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Predicting intra-abdominal hypertension using anthropometric measurements and machine learning

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Almost one in four critically ill patients suffer from intra-abdominal hypertension (IAH). Currently, the gold standard for measuring intra-abdominal pressure (IAP) is via the bladder. Measurement of IAP is important to identify IAH early and thus implement appropriate management in order to avoid complications. It may be possible to use anthropometric parameters to predict IAP and thus identify IAH non-invasively. This retrospective observational study investigated how the most relevant body parameters evolve in relation to IAP, and whether IAP can be predicted based on anthropometric parameters. The IAP and 28 body parameters of 96 critically ill patients were recorded. Following statistical analyses such as Pearson's and mutual information correlation, the collected data were used to train a simulation model to examine reliable relationships between IAP, predict IAP values, and detect IAH. Three metrics were shown to sufficiently predict intra-bladder pressure (IBP) with a Pearson's correlation of 0.75 (R^2 = 0.56). These parameters are the difference between the convex and horizontal xiphoid-to-pubis distance, sagittal abdominal diameter, and abdominal compliance. Subsequently, we found 1 metric that is able to predict the presence of IAH with Pearson correlation of 0.89 (R^2 = 0.79). This metric is the difference between the convex and horizontal xiphoid to pubis distance. Three measured body parameters showed a correlation of more than 50% with IBP and they are sufficient for a reliable prediction of IBP, however, IAH can be most reliably predicted based on the difference between the convex and horizontal xiphoid-pubis distance and sagittal abdominal diameter. Future studies with larger patient populations and diverse body shapes are warranted to confirm these findings.

Keywords Intra-abdominal pressure, Anthropometric parameters, Statistical analyses, Predictive models

Intra-abdominal pressure (IAP) as the steady-state pressure within the abdominal cavity has been recognized as a new vital sign in critically ill patients[1–3]. Previous studies revealed that almost one out of four critically ill patients suffer from intra-abdominal hypertension (IAH, defined as an IAP equal to or above 12 mmHg) on admission, and 50% will develop it during the first week of ICU stay[4]. Recent studies also show a relatively high prevalence (on average 55%) of IAH following cardiac surgery, burns, trauma, liver cirrhosis, severe acute pancreatitis, general surgery, and sepsis[5–11]. Delayed detection of IAH can lead to a more severe condition, known as poly-compartment syndrome, which arises from the intercommunication between various organ

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systems within different body compartments[12]. Early IAH detection together with appropriate management has the potential to improve treatment efficiency, shorten ICU stays, and lower treatment costs[13,14].

Currently, the gold standard for IAP measurement is via the bladder and is supported by the Abdominal Compartment Society (WSACS, www.wsacs.org, formerly known as the World Society of the Abdominal Compartment Syndrome)[1]. However, growing awareness of the pathophysiological role of IAP over the past few decades has led to numerous studies aimed at developing alternative measurement methods to improve the current standard. In this context, approaches ranging from ultrasound-based methods and tensiometry, to microwave reflectometry and bio-impedance analysis have been suggested within the last decade[15–20]. Compared to the current reference method, these alternatives can potentially provide continuous measurements, allowing for quicker IAH detection, prevention of urinary tract infections and trauma, and applicability to patients with pelvic masses who cannot be assessed using the current gold standard.

Anthropometric indices have long served a variety of purposes, from acting as markers for risk assessment to guiding interventions and evaluating their impact on nutrition and overall health[21]. For instance, previous research has demonstrated the connection between anthropometric measurements and various diseases, including cardiovascular disorders[22,23], diabetes[24,25], metabolic syndrome[26,27], respiratory disorders[28,29], and certain cancers[30,31]. As such, a positive correlation between IAP and sagittal abdominal diameter, as well as the body-mass-index (BMI), has previously been reported[32,33]. Similarly, IAP estimation based on the measurement of the abdominal perimeter has been studied[34]. However, no thorough analysis on the correlation between IAP and other different anthropometric parameters has been done yet.

The aim of this research was to investigate a wide range of anthropometric parameters versus IAP. We subsequently examined the feasibility of IAP prediction and IAH detection by using the collected parameters to train predictive models. The outcome of this study will bring further insights on how body parameters evolve when IAP increases. Moreover, the findings pave the way for future investigations into utilizing anthropometric parameters in monitoring critically ill patients. We also aim to show the importance and application of artificial intelligence and machine learning in clinical monitoring.

Patients and methods

Patient selection

A retrospective observational study was performed on the patients admitted at the Ziekenhuis Netwerk Antwerpen, ZNA Stuivenberg between 2008 and 2014. Inclusion criteria were admission to the ICU, adults above 18 years old, presence of bladder and/or gastric pressure measurements, and availability of anthropometric data. Ninety-six critically ill patients admitted to the ICU, and who had intra-gastric and intra-bladder pressure (IGP and IBP) measurements performed during the first week of their ICU stay, were included. Patients with and without IAH were included in the analysis.

Ethical considerations

The study was conducted in accordance with the study protocol, the Declaration of Helsinki and applicable regulatory requirements. Ethics approval was granted by the local Institutional Review Board and Ethics Committee of the Ziekenhuis Netwerk Antwerpen, ZNA Stuivenberg (EC approval number: 3001). Informed consent from patients or their next of kin was waived because of the retrospective nature of the study which did not deviate from standard ICU care.

Data collection

Patient demographics

General patient data such as age, gender, height, weight, body mass index (BMI), and body surface area (BSA), as well as the ICU admission and discharge dates, APACHE II (Acute Physiology and Chronic Health Evaluation), SAPS II (Simplified Acute Physiology Score), and SOFA (Sequential Organ Failure Evaluation) severity scores, together with body anthropometric data, IAP-derived parameters, and ventilator settings were collected from the medical records.

Body anthropometric data

We collected information on all the anthropometric data that could potentially be correlated with IAP to investigate the correlation between body metrics and IAP, and subsequently, trained the predictive models for IAH prediction (see Fig. 1).

IAP-derived parameters

Ninety-six mechanically ventilated patients had their IBP measured using a Foley's bladder catheter connected to a Foley-Manometer (Holtech Medical, Charlottenlund, Denmark) as previously described[35]. A maximal instillation volume of 25 ml was used and the Foley-Manometer was zeroed at the level where the mid-axillary line crosses the iliac crest. A CiMON balloon-tipped nasogastric probe (Pulsion Medical Systems, Getinge Group, Solna, Sweden) was used to record end-expiratory and end-inspiratory intra-gastric pressure (IGP_{ee} and IGP_{ei}).

Following the measurement stage, IAP-derived parameters were subsequently calculated as follows:

- ΔIGP: pressure difference between end-inspiratory and end-expiratory IGP ($IGP_{ei} - IGP_{ee}$) [mmHg];
- IGP_m: average of end-expiratory and end-inspiratory IGP ($(IGP_{ei} + IGP_{ee})/2$) [mmHg];
- IAP_m: average of mean intra-gastric pressure and intra-bladder pressure at the end of expiration ($(IGP_{ee} + IBP_{ee})/2$) [mmHg].

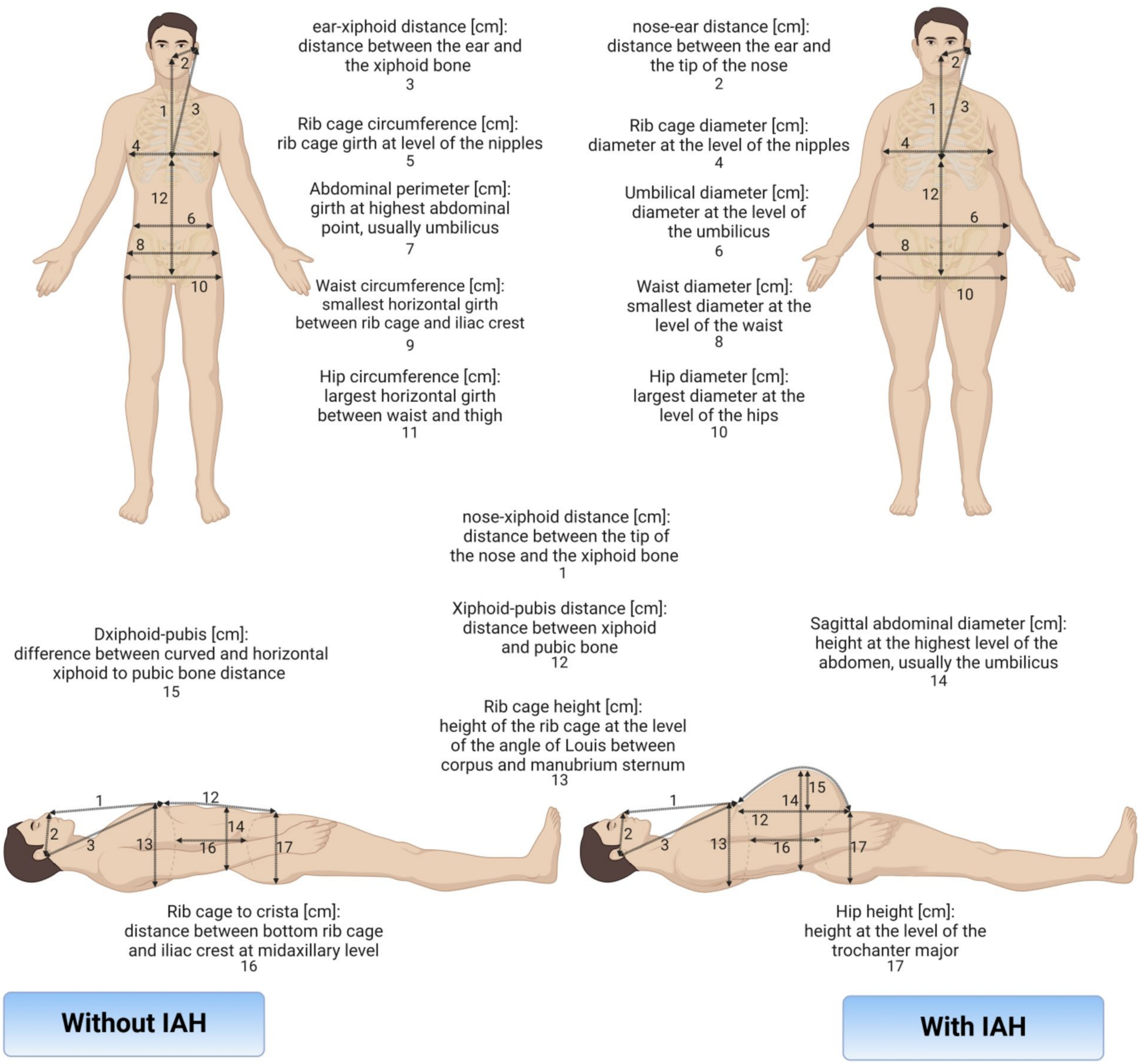

Fig. 1. Anthropometric parameters used in this study. All possible anthropometric parameters that might be linked to IAP were gathered. The evolution of these body parameters during IAP elevation is shown as a comparison between without and with IAH (Figure created in BioRender).

Ventilator settings and parameters

In addition to patient demographics and pressure values, each patient's ventilatory settings were collected. Each ventilator setting and derived dataset contained the following information:

- I: inspiratory time [s];
- E: expiratory time [s];
- TV: Tidal Volume [mL];
- RR: Respiratory Rate [bpm];
- P_{plat}: Plateau pressure [cmH_2O];
- PEEP: Positive End-Expiratory Pressure [cmH_2O];
- DP_{ALV}: Alveolar driving pressure (P_{plat} – PEEP) [mmHg];
- TAI: Thoraco-Abdominal Index of transmission ($\Delta IGP/DP_{ALV}$) [%];
- C_{ab}: abdominal compliance ($TV/\Delta IGP$) [mL/mmHg];
- C_{dyn}: dynamic respiratory compliance (TV/DP_{ALV}) [mL/cmH_2O];
- APV: Abdominal Pressure Variation ($\Delta IGP/IAP_m$) [%].

One of these parameters is abdominal compliance (C_{ab}), which is a key parameter in critically ill patients and can be effectively used for IAP estimation[36]. Along with C_{ab}, dynamic respiratory compliance (C_{dyn}) and driving pressure (DP_{ALV}) are other ventilator parameters that can potentially be correlated with IAP. Therefore, from all the ventilator parameters, C_{ab}, C_{dyn}, and DP_{ALV} were selected for further statistical analyses.

Statistical analyses and predictive models
The data processing was started with a 2-tailed unpaired student's *t*-test to highlight the parameters that were significantly different between patients with and without IAH. A *p*-value below 0.05 was considered as statistically significant. Pearson's correlation analysis was done to investigate the correlation between the collected data and IBP (or IAH). Variables with more than 20% correlation with IBP (or IAH) were further evaluated by mutual correlation analysis to investigate the amount of information that one variable can provide about another one. At this stage a minimal correlation strength of 50% was defined as the threshold.

Subsequently, 66,537 predictive models were created and trained (using the collected data) with Datastories' proprietary AI system (Turnhout, Belgium, www.datastories.com) to learn to predict IBP. Cross-validations were performed for the training of the models to avoid over-fitting and to maximize the predictive power of the models. Initial analysis of the learning process involved identifying how the metrics impacted the IBP individually. In the second part of the study, instead of the IBP values, patients were either assigned 0 or 1 as binary labels. Patients with IBP (or IGP_{ee}) equal to or above 12 mmHg were defined as 1 (with IAH), and patients without IAH were defined as 0. The general patient data, ICU severity scores, anthropometric data and binary IBP labels were used to retrain the predictive models. At this stage, however, the focus of the predictive models was on the IAH detection rather than predicting the IBP value.

Relationship between IBP and IGP was investigated using Bland-Altman analysis. The bias between IBP and IGP was defined as the mean difference between each pair of measurements. Subsequently, the precision and limits of agreement were defined as the standard deviation of the bias and the bias ± 1.96 times the precision according to Bland-Altman analysis[37].

The statistical analyses were performed in SPSS (IBM Statistical Package for the Social Sciences version 27, Chicago, IL, USA).

Results
General data and ICU severity scores
The mean and standard deviation of the general patient data together with the ICU severity score are presented in Table 1.

In general, patients with IAH showed a higher weight, BMI, BSA, and ICU stay when compared to patients without IAH.

Anthropometric data
The mean and standard deviation of the collected anthropometric parameters are provided in electronic supplementary material (ESM) Table S1. Based on the initial results, sagittal abdominal diameter, rib cage height, xiphoid-pubis distance, and abdominal perimeter had the most significant *p*-values. In general, patients with IAH showed a significantly higher sagittal abdominal diameter, Dxiphoid-pubis, and abdominal perimeter. Gender wise, women were notably smaller with lower average height, shorter nose-to-ear and ear-to-xiphoid distance, smaller rib cage height, and a shorter ribcage-to-crista distance. Women had larger hip diameters and hip circumferences. ESM Figure S1 illustrates a box plot showing hip diameter to IAH variations in males and females.

IAP-derived data
Recorded IAP-derived parameters are presented in Table 2.

Variable	Total	without IAH (*n* = 41)	with IAH (*n* = 55)	*p*-value
SAPS II	55.4 ± 12.9	54.3 ± 14.2	56.2 ± 12.1	0.53
APACHE II	26.4 ± 9.6	26.5 ± 9.1	26.4 ± 10.0	0.96
SOFA	11.3 ± 5.2	10.4 ± 4.7	11.9 ± 5.4	0.23
Age	57.5 ± 13.9	58.3 ± 13.9	57.0 ± 14.0	0.65
ICU stay [days]	30.8 ± 28.9	24.8 ± 14.1	37.2 ± 38.2	0.15
Height [cm]	174.4 ± 9.4	174.1 ± 10.4	174.7 ± 8.6	0.74
Weight [kg]	84.7 ± 20.0	78.2 ± 12.9	89.5 ± 22.8	0.01
BMI [kg/m^2]	27.9 ± 7.0	25.8 ± 3.8	29.4 ± 8.3	0.01
BSA [m^2]	2.0 ± 0.2	1.9 ± 0.2	2.0 ± 0.2	0.02
Male [*n*]	70	25	45	-
Female [*n*]	26	16	10	-

Table 1. Severity scores and patient demographics. Values are shown as mean with standard deviation (SD) for patients with and without intra-abdominal hypertension. SAPS: Simplified Acute Physiology Score; APACHE: Acute Physiology and Chronic Health Evaluation; SOFA: Sequential Organ Failure Assessment; BMI: Body Mass index; BSA: Body Surface Area.

Variable	Total	without IAH ($n=41$)	with IAH ($n=55$)	p-value
IGP_{ei} [mmHg]	14.8 ± 4.7	10.5 ± 2.4	17.9 ± 3.3	< 0.001
IGP_m [mmHg]	12.5 ± 3.9	8.9 ± 2.1	15.1 ± 2.7	< 0.001
IGP_{ee} [mmHg]	10.7 ± 3.4	7.7 ± 1.9	13.0 ± 2.4	< 0.001
ΔIGP [mmHg]	4.0 ± 1.6	2.8 ± 0.9	4.9 ± 1.5	< 0.001
IAP_m [mmHg]	12.4 ± 3.9	8.8 ± 2.1	14.8 ± 2.7	< 0.001
IBP_{ee} [mmHg]	12.3 ± 3.8	8.9 ± 2.0	14.8 ± 2.5	< 0.001

Table 2. Intra-gastric and intra-bladder pressure values. Values are presented as mean with standard deviation. IGP_{ei}: end-inspiratory intra-gastric pressure; IGP_m: mean intra-gastric pressure; IGP_{ee}: end-expiratory intra-gastric pressure; ΔIGP: difference between IGP_{ei} and IGP_{ee}; IAP_m: mean intra-abdominal pressure; IBP: intra-bladder pressure.

Variable	Total	Without IAH ($n=41$)	With IAH ($n=55$)	p -value
I [s]	1.0 ± 0.1	1.0 ± 0.0	1.0 ± 0.1	0.15
E [s]	1.8 ± 0.4	1.8 ± 0.3	1.8 ± 0.4	0.57
TV [mL]	593.9 ± 110.0	582.4 ± 125.2	601.8 ± 98.9	0.42
RR [bpm]	17.9 ± 3.4	18.0 ± 3.4	17.8 ± 3.3	0.85
Pplat [cm H_2O]	27.0 ± 5.3	24.5 ± 4.7	28.6 ± 5.1	< 0.001
PEEP [cm H_2O]	8.9 ± 3.1	7.8 ± 2.7	9.6 ± 3.1	< 0.001
DP_{ALV} [cmH_2O]	18.1 ± 4.0	16.8 ± 4.3	19.0 ± 3.6	0.01
DP_{ALV} [mmHg]	13.3 ± 3.0	12.3 ± 3.2	14.0 ± 2.6	0.01
TAI [%]	30.9 ± 11.0	24.9 ± 10.5	35.1 ± 9.4	< 0.001
C_{ab} [mL/mmHg]	171.6 ± 80.0	222.2 ± 85	137.3 ± 54.7	< 0.001
C_{dyn} [mL/cm H_2O]	34.8 ± 11.2	37.2 ± 12.5	33.2 ± 10.0	0.01
APV [%]	32.3 ± 8.4	32.6 ± 9.0	32.1 ± 8.0	0.80

Table 3. Ventilator settings and derived parameters collected from 96 critically ill patients. Data include mean with standard deviation. I: inspiratory time; E: expiratory time; TV: Tidal Volume; RR: Respiratory Rate; P_{plat}: Plateau pressure; PEEP: Positive End-Expiratory Pressure; DP_{ALV}: driving pressure; TAI: Thoraco-Abdominal Index of transmission; C_{ab}: abdominal compliance; C_{dyn}: dynamic respiratory compliance; APV: Abdominal Pressure Variation.

IBP, IGP_m, and IAP_m showed good agreement. Moreover, ΔIGP was significantly higher in patients with IAH. This suggests that IGP_{ei} increases more than IGP_{ee} as intra-abdominal hypertension (IAH) develops. Changes of ΔIGP versus IAP_m are presented in ESM Figure S2 .

Ventilatory settings and parameters
All the recorded ventilator settings are presented in Table 3. However, only C_{ab}, C_{dyn}, and DP_{ALV} were processed for the rest of the study.

As depicted, DP_{ALV} and thoraco-abdominal index of transmission were significantly higher in patients with IAH (see ESM Figure S7). In contrast, patients with IAH had lower C_{ab} and C_{dyn} compared to patients without IAH (see ESM Figure S8).

Figure 2 shows an overview of all the studied parameters that were significantly different between patients with and without IAH.

IBP prediction model
Following the data collection, correlation analysis with a minimal strength of correlation of 20% was performed to measure the impact of each body parameter on IBP. The results demonstrated that 15 out of 28 body parameters showed a linear correlation greater than 20% with IBP (see Fig. 3). Further correlation analysis of the mutual information content between IBP and all other data inputs with a minimum correlation strength of 50% revealed C_{ab}, Dxiphoid-pubis, and sagittal abdominal diameter to be the most impactful parameters in IBP value prediction (see Fig. 3). The numeric results of the 15 parameters with a correlation higher than 20% with IBP is presented in ESM Figure S3.

The C_{ab} (impact: 58%), Dxiphoid-pubis (impact: 37%), and sagittal abdominal diameter (impact: 4%) effectively predicted IBP with a Pearson's correlation coefficient of 0.745 ($R^2 = 0.56$). Figure 4 shows the evolution of IBP versus each independent predictor separately.

IAH detection model
Once more, the predictive models were trained to predict the presence of IAH rather than determining the IBP value. The correlation strength of the parameters with IAH is presented in Fig. 5. The numeric results of the

Fig. 2. An overview of the metrics that showed a significant difference when comparing patients with and without IAH.

15 parameters with a correlation higher than 20% with IAH occurrence is presented in ESM Figure S4. All the individual pairwise relationships of the 15 most effective parameters were examined using a mutual information test (see Fig. 5).

We found that the Dxiphoid-pubis and sagittal abdominal diameter are the metrics that matter in order to detect IAH. Nevertheless, predictive models showed that Dxiphoid-pubis can sufficiently detect IAH with a Pearson's correlation of 0.89 ($R^2=0.79$). The IAH detection graph as a function of Dxiphoid-pubis is shown in Fig. 6.

Correlation between IBP and IGP

A strong Pearson's correlation ($R^2=0.91$, $p<0.0001$) was observed between IBP_{ee} and IGP_{ee}. Bland and Altman analysis revealed a mean bias of 1.6 ± 1.1 mmHg, with the limits of agreement ranging from −0.7 to 3.9 mmHg, and a percentage error of 26% between IBP_{ee} and IGP_{ee} (see ESM Figure S5 and S6).

Discussion

Overall results

General patient data, ICU severity scores, body anthropometric data, IAP-derived parameters, and ventilator settings of 96 ICU admitted patients were collected from the medical records and used to study the pairwise relationships between them by statistical analyses and to train computer models to predict IAP value and detect IAH. Although 15 parameters showed a correlation higher than 20% with IBP, the abdominal compliance (impact: 58%), Dxiphoid-pubis (impact: 37%), and sagittal abdominal diameter (impact: 4%) demonstrated an effective prediction of IBP value, achieving a Pearson's correlation coefficient of 0.745 ($R^2=0.56$). These parameters influence the predictions by varying amounts and are best used together to make a more robust prediction. We discovered that the Dxiphoid-pubis and the sagittal abdominal diameter are crucial metrics for

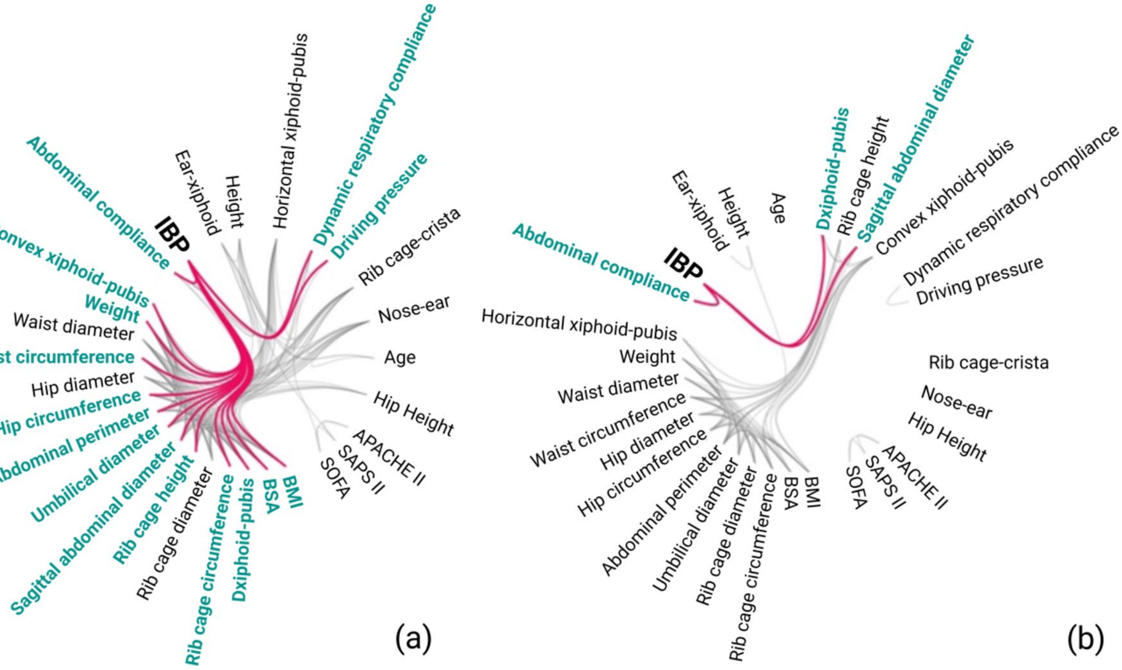

Fig. 3. Circular correlation network between IBP and body parameters. (a) Pearson's correlation analysis between the different parameters and IBP (all the body parameters that showed a linear correlation higher than 20% are highlighted in green) and (b) Mutual correlation analysis between different parameters and IBP (minimal strength of correlation 50%).

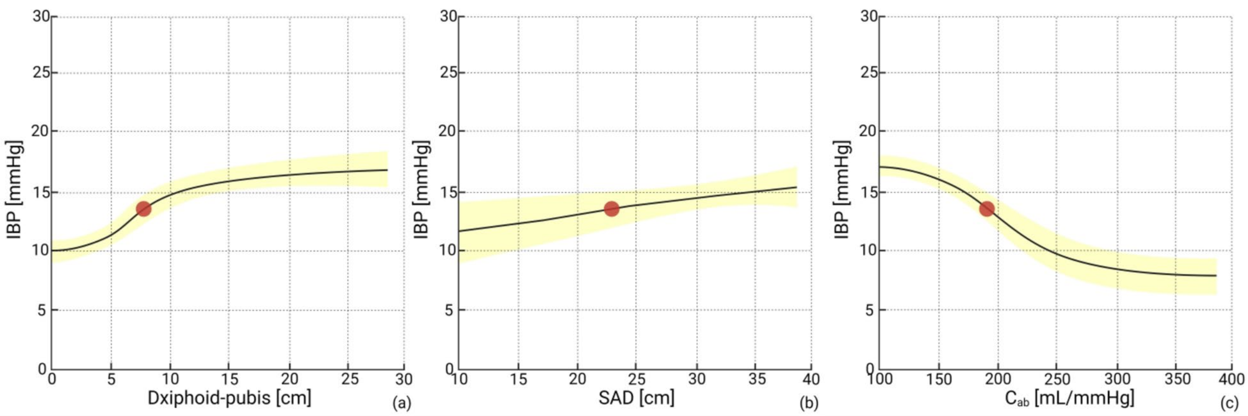

Fig. 4. Data plots with confidence intervals showing the evolution of IBP when one of the three independent predictors changes. Abdominal compliance (C_{ab}) and the difference between the convex and horizontal xiphoid to pubis distance (Dxiphoid-pubis) are more effective in IBP prediction. SAD represents sagittal abdominal diameter.

detecting IAH. However, predictive models indicated that Dxiphoid-pubis alone can effectively detect IAH, with a Pearson's correlation of 0.89 ($R^2 = 0.79$). A strong agreement was observed between IBP_{ee} and IGP_{ee} ($R^2=0.91$, $p<0.0001$).

Taking the findings of this study into account, IAH is associated with different anthropometric characteristics such as increased waist and abdominal perimeter, Dxiphoid-pubis distance, rib cage height, and sagittal abdominal diameter. Abdominal compliance is another significantly different parameter between patients with and without IAH. However, among these important parameters, Dxiphoid-pubis seems to be the most effective parameter in either predicting the IAP value or detecting the IAH. This is probably because it is being measured with respect to a reference parameter, which is the horizontal xiphoid-pubis distance. The horizontal distance remains constant during IAP elevation, however, the convex distance changes significantly due to IAP elevation. When the difference between these variables is measured, a general overview of IAP non-dependent parameters is given to the predictive models than can further calibrate the models and therefore, provide a more accurate prediction and detection. The agreement between IBP_{ee} and IGP_{ee}, reflects the interchangeability of the

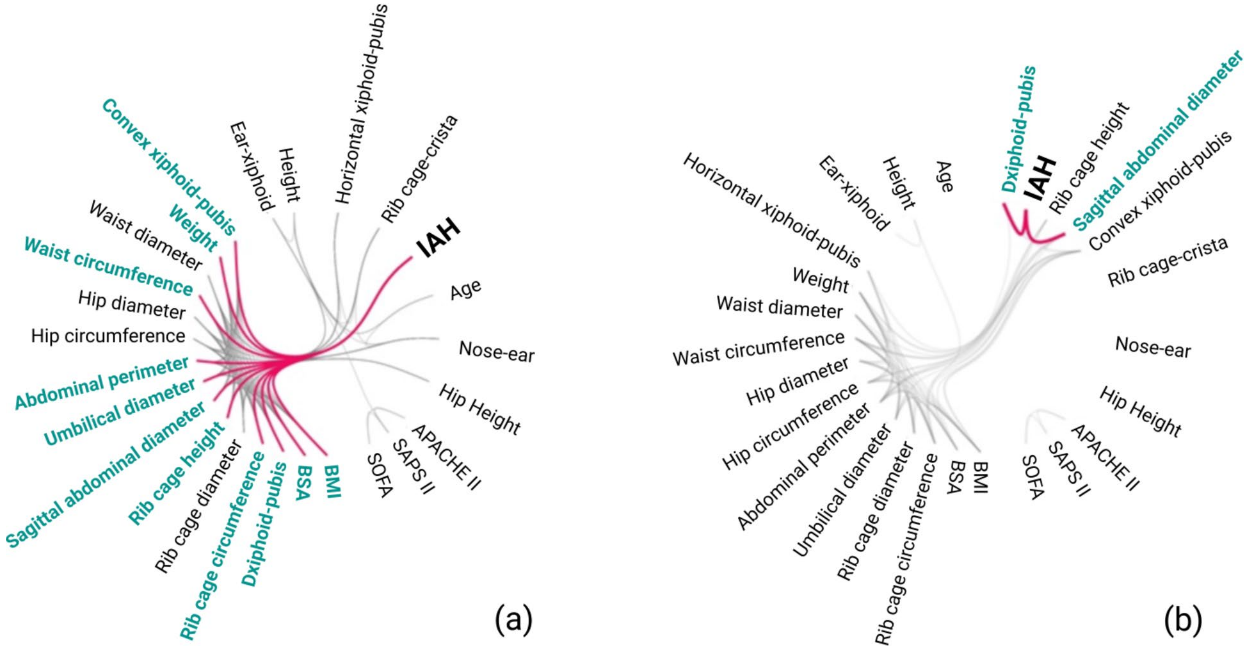

Fig. 5. Circular correlation network plot between IAH and body parameters. (a) Linear correlation analysis between different studied parameters and IAH (minimal strength of correlation 20%) and (b) Mutual correlation analysis between different studied parameters and IAH (minimal strength of correlation 50%).

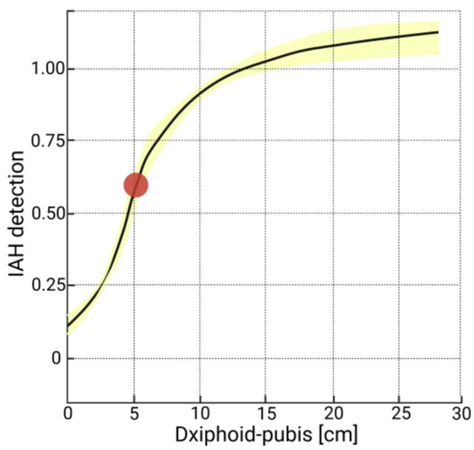

Fig. 6. The relationship between the IAH detection and the difference between the convex and horizontal xiphoid to pubis distance (Dxiphoid-pubis). Based on this simulated relation, the presence of IAH can be predicted with 90% accuracy when the Dxiphoid-pubis sharply increases by more than 10 cm.

measurement methods. Hence, the findings of this study can be applied to intra-gastric pressure measurements as well.

Intra-abdominal pressure and obesity

In this study, we observed a strong correlation between IAP, sagittal abdominal diameter, and Dxiphoid-pubis distance, which can also be seen in obese populations without IAH. At first glance, this may limit the findings of this study, as high SAD and Dxiphoid-pubis distance could be mistakenly interpreted as indicative of IAH, when it may simply reflect obesity without IAH being present. To address this, it is important to consider the patient's BMI when dealing with high SAD and Dxiphoid-pubis distance. If the BMI falls below the range of 25–30 kg/m², elevated SAD and xiphoid-pubis distance likely indicate high IAP. However, if the BMI exceeds 30 kg/m², these measurements should be interpreted with caution, as they may primarily reflect obesity rather than IAH. Regarding the latter case, abdominal compliance is also a factor that determines if the obese patient has IAH. In general, obesity is defined as a BMI higher than 25–30 kg/m². Several previous studies have investigated the correlation between IAP and BMI. Although some papers have found a correlation between these parameters and suggested obesity as one of the IAH markers[38–40], some other studies have not found such a correlation between IAP and BMI[41–43].

Implementing findings into clinical monitoring

The findings of this study demonstrate the feasibility of predicting IAP and detecting IAH using anthropometric parameters and machine learning. Building on these results, additional monitoring methods can be implemented in ICU settings to integrate these findings into clinical practice.

Using imaging methods such as digital image correlation presents a promising approach for continuous monitoring of the body parameters evolution during ICU stays. Digital image correlation is a non-contact optical method used to measure deformation, displacement, and strain in structures. Using this methodology, the sagittal abdominal diameter and Dxiphoid-pubis distance can be monitored and interpreted in relation to the IAP. Although digital image correlation has not been used for IAP measurement, researchers have used a similar concept to investigate the mechanical properties of the abdominal wall during insufflation[44,45].

Another promising method to translate the findings of this study into clinical monitoring is the application of microwave reflectometry. This technique measures the reflection response of the abdominal compartment to electromagnetic radiations at a specific frequency. Any variation in the body parameters including sagittal abdominal diameter and Dxiphoid-pubis distance will alter the reflection response of the abdominal compartment. Therefore, by extracting signal features such as reflection amplitude and phase and time-of-flight from the reflection response of the abdomen, the anthropometric changes of the abdominal compartment during the ICU stay and, therefore, IAP fluctuations can be monitored. Compared to optical methods, microwave reflectometry is capable of providing information about the mechanical properties of the abdominal wall as well. This is of great importance as it enables the application of microwave reflectometry in monitoring the abdominal compliance and, subsequently, having a more comprehensive understanding of the abdominal compartment evolution. Although previous studies showed the application of such techniques in IAP monitoring[18–20], these methods are still under research and development.

Other more simple and cost-effective solutions in monitoring the changes in sagittal abdominal diameter and Dxiphoid-pubis distance could be the application of respiratory inductance plethysmography and strain gauge-based sensors as previously discussed[45]. In this context, the application of tensiometers in checking the abdominal compliance is another promising concept to translate the findings of this study into clinical monitoring.

Overall, this study confirmed previous findings[46] and revealed the most important body parameters in evaluation of the critically ill patients that are suspected for IAH development. These anthropometric data can be used in the future as a predictor of IAH. Moreover, by integrating the abovementioned methodologies it can result in the development of a non-invasive approach to IAP monitoring in the future.

Limitations

Most notable limitations lie around reproducibility in a variety of different shaped patients. Also, patient's abdominal sizes may change unpredictably over long periods, due to other causes which cannot be measured over a short time, for example, subcutaneous fluid collection (extra-peritoneal fluid), fat and muscle loss. The phenotypical variation in different subpopulations may also need to be accounted for particularly in terms of height, and muscle bulk.

It is important to recognize that anthropometric measurements serve as a screening tool for identifying patients who are at risk of IAH, rather than directly measuring IAP itself. Therefore, it is possible to identify obese patients who do not have any significant or curable types of IAH, while slender patients are at risk of having undiscovered IAH. Presently, the evaluation of IAP using approved methods remains crucial for detecting this important clinical condition.

Another limitation of this study is the lack of performance metrics of the predictive models, such as sensitivity and specificity. As the development and training of these models were done using DataStories' proprietary AI system, we did not have access to these specific metrics. The machine learning models, along with their evaluation metrics like sensitivity and specificity, are part of DataStories' internal processes and are not available for public disclosure.

Conclusions

Three measured body parameters showed a correlation of more than 50% with IBP (the difference between the convex and horizontal xiphoid-to-pubis distance, sagittal abdominal diameter, and abdominal compliance). These parameters are sufficient for a reliable prediction of IBP, however, IAH can be most reliably predicted based on the difference between the convex and horizontal xiphoid-pubis distance and the sagittal abdominal diameter.

Although this study shows the high potential of using body parameters and artificial intelligence in IAP monitoring, several further studies over a wide range of patients with different body shapes and sizes are warranted to further validate these findings.

Data availability

The data generated or analyzed during this study are available on request from the correspondence author.

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Declarations

Competing interests
M.L.N.G.M. is a Professor of Critical Care Research in the 1st Department of Anaesthesiology and Intensive Therapy, Medical University of Lublin, Poland. He is a co-founder, past President, and current Treasurer of The Abdominal Compartment Society (WSACS, http://www.wsacs.org). He is a member of the Medical Advisory Board of Pulsion Medical Systems (part of the Getinge Group), Serenno Medical, Potrero Medical, Sentinel Medical Technologies, and Baxter, and consults for B. Braun, Becton Dickinson, ConvaTec, Spiegelberg, Medtronic, and Holtech Medical. He holds stock options for Serenno Medical and Potrero Medical. He received speaker's fees from PeerVoice. He is a co-founder and the President of the International Fluid Academy (IFA). The IFA (http://www.fluidacademy.org) is integrated into the not-for-profit charitable organization "International Medical Education and Research Initiative (iMERiT) under Belgian law. The other authors have no potential conflicts of interest in relation to the contents of this paper.

Ethics declarations
The study protocol was approved by the institutional review board of the local ethics committee (EC: 3001).

Additional information
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