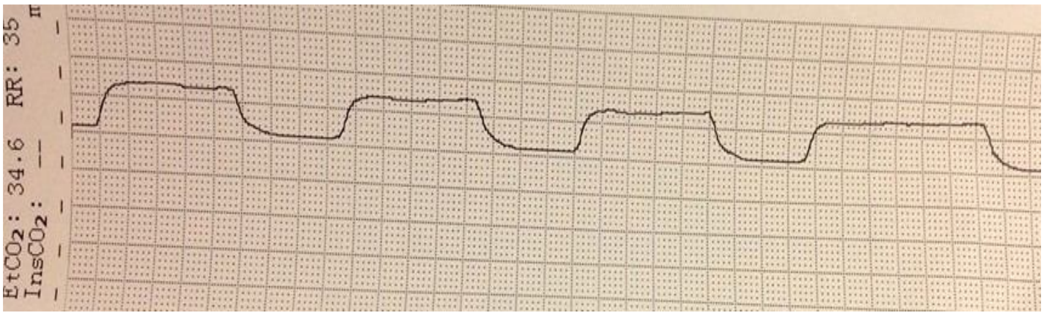

Figure (2): A normal capnogram waveform performed in our study.

Rebreathing occurred either due to short expiratory time, expiratory valve malfunction, or short inspiratory flow time **(Fig. 3)**.

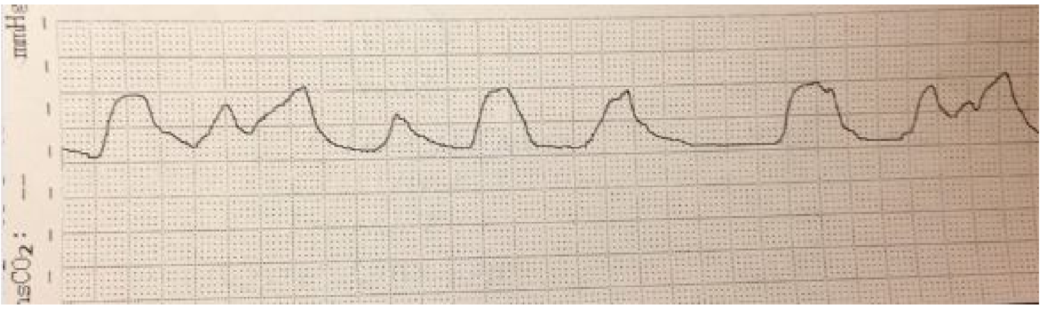

Figure (3): Rebreathing waveform capnogram.

Cardiogenic oscillation waveform occurred during low frequency ventilation, due to movement of gas inside the airway by the effect of cardiac pulsations **(Fig. 4)**.

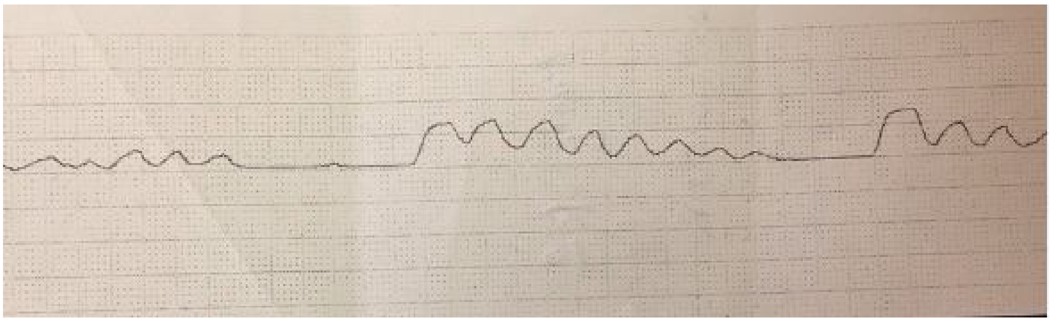

Figure (4): Cardiogenic oscillation waveform capnogram (Ripple effect).

Curare cleft is a second peak occurred during expiration due to sensor disconnection or occurrence of a second breath during expiration during recovery of the patient from the muscle relaxant effect, and restoration of spontaneous ventilation.

Signature capnogram occurred when a rebreathing wave occurs during inspiration due to inhalation of CO_2 **(Fig. 5)**.

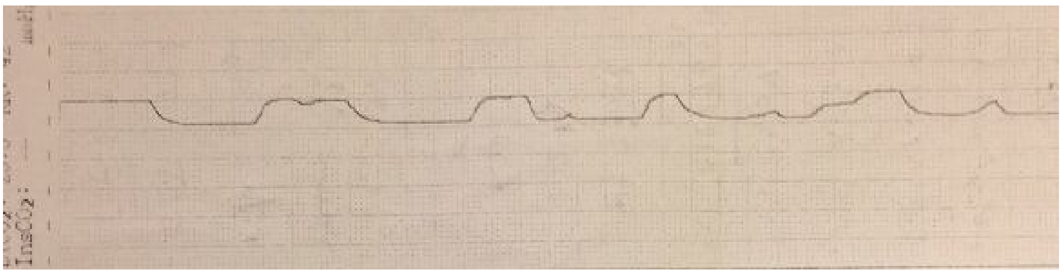

Figure (5): Curare cleft and signature capnogram waveforms.

Hyperventilation occurred with high rate states **(Fig. 6)**, whereas hypoventilation occurred with low rate states **(Fig. 7)**.

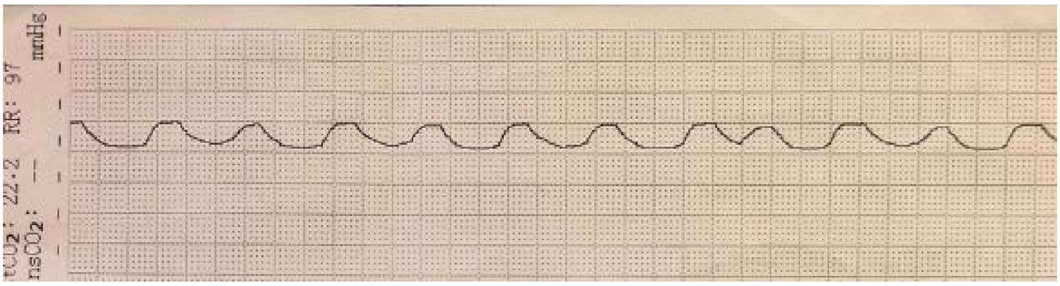

Figure (6): Hyperventilation capnogram waveform.

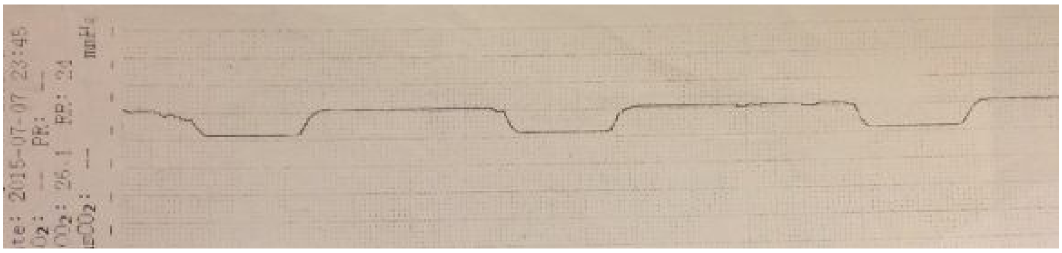

Figure (7): Hypoventilation capnogram waveform.

Shark fin capnogram occurred in patients with partial airway obstruction, bronchospasm or patients fighting the mechanical ventilator **(Fig. 8)**.

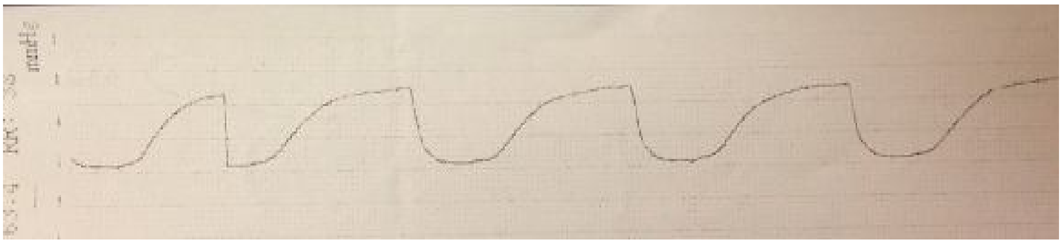

Figure (8): Shark fin capnogram waveform.

In effective cardiopulmonary resuscitation (CPR) and return of spontaneous circulation (ROSC), carbon dioxide changed from zero level to level above 10 mmHg, denoting restoration of circulation and an effective cardiopulmonary resuscitation **(Fig. 9)**.

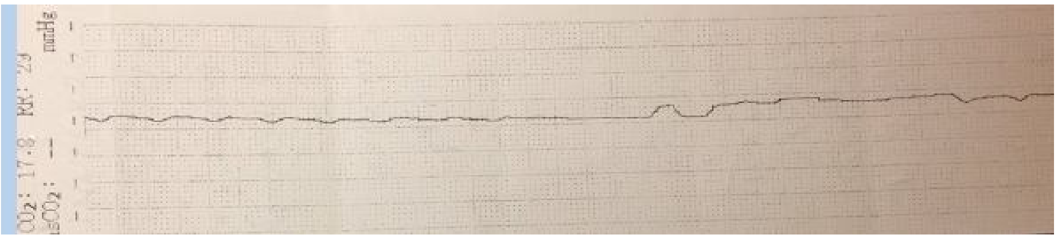

Figure (9): Effective (CPR) and (ROSC)

In non-effective CPR and no ROSC (baseline capnogram), carbon dioxide did not change from zero level, denoting no restoration of circulation, and non-effective cardiopulmonary resuscitation **(Fig. 10)**.

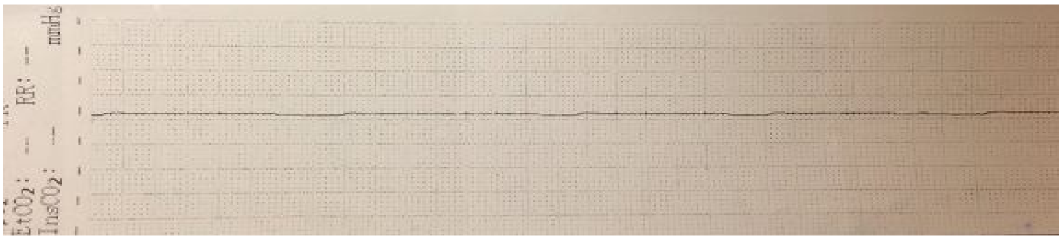

Figure (10): non-effective CPR and no ROSC.

Dual or biphasic capnogram occurred due to sequential lung emptying as one of them is normal, and the other is diseased. This occurs in cases of lung pathology affecting one side, selective intubation of the right lung, lung transplantation and severe kyphoscoliosis causes compression of one lung **(Fig. 11)**.

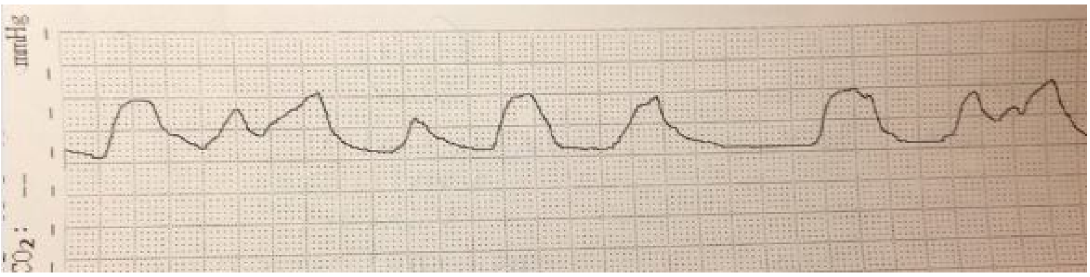

Figure (11): dual or biphasic capnogram waveform.

Gradual decrease in the $PetCO_2$ occurred in cases of endotracheal tube cuff leak, tube in the hypopharynx, or partial airway obstruction **(Fig. 12)**.

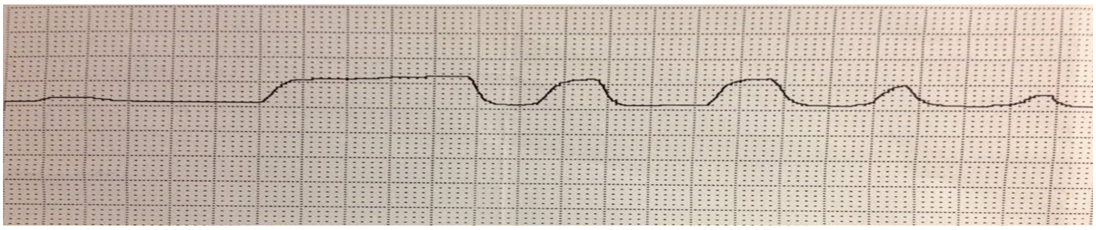

Figure (12): gradual decrease in the $PetCO_2$.

Iceberg capnogram is a combination of curare cleft and Ripple effect **(**cardiogenic oscillations-**Fig. 13).**

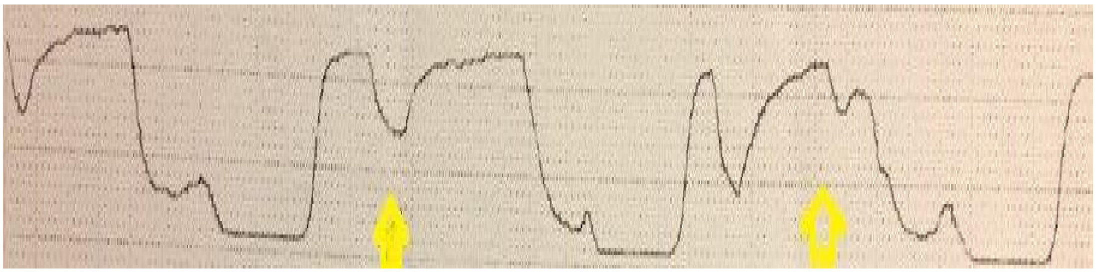

Figure (13): Iceberg capnogram.

Single triggering by the patient can be seen in between normal capnogram waveform **(Fig. 14)**.

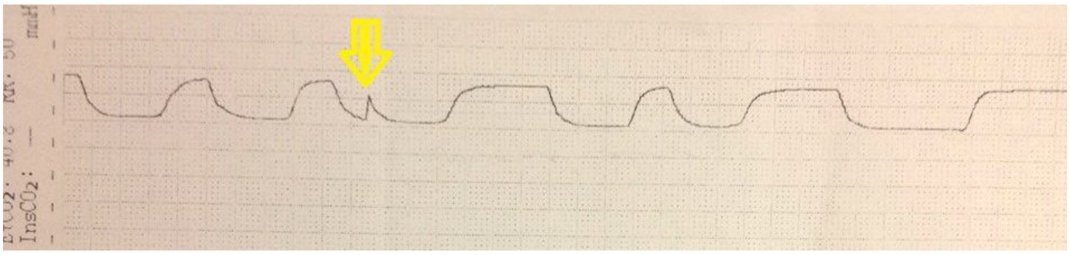

Figure (14): Single triggering by the patient in between normal capnogram waveform.

In expiratory valve malfunction there is prolonged plateau and abnormal phase zero (baseline) denoting expiratory valve malfunction that is needed to be; cleaned, dried, or replaced **(Fig. 15)**.

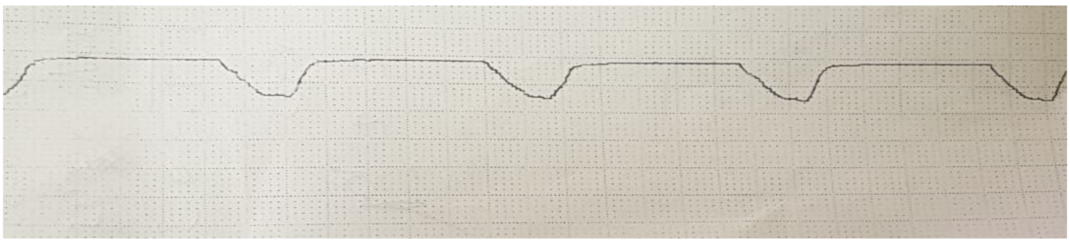

Figure (15): expiratory valve malfunction capnogram waveform.

Prolonged plateau is another form of expiratory valve malfunction **(Fig. 16)**.

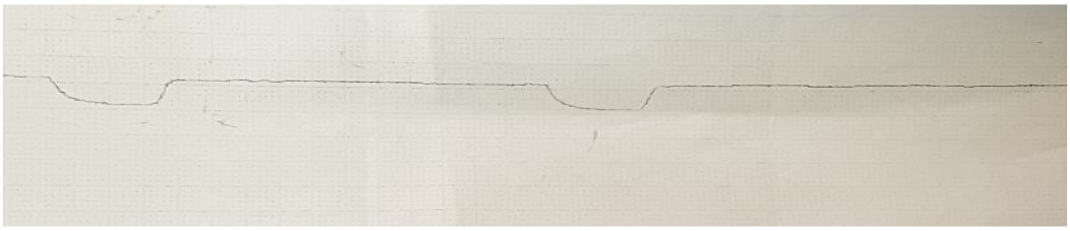

Figure (16): Prolonged plateau capnogram waveform.

In esophageal intubation capnogram, Small spikes were present due to presence of carbonated gases in the stomch **(Fig. 17)**.

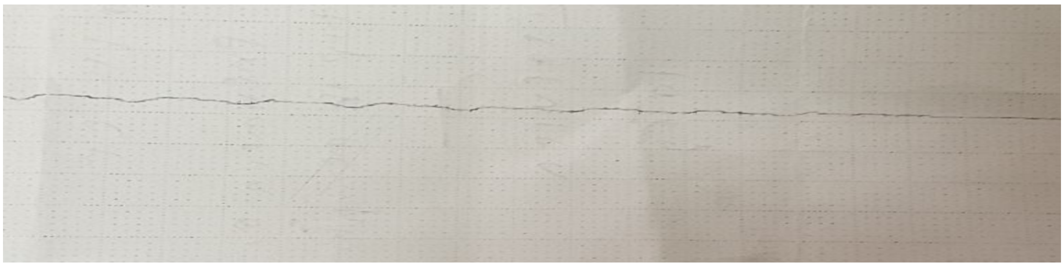

Figure (17): esophageal intubation capnogram

Terminal upswing of phase 3 was observed in low compliance states, and also occurred in obese children **(Fig. 18)**.

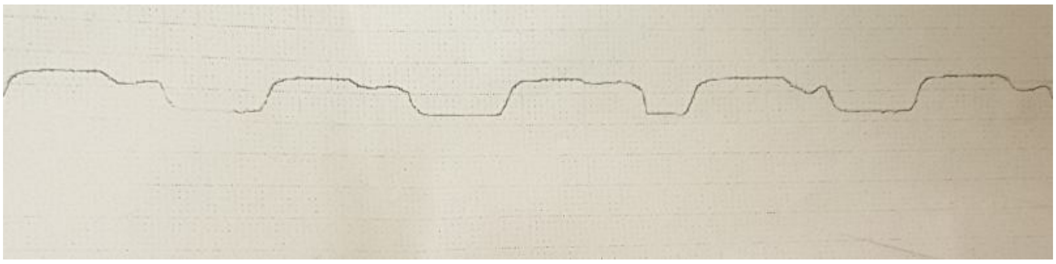

Figure (18): Terminal upswing of phase 3 capnogram.

The frequency of capnography-guided corrective actions were in the form of drugs administration (42% of cases), adjustment of ventilator settings (17%) of cases, and checking the integrity of ventilator circuit (17%) of cases **(Table 3)**.

Table (3): Frequency of Capnography-Guided Corrective Actions among the Study Population.

Frequency / Corrective actions	Number	Percent
Drug administration	42	42.0
Adjustment of ventilator settings	17	17.0
Checking integrity of ventilator circuit	17	17.0

Relation between abnormal $PaCO_2$-$PetCO_2$ gradient and duration of MV among the study population **(Table 4)** revealed high statistical significant relation between abnormal $PaCO_2$-$PetCO_2$ gradient and duration of MV **(Table 4)**.

Table (4): Relation between Abnormal $PaCO_2$-$PetCO_2$ Gradient and Duration of MV among the Study Population

Groups / Parameters	Normal $PaCO_2$ - PetCO2 gradient	Abnormal $PaCO_2$-$PetCO_2$ gradient	Mann-Whitney U	Z	p-value¶
Number	57	43	380.5	5.926	**0.0001**
Lowest value	1	1			
Highest value	13	15			
Median	3	9			
Interquartile range	2 to 4.3	5.3 to 11			

¶Mann-Whitney test.
$PetCO_2$ = Partial pressure of end-tidal carbon dioxide.
$PaCO_2$ = partial pressure of arterial carbon dioxide.
MV = mechanical ventilation.

DISCUSSION

Capnography is a noninvasive measurement of the partial pressure of carbon dioxide in exhaled breath displayed as a numerical value and a waveform **(Toumaa and Davies, 2013)**.

As regard the correlation between $PaCO_2$ and $PetCO_2$ in the study population, there was a high statistical significant relation between $PaCO_2$ and $PetCO_2$ among the study group. This denoted that PetCO2 was a reliable tool for continuous monitoring of PaCO2, avoiding frequent ABG samples. Our results came in agreement with **Zwerneman (2006) and Goonasekera et al. (2014).**

In partial agreement with our results, **Bhat and Abhishek (2008)** observed a higher correlation in babies ventilated for sepsis and asphyxia, compared to those with HMD and MAS, suggested that $PetCO_2$ monitoring is affected by the degree of pulmonary disorders. **Greenbaum (2016)** recorded the normal value of PaCO2 35-45 mmHg, and **Matin et al. (2015)** found that the normal PetCO2 is less than PaCO2 by 1-5 mmHg.

In contrast with our results, **Jacob et al. (2014)** reported a poor correlation in neonates with pulmonary disease. This is because the patient's tidal volume, whether spontaneous or not, is too small to deliver undiluted alveolar gas to the capnograph, and so the PetCO2 will be falsely low.

On the other hand, **Doğan et al. (2014)** stated that if the patient's tidal volume, whether spontaneous or not, is too small to deliver undiluted alveolar gas to the capnograph, the $PetCO_2$ will be falsely low, and this concern arises particularly in premature newborns.

As regard the frequency of various capnographic waveforms among the study population, we recorded 18 different waveform patterns. This was in agreement with **Mehta et al. (2014)** who documented that the waveform of capnography may be useful in detecting certain type of pulmonary pathology. **Young et al. (2013)** found a dip in phase III which can occur in mechanically-ventilated patients with spontaneous breathing and he explained, this dip results from spontaneous breath initiation after a ventilator delivered breath, during this time, a small amount of fresh gas is drawn over the detector. This is known as a curare cleft because it occurs commonly when patients are emerging from neuromuscular blockade. The same results were obtained by **Sandlin (2002)** who stated when the waveform displays a cleft, this indicates the initiation of spontaneous ventilation and indicates partial recovery from neuromuscular blockade. Cardiogenic oscillations were recorded by **Sandlin (2002)** and **Grmec et al. (2007)**. They stated that cardiogenic oscillations appeared as small, regular, tooth like humps at the end of the expiratory phase. They are believed to be due to the contraction and relaxation of the heart and intrathoracic great vessels on the lungs, forcing air in and out. They are usually seen at low respiratory rates and in children. Also, **Scarth (2012)** recorded the oscillations synchronous with the heart beats and he mentioned it represent the complex summation of transient alterations in the proportion of the total flow coming from different lung units and containing gases of different concentrations.

The other forms of the capnographic waves were obtained also by **Sandlin (2002)**. He recorded circuit disconnection pattern and hypoventilation pattern of the waveform. Hypoventilation also was recorded by **Hackett (2002)** who stated that the addition of capnography can detect early signs of hypoventilation that pulse oximetry cannot detect.

In concordance with our results, shark-fin appearance which denotes airway obstruction was recorded by **Guirgis et al. (2014)** who stated that a slow upstroke of Phase II can be due to delayed delivery of CO_2 from lungs to the sampling device and can be due to bronchospasm, upper airway obstruction, kinking of the endotracheal tube. The same results were obtained by **Gilboy and Hawkins (2006)**.

Rebreathing waves were documented by **Sandlin (2002)** who mentioned that evaluation of the capnogram may be useful in detecting rebreathing of CO_2. The same results were given by **Jabre et al. (2009)**.

The biphasic wave form was recorded by **Cong and Mohan (2013)** who explained it due to differing ventilation-perfusion ratios in each lung. The first peak represents expired CO_2 from the lung, which has good ventilation-perfusion ratios, and the second peak, with a steeper plateau, represents the lung with mismatched ventilation- perfusion ratios.

As regard the capnography- guided corrective actions among the study population, our cases underwent 3 major corrective actions in the form of drugs administration (42% of cases), adjustment of ventilator settings (17%) of cases, and checking the integrity of ventilator circuit (17%) of cases.

This came in agreement with **Keller et al. (2009)** who used capnography as a guide for identification of partial recovery from neuromuscular blockade. On the other hand, **Totapally (2014)** used it to track response for drugs (bronchodilators), whereas **Deitch et al. (2010)** used capnography to diagnose effect of the drugs by increased $PetCO_2$ with drug administration (fentanyl and midazolam or diazepam).

Also, **Bhat and Abhishek (2008)** documented that $PetCO_2$ may guide to adjust the ventilatory settings. The same results were obtained by **Jabre et al. (2009)** and **Doğan et al. (2014)** who used capnography for titration of PEEP, whereas **Gilboy and Hawkins (2006)** and **Jabre et al. (2009)** used capnography to monitor integrity of ventilator circuit. **Manifold et al. (2013)** said that a change in the PetCO2 value or waveform is a signal to check the patient and the equipment.

As regard the relation between abnormal $PaCO_2$-$PetCO_2$ gradient and duration of mechanical ventilation among the study population, our results came in partial agreement with **Hubble et al. (2000)** who reported that capnography provides information on breathing patterns and illustrates the importance of breathing consistency before successful weaning can occur.

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التطبيقات الإكلينيكية لمخطط ثاني أكسيد الكربون في الأطفال تحت التنفس الصناعي

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خلفية البحث : يوفر مخطط قياس ثاني أكسيد الكربون نظرة ثاقبة في إدارة العديد من حالات الطوارئ، كما أنه يدلل علي العوامل التي تؤثر علي النضح والتمثيل الغذائي ويستخدم بكفاءة في المراقبة المستمرة للمرضي الذين يتم تنفسهم صناعيا.

الهدف من البحث: تهدف الدراسة إلي إستبيان العلاقة بين ثاني أكسيد الكربون الزفيري وثاني أكسيد الكربون الشرياني مع إستيبيان مدي دقة التغير في شكل موجات مخطط قياس ثاني أكسيد الكربون لتشخيص حالات مرضية معينة.

المرضي وطرق البحث : أجريت هذه الدراسة علي مائة طفل (من سن يوم واحد وحتى سن خمسة عشر عاما) ممن تم وضعهم علي جهاز التنفس الصناعي لأسباب متنوعة وتمت متابعتهم بقياس ثاني أكسيد الكربون الزفيري ، وقد تم قياس ثاني أكسيد الكربون الشرياني بالتزامن مع قياس ثاني أكسيد الكربون الزفيري.

النتائج: خلصت الدراسة إلي أن هناك إرتباطاً وثيقاً بين ثاني أكسيد الكربون الزفيري وثاني أكسيد الكربون الشرياني ، ووجود إرتباط بين الفارق بين ثاني أكسيد الكربون الزفيري والشرياني ومدة مكوث المريض علي جهاز التنفس الصناعي. وقد تم تسجيل أشكال مختلفة لموجات مخطط قياس ثاني أكسيد الكربون.

الإستنتاج: توصي هذه الدراسة بإستخدام مخطط قياس ثاني أكسيد الكربون لمتابعة المرضي ذوي الحالات الحرجة والتأكد من وضع الأنبوبة الحنجرية. كما أن للمخطط دور كبير أثناء عملية إنعاش القلب والرئة، وذلك من أجل التأكد من كفاءة عملية الإنعاش القلبي الرئوي. وتوصي الدراسة بإستخدام مخطط قياس ثاني أكسيد الكربون لفحص تكامل التعاطي بين المريض وبين جهاز التنفس الصناعي، والتعرف علي إحتياج المرضي للتسكين الدوائي أو لبسط العضلات الدوائي للمرضي الذين تم وضعهم علي جهاز التنفس الصناعي، ولإعادة ضبط قيم جهاز التنفس الصناعي.