[16]. However, when gas embolism does develop, the mortality rate can be as high as 30 % [14, 17]. Thus, although laparoscopic procedures are minimally invasive, they can lead to potentially life-threatening complications.

Because the risk of gas embolism during pneumoperitoneum has always been present in LH due to the unique anatomy of the liver, many studies performed LH with PP minimized in order to avoid the risk of gas embolism [18]. In the animal model, however, any levels of PP can be considered potentially dangerous, and so gasless laparoscopy, either abdominal wall lifting or laparoscopy-assisted surgery, was recommended [9, 19].

Increased pressure to control bleeding in LH

It is believed that the lower blood loss in LH as compared with open hepatectomy (OH) is due to PP and the magnified view offered by laparoscopy. It has been suggested that high PP is occasionally advantageous for hemostasis, and poses few clinical risks because the solubility of carbon dioxide in human plasma at 37 °C is greater than that of air [20]. Several clinical studies of LH also suggested that higher PP was effective in controlling bleeding during liver parenchymal transection [21], and one study used PP ranging from 18 to 20 mmHg [22]. In addition, Jaskille et al. [23] reported that maintenance of constant PP during surgery reduced blood loss in an animal model of liver trauma.

Dissection of major hepatic veins and decreased central venous pressure in major hepatectomy

In major hepatectomy, many authors insist that the hepatic vein must be sufficiently exposed on the surface to be transected during anatomical resection [24]. Furthermore, by maintaining low central venous pressure (CVP), bleeding from blood vessels on the resectioned surface can be minimized [25, 26]. Although there is a risk of air embolism caused by absorption of air into the vena cava through the branches of the hepatic veins during OH [27], the incidence of clinically significant air embolism is low, as lower CVP is commonly used during OH [28]. However, it is assumed that the risk of gas embolism would be enhanced by low CVP combined with high PP.

Experimental studies of laparoscopic major hepatectomy

Schmandra et al. [29] performed left hepatectomies on pigs divided into a totally LH group at a PP of 12 mmHg and an OH group. There was no case of air embolism in the OH group; however, gas embolism developed in all pigs that underwent LH. As operative time increased, the partial pressure of oxygen in arterial blood decreased. The authors later conducted a sililar study using hand-assisted technique and found that the incidence of gas embolism decreased [30].

Eiriksson et al. [31] also performed laparoscopic left hepatectomy on pigs using PPs of 8 and 16 mmHg. Blood loss was significantly lower at the higher pressure; however, the incidence of gas embolism was higher. The authors concluded that close monitoring for gas embolism is necessary when using high pressure; in addition, changes in the systemic circulation, such as mean arterial pressure or pulse rate, are not sensitive or specific for gas embolism except in a very late, fatal phase.

Jayaraman et al. [32] performed hand-assisted laparoscopic left hepatectomies in 3 groups of different PP-to-CVP gradient. In the positive gradient group, PP was normal (14 mmHg) and CVP was decreased to less than 5 mmHg; in the negative gradient group, CVP was normal (10–12 mmHg) and PP was decreased to 7 mmHg; in the neutral gradient group, the pressures were equal (either both at normal levels or both lowered to the reduced levels described above). The authors suggested that the risk of gas embolism increased as the PP-to-CVP ratio increased.

Clinical studies of laparoscopic major hepatectomy

There have been more than fifty English-language reports of laparoscopic major hepatectomy, comprising nearly a thousand cases, up to May 2012. Table 1 shows the characteristics of studies with more than 10 enrolled subjects undergoing laparoscopic major hepatectomy at single centers, with hepatic parenchymal transection under the pneumoperitoneum [3, 6, 8, 33–39]. Studies featuring LH using the laparoscopy-assisted technique, which divide the liver parenchyma through a small laparotomy, are excluded from this result. These reports comprise 477 laparoscopic major hepatectomies involving 3 or more Couinaud's segments. Among the 10 studies, information regarding PP during hepatic parenchymal transection was available in 8 studies. In 6 of these 8 studies, PP was usually maintained at 12 mmHg or lower; the other 2 studies used pressures higher than 12 mmHg. Cannon et al. [37] used pressures of 12–15 mmHg to control bleeding from veins on the surface of the transected liver (including exudative bleeding); however, pressure was not maintained routinely at these high levels. A detailed report by Gayat et al. [6] described that PP was maintained between 8 and 12 mmHg, but before transection of the liver parenchyma, pressure was reduced to the minimum required to maintain a clear operative field (8–10 mmHg), to reduce the risk of gas embolism. Furthermore, to control bleeding from the hepatic veins, the authors reported that it was useful to keep the inferior vena cava in a "half-filled" state (i.e., with visible motion in the vein in response to pulse and respiration). Because of the pressure effects of pneumoperitoneum, CVP readings transduced from a central venous catheter do not accurately reflect actual CVP, which suggests that it is advantageous to maintain both low PP and low CVP.

Three (0.2 %) patients developed gas embolism in this series, but there was no causal relationship between the pressures used and the development of clinically important gas embolisms. The Henri Mondor Hospital Group reported 2 cases (1.72 %) of gas embolism among a total of 166 LH patients. During surgery, there were sudden slight or temporary decreases in end-tidal CO_2 concentration ($ETCO_2$), which were diagnosed to be due to gas embolism. However, there were no complications related to gas embolism during postoperative recovery in either case [36]. Dagher et al. [3] reported a case of gas embolism caused by a tear in the section line of the right hepatic vein. This incident resulted in a transient lowering of blood pressure and was treated by laparoscopic suture.

Dagher et al. [40] also reported 210 cases of laparoscopic major hepatectomy performed at high-volume centers in Western countries; 3 (1.43 %) patients developed gas embolism. All 3 had undergone right hepatectomy, and the embolisms developed during the dissection of the hepatic veins. However, the influence of gas embolism on postoperative morbidity and mortality was not indicated.

Finally, a study of registry data collected during an 8-year period revealed 1 case (0.55 %) of gas embolism without mortality among 182 LHs performed at multiple centers in Spain [41].

Conclusions

Studies of LH procedures performed at experienced high-volume centers found low incidences of gas embolism, but the rates were higher than those for other types of laparoscopic surgery. PP is maintained at less than 12 mmHg in many centers, which appears to be a suitable pressure; however, experimental studies have shown that gas embolism can frequently occur even at such pressures. In addition, careful consideration must be taken of the PP-to-CVP gradient to reduce the risks of gas embolism. It is also important to continue developing safer surgical techniques that avoid hepatic venous injuries and shorten operative time, thus minimizing the duration of PP. Moreover, additional data on peri-operative complications, including available registry information, should be collected to determine the optimal PP and the incidence of gas embolism in LH.

Table 1 Characteristics of studies of laparoscopic major hepatectomy that enrolled more than 10 patients (at single centers)*

References	Years	No. of LH cases	Laparoscopic major hepatectomies		Procedure of LH	Mortality		Morbidity		Pneumoperitoneal pressure during parenchymal transection (mmHg)	Incidence of gas embolism	
			n	%		*n*	%	*n*	%		*n*	%
Dulucq et al. [33]	2005	32	11	34.4	TL	0	0.0	NA	NA	~12	0	0.0
Koffron et al. [8]	2007	300	119	39.7	TL/HA/LA(241/32/27)	NA	NA	28	9.3	NA	NA	NA
Gayat et al. [6]	2007	42	42	100.0	TL	1	2.4	NA	NA	8~10	NA	NA
Topal et al. [34]	2008	109	21	19.3	TL	0	0.0	6	5.5	6~8	NA	NA
Cho et al. [35]	2008	128	36	28.1	TL	1	0.8	22	17.2	~12	0	0.0
Bryant et al. [36]	2009	166	31	18.7	TL/HA (150/16)	0	0.0	25	15.1	~12	2	1.2
Dagher et al. [3]	2009	22	22	100.0	TL	0	0.0	3	13.6	NA	1	4.5
Cannon et al. [37]	2011	300	133	44.3	TL/HA (89/211)	5	1.7	32	10.7	12~15 (temporary)	0	0.0
Choi et al. [38]	2012	30	20	66.7	TL (Robot)	0	0.0	13	43.3	12	NA	NA
Abu Hilal et al. [39]	2012	133	42	31.6	TL	1	0.8	16	12.0	12~14	NA	NA
Total		1262	477	37.2		8	0.6	145	11.5		3	0.2

*Studies performing laparoscopic major hepatectomy only by laparoscopy-assisted technique are excluded

NA not available, *TL* totally laparoscopic procedure, *HA* hand-assisted laparoscopic procedure, *LA* laparoscopy-assisted procedure

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