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LUNG DENSITY ON POST-MORTEM COMPUTED TOMOGRAPHY USING THREE-DIMENSIONAL DATA : A COMPARISON BETWEEN FRESHWATER AND SALTWATER DROWNING

Makoto Sugawara, Koichi Ishiyama, Takahiro Otani, Makoto Koga and Manabu Hashimoto

Division of Diagnostic Radiology, Akita University School of Medicine

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Abstract

Purpose : To compare the density of the whole human lungs between freshwater drowning cases (FWDC) and saltwater drowning cases (SWDC) by using three-dimensional data obtained via postmortem computed tomography (PMCT).

Materials and methods : Of 278 drowning cases in our database, 37 cases (18 men, 19 women ; mean age 70.8 y ; range 43-95 y) were selected for the study. Twenty-five were FWDC and 12 were SWDC. Three-dimensional data of the bilateral lungs were obtained from the PMCT. The mean, standard deviation, maximum, and minimum values of the CT number of the whole lungs were calculated. The mean CT numbers of lungs in FWDC and SWDC were compared. Unpaired t-tests were used to analyze the data. A P value of < 0.05 was considered statistically significant.

Results : The mean (±SD) CT number of whole lungs was higher in the SWDC group than that in the FWDC group (−522.87 ± 66.80 Hounsfield Unit [HU], and −616.40 ± 86.34 HU, respectively, $P = 0.001$).

Conclusion : Based on the PMCT findings, a higher lung density was observed in individuals who drowned in saltwater than those in freshwater, which may reflect the differences in the condition of the interstitial edema in the two types of drowning.

Key words : drowning, near-drowning, post-mortem computed tomography, pulmonary edema

Introduction

Drowning is an unexpected tragedy, wherein previously healthy people are exposed to severe cerebral hypoxia, leading to death[1]. It is a serious yet neglected public health threat that claims annually the lives of approximately 372,000 people worldwide[2].

Postmortem computed tomography (PMCT) has been increasingly used in Japan in the past decade, and some PMCT studies involving drowning cases have been reported in forensic medicine. An article classified the lung shadows observed on PMCT of drowning cases into three types : Type 1, Type 2, and Type 1+2[3]. Type 1 shows diffuse ground-glass opacities (GGOs), with thickening of the acinar and lobular interstitium, while Type 2 shows ill-defined centrilobular nodules and patchy GGOs spread along the airways[3]. Type 1+2 shows a mix of the aforementioned types. The authors found Type 1 to have a significantly higher computed tomography (CT) number than Type 2[3], which may have been due to hyperexpanded and waterlogged lungs (emphysema aquosum)[3]. However, there is a lack of studies on the differ-

Corresponding author : Makoto Sugawara
Akita University Hospital, 1-1-1 Hondo, Akita City, Akita 010-8543, Japan
Tel : +81-18-834-1111
Fax : +81-18-836-2623
E-mail : masugawa@doc.med.akita-u.ac.jp

ences between the lung density of human freshwater and saltwater drowning cases.

In a PMCT study involving the drowning of rabbit models, the rabbits' lungs showed no difference between freshwater and saltwater drowning conditions in terms of the percentage of aerated lung volumes (%ALV) within 24 hours[4]. To the best of our knowledge, the difference in the lung densities between freshwater and saltwater drowning cases in humans (i.e., actual cases in forensic medicine) has not been investigated yet. A study reported that the left atrium of freshwater drowning cases (FWDC) had a lower density than that of saltwater drowning cases (SWDC)[5]. However, the lung density (CT number) between both types of cases was not compared in the study[5]. If differences are observed in the lung PMCT findings between FWDC and SWDC, PMCT may play a supportive role in the diagnosis of drowned victims. Based on our experiences of routine interpretation of PMCT in drowning cases, we hypothesized that the lung density is higher in SWDC than in FWDC. Further, we assumed that this difference in density may be due to the difference in the type of pulmonary edema in the two types of drowning cases.

Hence, the aim of our study was to compare the whole lung density of FWDC and SWDC in humans and examine whether a difference exists between the two. We also tried to compare the lung densities between the aforementioned types using PMCT.

Materials and Methods

This study was approved by the institutional review board (Akita University School of Medicine Ethics Committee; approval number: 1894), which waived the requirement for informed consent for this retrospective study. The authors declare that they have no conflicts of interest.

We included cases that underwent PMCT immediately before forensic autopsies at our institute between April 2010 and December 2016. The information, including the diagnosis (causes of death), the locations where the victims were found, death scene details, and other relevant information (e.g., the state of putrefaction), was obtained by examining police investigation and medicolegal autopsy reports. Among the 1,145 cases in our database, 278 involved drowning. Cases with putrefaction, injuries (or hemorrhage), questionable drowning, insufficient information, or a postmortem interval >48 hours were excluded. Cases in which cardiopulmonary resuscitation was performed or suspected to be performed were also excluded. We excluded individuals who drowned while bathing to eliminate potential circulatory system diseases as potential confounders[6].

Overall, 37 drowning cases (18 males, 19 females; mean age, 70.8 y; range, 43-95 y) were obtained. These cases were divided into two groups according to the place where the victims were found. The victims found in the sea or by the sea were assigned to SWDC, while those who were found in water other than seawater or by the waterside other than the sea (river, irrigation ditch, pond, canal, swamp, and water storage tank) were allocated to FWDC. The FWDC consisted of 25 subjects (13 males, 12 females; mean age 73.1 y; range 43-95 y). The SWDC group included 12 subjects (5 males, 7 females; mean age, 65.9 y; range, 55-76 y). Demographics of the FWDCs and SWDCs are shown in Tables 1 and 2, respectively.

After selecting the drowning cases, we identified controls from the remaining 867 victims, using the same exclusion criteria as the drowning cases. We excluded cases where the cause of death was likely to have a strong influence on the lung density, such as cases involving suffocation (including hanging, strangulation, foreign body in the airway; $n = 8$), hypothermia ($n = 7$), and cardiac death (including ischemic heart disease, aortic stenosis; $n = 3$). Finally, six cases were obtained (three males, three females; mean [± SD] age: 38.2 ± 13.8 y; age range: 25-62 y). This sample size was too small for precise statistical analysis. Therefore, we did not include a control group in this study.

A CT scan was performed using an ECLOS scanner (16-row multidetector CT, HITACHI Medical Corporation, Tokyo, Japan). Series 1 images (head only) were obtained using the following parameters: 120 kV; 200 mA; scan time, 2 s; collimation, 16 mm × 0.625 mm; and reconstructed slice thickness, 5.0 mm. Series 2 images (head to lower extremities) were obtained using the following parameters: 120 kV; 225 mA; scan

Table 1. Characteristics of freshwater drowning cases (n=25)

Case No.	Sex	Age (years)	Mean CT number of bilateral lungs (HU)	Standard deviation of CT number of bilateral lungs (HU)	Maximum CT number of bilateral lungs (HU)	Minimum CT number of bilateral lungs (HU)	Volume of bilateral lungs (mL)
1	F	77	−642.849	210.513	498	−970	2,315.929
2	M	63	−627.101	167.69	964	−919	3,167.688
3	F	95	−655.764	178.931	535	−988	1,936.356
4	F	87	−637.894	182.447	803	−941	2,188.484
5	F	76	−570.457	174.03	759	−977	2,355.039
6	F	69	−683.022	119.143	638	−905	2,364.423
7	F	77	−761.586	129.194	527	−973	4,362.66
8	F	92	−653.666	165.415	747	−981	2,817.467
9	F	75	−726.874	170.512	752	−969	2,814.923
10	F	95	−640.692	151.395	314	−976	2,210.036
11	M	43	−656.741	139.389	547	−948	2,254.693
12	M	78	−581.333	174.014	735	−939	3,129.696
13	M	66	−542.131	140.731	879	−932	3,269.456
14	M	74	−487.389	217.85	1,244	−967	3,505.671
15	F	82	−745.657	126.055	607	−990	2,602.517
16	F	72	−645.042	133.061	447	−989	2,726.926
17	M	80	−557.492	199.135	761	−985	2,160.739
18	M	46	−711.788	139.034	1,218	−954	2,926.447
19	M	85	−580.825	170.395	608	−953	2,628.626
20	M	82	−684.403	148.314	810	−986	3,596.701
21	F	70	−455.175	224.244	703	−938	1,677.744
22	M	67	−589.355	188.012	683	−983	2,288.559
23	M	43	−624.109	167.078	714	−973	2,885.353
24	M	61	−419.108	197.161	926	−932	2,799.091
25	M	72	−529.562	219.504	754	−994	3,746.481

time, 0.8 s/175 mA ; scan time, 0.8 s ; collimation, 16 mm × 1.25 mm ; and reconstructed slice thickness, 2.5 mm. A contrast medium was not administered. The lungs were studied in 2.5 mm-thick slices.

A board-certified radiologist used a workstation (SYNAPSE VINCENT, FUJIFILM Corporation, Tokyo, Japan) to construct three-dimensional bilateral lung data, and four board-certified radiologists checked the data. First, the lung fields were extracted automatically using the built-in software (the threshold CT number for this extraction was not available). After automatic extraction, incorrect or inappropriate lung field margins were modified manually using the drawing tool. Each axial slice of the lung fields (regions-of-interest [ROI]) was obtained semi-automatically, as described above. The slices were assembled to provide three-dimensional data of the bilateral lungs in each case. The trachea and bilateral main bronchi were manually excluded from the ROI.

Similarly, the lobar and segmental bronchi and accompanying pulmonary arteries and veins were excluded from the ROI or lung field. These structures can produce erroneous CT numbers in the lungs. In contrast, subsegmental and distal bronchi and accompanying vessels were included in the lung field. Although peripheral bronchi and accompanying vessels could influence the lung field CT number, the effect seemed minimal. Moreover, the complete exclusion of all the bronchi, pulmonary arteries, and veins was considered practically

Table 2. Characteristics of saltwater drowning cases (n=12)

Case No.	Sex	Age (years)	Mean CT number of bilateral lungs (HU)	Standard deviation of CT number of bilateral lungs (HU)	Maximum CT number of bilateral lungs (HU)	Minimum CT number of bilateral lungs (HU)	Volume of bilateral lungs (mL)
1	M	68	−504.106	208.917	268	−994	2,746.708
2	F	63	−520.04	148.041	450	−877	2,337.424
3	F	57	−432.58	200.5	1,029	−930	2,506.133
4	M	68	−535.806	192.301	985	−1,010	2,862.57
5	M	77	−514.965	221.445	836	−985	3,375.93
6	F	62	−662.106	157.076	432	−985	2,321.228
7	M	62	−484.448	200.079	670	−988	3,866.821
8	F	76	−580.403	164.503	705	−980	2,820.531
9	M	55	−439.407	166.643	821	−914	2,481.483
10	F	76	−456.857	193.023	1,002	−1,007	2,147.828
11	F	67	−567.52	145.704	606	−932	2,312.934
12	F	60	−576.242	137.212	515	−991	2,949.182

impossible. Examples of the axial, coronal, sagittal, and three-dimensional ROIs of an SWDC are represented in Figures 1a-1d, respectively. The CT number of the three-dimensional data was calculated, and the mean, standard deviation, maximum, and minimum values were evaluated. The whole lung volume was also calculated.

The PMCT findings (shadow) of the lungs were divided into three major types : Type 1, Type 2, and Type 1+2, as previously reported[3].

The CT values and the number of cases in this study for each PMCT type were assessed. Statistical analyses were performed using the SPBS software version 9.6 (Winesteen Institute of Community Medicine, Toda, Japan). Unpaired *t*-tests (Welch's, unequal variance) were used to assess the data. A *P*-value < 0.05 was considered statistically significant.

Results

The mean (±SD) CT number of the bilateral whole lungs was higher in the SWDC group than that in the FWDC group (−522.87 ± 66.80 and −616.40 ± 86.34 Hounsfield Unit [HU], respectively, $P = 0.001$). The data is represented in Table 3. CT findings of lungs in a freshwater drowning case and that in a saltwater drowning case are represented in Figures 2 and 3, respectively.

The mean (±SD) volume of the bilateral whole lungs showed no significant difference between the FWDC and SWDC groups (2,749.27 ± 621.99 mL and 2,727.40 ± 498.14 mL, respectively ; $P = 0.909$).

The number of cases with Types 1, 2, and 1+2 PMCT shadows are shown in Table 4. The proportion of Type 1 was larger in the SWDC group than that in the FWDC group. However, due to the small number of Type 2 cases in the SWDC group ($n = 2$), the proportion of the three types could not be compared statistically in the SWDC group. There was no significant difference found between the mean (±SD) CT number of Types 1 and 2 in the FWDC group (−573.94 ± 107.85 and −629.68 ± 103.95, respectively, $P = 0.354$).

Discussion

Based on the PMCT findings, we compared the mean lung densities (CT number) between the two main types of drowning in humans. The CT number — indicating density — was higher in the SWDC than in the FWDC group, likely secondary to differences in pulmonary edema between the two types of drowning cases. Drowning in either fresh or saltwater results in pulmonary edema[1], either of the hemodynamic or permeability/capillary leak type[7]. Pulmonary edema associated with drowning

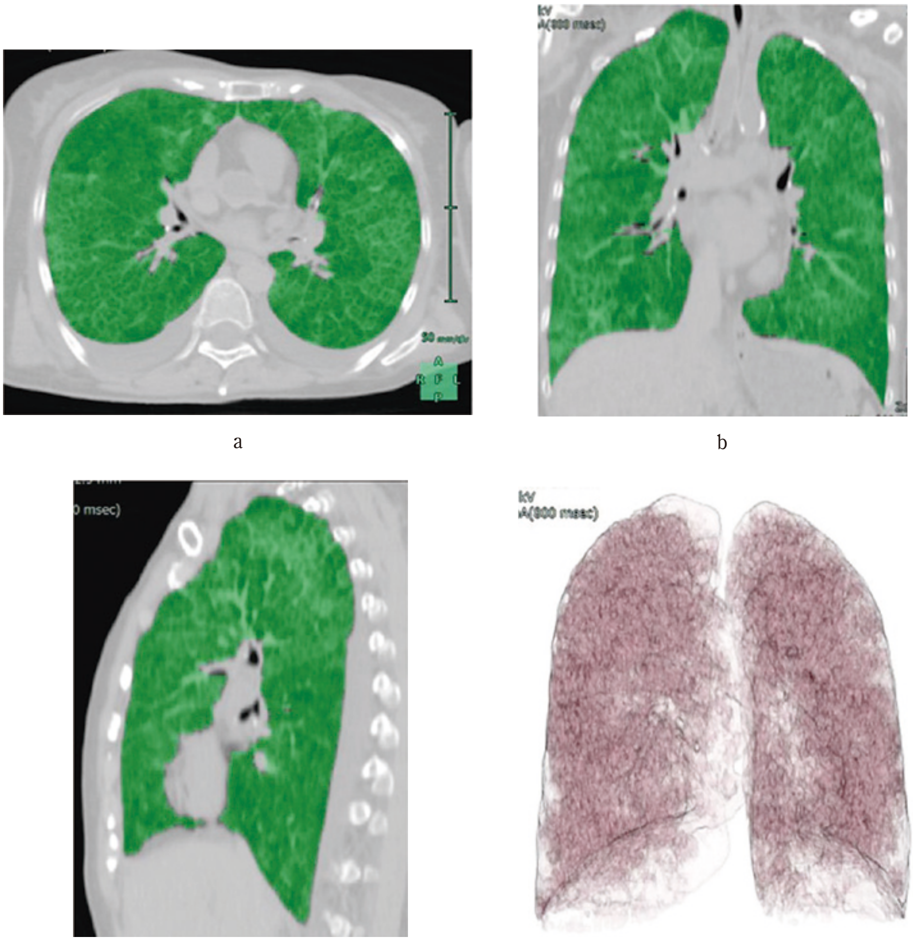


Fig. 1. The three-dimensional region-of-interest (ROI) of the whole lung based on axial ROIs
(a) Each axial ROI was stacked and reconstructed into a three-dimensional, bilateral whole lung ROI, with confirmation from the coronal and sagittal sections. This figure shows an example of an axial ROI in a saltwater drowning case.
(b) An example of a coronal ROI in the same case as shown in a.
(c) An example of a sagittal ROI in the same case as shown in a and b.
(d) An example of a three-dimensional ROI obtained from an assembly of axial ROIs in the same case as shown in (a) and (c).

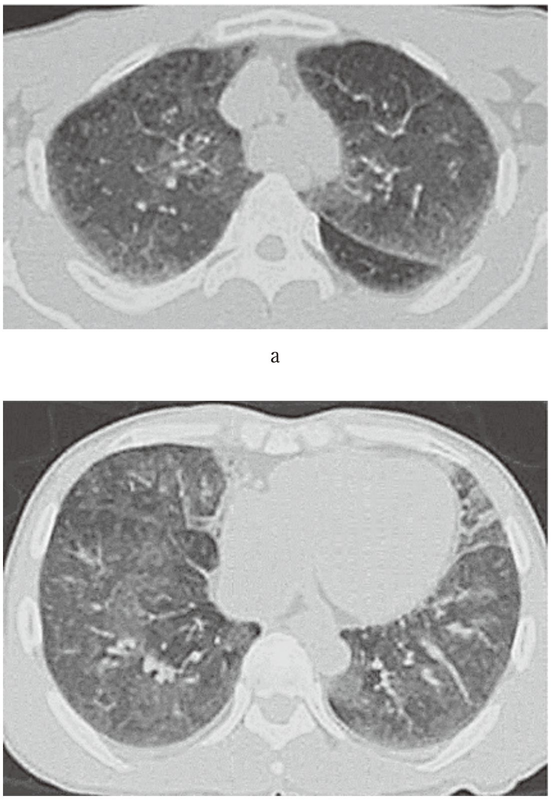
is a *permeability* type ; it is associated with near-drowning[7] and only differs from drowning in terms of the victim's survival[8]. The mechanisms of pulmonary edema are specific to each type of drowning and reflect differences in the movement of inhaled water within the lungs.

The gas-exchanging lung parenchyma contains three extracellular fluid spaces : the capillary (CAP) blood space, interstitial space (INT), and alveolar space (AVS)[9]. The barrier between the CAP and INT is the capillary endothelium, a relatively weak and leaky layer that allows free exchange of molecules between the two fluid-filled spaces[9]. The barrier between the INT and AVS consists of alveolar (type 1 and 2) epithelia. This barrier is sufficiently tight to prevent free molecular ex-

Table 3. Comparison of mean CT number of the lung in postmortem CT, sex, and mean age between freshwater drowning cases and saltwater drowning cases

		Fresh water drowning	Saltwater drowning	P-value
Mean CT number of the lungs ± SD (HU)		−616.40±86.34	−522.87±66.80	0.001 [a]
Sex*	Male	13 (52.0)	5 (41.7)	0.7281 [b]
	Female	12 (48.0)	7 (58.3)	
Mean age ± SD (years)		73.08±14.19	65.92±7.44	0.0522 [c]
Age range		43-95	55-76	

[a,c]Welch's *t* test
[b]Fisher's exact test.
*Sex indicates the number of the cases. The number in the parentheses indicate the percentage.



a

b

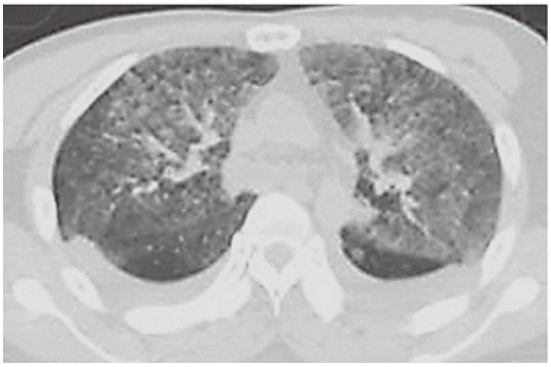
Fig. 2. A case of freshwater drowning (sixty-six-year-old male)
The CT of upper lung field (a) and lower lung field (b) represent diffuse ground-glass opacity, which is considered to reflect pulmonary edema.

change between the two fluid spaces[9].

In saltwater drowning, the hypertonic saltwater that fills the AVS pulls the fluid from the CAP into the AVS via the INT; this water movement is opposite that seen in freshwater drowning[10-12]. In freshwater drowning, the hypotonic liquid (inhaled water) moves rapidly from the AVS into the CAP via the INT[10]. Differences in edema location or severity led to the lung density differences observed in our study.

Pulmonary edema occurs in two stages: the first stage is interstitial edema, and the second stage is alveolar edema[13]. In saltwater drowning, molecular exchange occurs more easily between CAP and INT through the highly permeable barrier[9]. The tight barrier between the INT and AVS prevents water from moving easily from the INT to AVS. Consequently, fluid readily accumulates in the INT. In freshwater drowning, the water cannot move easily from the AVS to INT because of the tight barrier between the AVS and INT. Because of this, water is less likely to accumulate in the INT as it can move from the INT to CAP relatively easily. Therefore, water accumulates in the INT more readily during saltwater, compared to freshwater, drowning events. Our results may have influenced by differences in the severity of interstitial density or edema between SWDCs and FWDCs. Figure 4 shows the presumed mechanism behind the higher CT number in SWDC than in FWDC.

Hyodoh *et al.* demonstrated no significant difference in the percentage of aerated lung volume per total lung volume (% ALV) between rabbits subjected to fresh- or saltwater drowning. The ALV was the volume of parts of the lungs whose CT number ranged from −700 to −1,000 HU. Postmortem lung CT scans revealed no significant between-group differences[4]. However, the authors did not focus on the lung parts where the CT number was out-of-range (greater than −700 HU). In contrast, we focused on the (CT number of the) bilateral whole lungs. We believe that the higher lung densities



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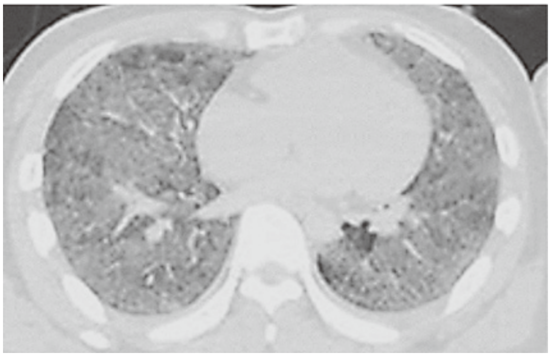

b

Fig. 3. A case of saltwater drowning (fifty-five-year-old male)
The CT of upper lung field (a) and lower lung field (b) represent diffuse ground-glass opacity, which is considered to reflect pulmonary edema. The shadows seem denser than those in Figure 2 (the case of freshwater drowning). Thickened interlobular septa are seen diffusely.

Table 4. Number of cases according to postmortem computed tomography shadow type in freshwater drowning cases and saltwater drowning cases

	Freshwater drowning (n = 25)	Saltwater drowning (n = 12)
Type 1	6 (24.0%)	8 (66.7%)
Type 2	8 (32.0%)	2 (16.6%)
Type 1+2	7 (28.0%)	2 (16.6%)
Others	4 (16.0%)	0 (0%)

in saltwater drowning than in freshwater drowning is due to phenomena that occur in at least one of the three parts of the lungs : the AVS, the INT, or the CAP. Based on the results of a study by Hyodoh *et al.*, we considered that the cause of the difference in CT number in the current study was not likely to exist in the air-filled part of the lung (including the AVS). We believed that the cause of the difference was in the remaining two lung compartments : the INT, the CAP, or both.

Because water accumulates in the INT more easily during saltwater drowning, this compartment was most likely the reason for the increased density. The difference in the density between SWDC and FWDC might be due to the discrepancy of the CT number of the INT between the two groups, reflecting the difference in severity of interstitial pulmonary edema. We hypothesized that more severe interstitial pulmonary edema occurred in saltwater drowning compared to freshwater drowning ; our results might reflect this difference.

We compared lung densities as measured by PMCT among Types 1, 2, and 1+2[3]. Due to fewer Type 2 cases (n = 2) in the SWDCs group, we could not compare them ; therefore, future well-powered studies are recommended. We also found no significant between-group differences in lung volume between the FWDCs and SWDCs. Thus, lung volume on PMCT may not be related to the type of drowning.

There are some limitations to this study. First, our method of determining the ROI was not strict. Nevertheless, since the decision was based on the anatomical identity of the bronchi and blood vessels and all cases were analyzed similarly. Second, the sample size of our study was small, particularly in the subgroups (e.g., PMCT Type 2 in SWDCs). Further studies with larger sample sizes are recommended.

In conclusion, three-dimensional data obtained from PMCT findings revealed higher whole lung density (CT number) in victims of saltwater versus freshwater drowning. This may reflect differences in interstitial edema between the two types of drowning.

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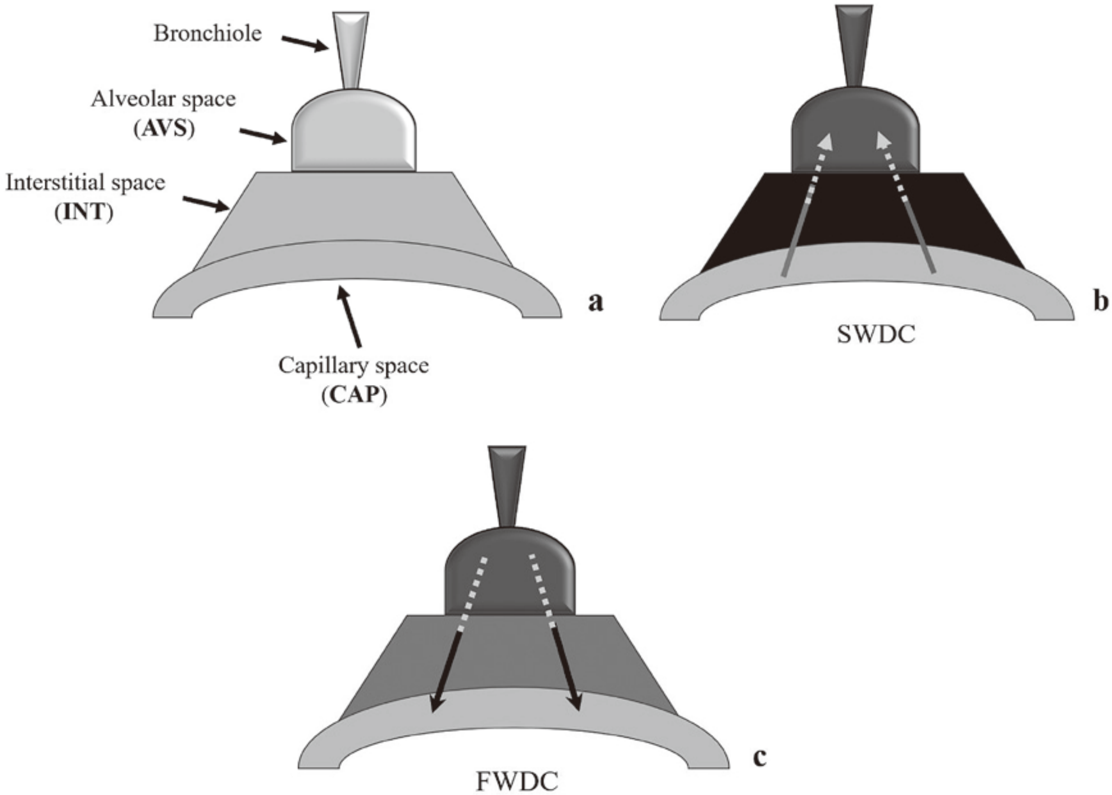

Fig. 4. Diagrammatic representation of the supposed mechanism behind the higher computed tomography number in saltwater drowning cases (SWDC) than in freshwater drowning cases (FWDC).
(a) A diagram of normal lungs. There are three extracellular fluid spaces : the blood space of the capillary (CAP), the interstitial space (INT), and the alveolar space (AVS).
(b) The condition of pulmonary edema in SWDC. The gray-colored solid and dotted arrows indicate the movement of water from the CAP to AVS (via the INT). The solid part of the arrow expresses strong movement of water, while the dotted part of the arrow shows weak movement of water. First, the water moves easily from the CAP to INT through the leaky barrier (endothelial junction). This water is pulled by the hypertonic seawater in the AVS. Because there is a tight barrier (alveolar epithelium layer) between the INT and AVS, water cannot move from the INT to AVS easily, and it tends to accumulate in the INT. As a result, severe interstitial edema in the lung presents as high density on PMCT. The water accumulation is represented by deep black color of the INT.
(c) The condition of pulmonary edema in FWDC. The hypotonic inhaled water in the AVS cannot move easily to the INT, because of a tight barrier (alveolar epithelium layer).
Water, which can arrive in the INT, readily moves to the CAP because the barrier between the INT and CAP is thin (leaky). Therefore, water in the INT does not tend to accumulate in it. The interstitial edema is not as severe as that seen in SWDC. As a result, the lung density in this case becomes lower than that in SWDC. The different colors of the INTs in Fig. 4b and Fig. 4c (deep black and gray, respectively) indicates this discrepancy.

English language editing.

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