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Quality efforts in medical supply chains considering patient benefits

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ABSTRACT

We consider supply chain (SC) contracts in a new setting, the medical equipment industry, where concern for patient benefits is essential and quality efforts are critical for profits compared with supply chains (SCs) in other industries. It remains unclear how quality efforts and patient concern levels affect SC performance and how medical equipment manufacturers' quality effort levels are linked to their patient concern levels. This study focuses on the impact of a manufacturer's and a retailer's patient concern levels on optimal pricing and quality decisions in an SC consisting of a manufacturer facing quality effort-dependent demand and a retailer in the medical equipment industry. We use the Stackelberg game to characterize and determine the optimal operational decisions in five scenarios and address the effects of patient concern levels under above five scenarios. A real case is studied and shows that optimized quality efforts can improve SC profits. The parameters settings are derived from the real data. Our findings bridge the gap between SC quality management and patient benefits and help to understand contract design in relation to patient concerns in different SC structures. This paper is among the earliest to investigate quality efforts for SC contract design in relation to patient concerns and to study SC contract design in the medical equipment industry. Our managerial insights are expected to help manufacturers move toward better quality effort decisions considering patient benefits and are also applicable to other SCs with effort-dependent demand and the effect of altruistic preferences.

1. Introduction

This research was mainly motivated by quality effort decisions faced by a medical equipment supply chain (SC) comprising a medical equipment manufacturer in Asia and a healthcare equipment retailer in Europe selling products to North America and Europe that provide diagnostic solutions (reagents, instruments, software, etc.) for determining the source of disease and contamination to improve patient health and ensure consumer safety. The products are focused on diagnosing infectious diseases, providing high medical value results for cancer screening, and monitoring cardiovascular emergencies. The medical equipment manufacturer strives to fulfill its Corporate Social Responsibility (CSR) by serving public health, which is critical for all players in healthcare supply chains (SCs). However, the manufacturer's products have suffered from quality problems, which impacted sales in 2013 and led to recalls in March 2014. Subsequently, the manufacturer invested in product quality, but this came with a tradeoff: too little quality effort decreases patient concern levels, while too much quality effort may hurt profits. Therefore, a critical problem for practitioners in the medical equipment industry is how to determine the optimal quality effort for SCs with patient concerns.

The issue of quality goes beyond the medical equipment industry. In 2016, the batteries of Samsung's Galaxy Note 7 devices exploded in South Korea and other markets. These battery explosions caused significant environmental concerns and evolved into a public safety issue. The above incident affected Samsung's operations in many countries and resulted in profit reductions. Most of the batteries used in Samsung's Galaxy Note 7 were made by Samsung SDI, which needed to optimize quality efforts to handle the challenges of financial performance and social concerns.

In recent years, interest among managers and politicians in CSR has increased sharply (Amalric, 2006; Donaldson & Fafaliou, 2003; McWilliams & Siegal, 2001), which suggests that corporations are embracing responsibilities for a broader group of stakeholders, such as customers and employees, alongside their financial obligations to stockholders (Hernandez-Murillo & Martinek, 2009). Introducing consumer welfare into organizational considerations is also very important for the development of sustainable SCs, as customer surplus is becoming an important element for organizations and SCs (Goering, 2007, 2008a, 2008b; Goering, 2012; Panda, 2014; Panda, 2015; Bian, Li & Guo, 2016; Brand & Grothe, 2015). In most

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countries, patients and end consumers of medical equipment SCs complain about increasing healthcare costs. Since medical equipment manufacturers and healthcare equipment retailers' concerns go beyond economic values in a conventional SC, this introduces multiple new problems in the SC, such as pricing strategies, societal fairness, etc. High healthcare costs not only hurt patients' economic benefits, but also influence economically disadvantaged people's access to healthcare service. This paper focuses on analyzing and comparing several contracts for decentralized medical equipment SC models.

A revenue-sharing contract was first applied in the video rental industry, in which the cost of a tape is higher than the price of a rental (Cachon & Lariviere, 2005). Since then, many studies have compared the possible outcomes of revenue-sharing contracts with other contracts (EI Ouardighi, 2014; EI Ouardighi & Kim, 2010; Kaya, 2011; Panda, 2014). Several authors have used the revenue-sharing contract alone or together with other contracts to coordinate SCs (Govindan & Popiuc, 2014; Hsueh, 2014; Vafa Arani, Rabbani & Rafiei, 2016; Zhang, Liu, Zhang & Bai, 2015). As in the movie industry, medical equipment production typically has a high fixed cost (e.g., R&D costs and costs for FDA certification) and a relatively low variable production cost. Thus revenue-sharing contracts are widely used in medical equipment SCs. However, most SC contracting literature has focused on self-interested rational members and ignored social preferences (Loch & Wu, 2008). We examined revenue-sharing contracts with regard to patient benefits. Under a revenue-sharing contract, a healthcare equipment retailer pays a price for each unit purchased in addition to a percentage of the revenue that the retailer generates.

Medical equipment SC contract design has new implications when considering both quality efforts and patient benefits. In general, manufacturers must not only maintain a quality effort level for sustainable development, but also consider patient surplus to improve CSR. On the other hand, the retailer also considers the patient surplus into its objective function. However, it remains unclear how quality efforts and patient concern levels affect SC performance and SC contract design, and how a medical equipment manufacturer's quality effort level is linked to their patient concern level. Therefore, this study attempts to investigate the impact of medical equipment manufacturers' and retailer's concern level of patient benefits on both retailers and the entire SC when demand depends on manufacturers' quality effort levels and retailers' retail prices.

Overall, this research bridges three research gaps: (1) the role of patient concern level in the medical supply chain, (2) quality efforts decision with considering patients' welfare constraints, and (3) introduce a real case into medical SC contract design. Our research question is: *How can optimal quality efforts be determined for SC contract design with patient concerns in the medical equipment industry*? To understand this question, we also needed to answer another one: How does a manufacturer's and a retailer's patient concern level affect the manufacturer's quality effort decision and SC performance under various SC structures and mechanisms?

To answer the above research questions, we considered a two-stage SC with a medical equipment manufacturer and a healthcare equipment retailer in which the manufacturer considers patient surplus in addition to profit. We investigated the following five models: wholesale price contract with no patient concern (Model I), wholesale price contract with patient concern (Model II), revenue-sharing contract with no patient concern (Model III), revenue-sharing contract with patient concern (Model IV), and revenue-sharing contract with welfare constraints on patient surplus (Model V, which is put in appendix B). In the wholesale price contract with no patient concern (Model I), the manufacturer determines the wholesale price and the quality efforts, and the retailer determines the retail price separately. In the Models II, III and IV, the manufacturer also determines the wholesale price and the quality efforts, while the retailer determines the retail price. In the revenue-sharing contract with welfare constraints on patient surplus (Model V), the manufacturer maximizes profit by considering consumer-welfare constraints. More specifically, we investigated the effects of patient concern levels on profits, quality effort levels, sales quantities, the wholesale prices and retail prices in the above Models I, II, III and IV. We used a case study to validate the analytical results. We also studied the effects of the retailer's revenue-sharing fraction on the sales quantity, the wholesale price, the retail price, the quality effort level and the SC performance.

This paper makes the following contributions. (1) In the application field, we study SC contract design in the medical equipment industry. This type of SC is relevant to public health, and therefore patient concerns are essential and quality efforts are relevant to medical equipment manufacturers and retailers' profits and patient concern levels. (2) In the field of SC quality management, we investigate quality efforts in medical equipment SCs with patient concern. (3) We contribute to the field of SC contract design by developing optimal models for five SC structures considering the joint effects of manufacturer's and retailer's patient concern. (4) We collect the real data, introduce the data into the models and find that new parameters settings are rigorous.

We find that the retail price will always decreases with the manufacturer's and retailer's patient concern in Models II and IV. We also find that the product's sales quantity increases with manufacturer's and retailer's patient concern in Models II and IV respectively. Then, we find that the quality effort level increases with manufacturer's and retailer's patient concern level in Models II and IV. We also investigate the effects of patient concern on the profits of the retailer, the manufacturer and the SC. For the Model V, the above problem will have different results if constraint condition is binding or not.

2. Literature review

In general, our paper is related to five streams of literature: SC management with considering consumer surplus, contract design with effort-dependent demand, the medical SC management, quality management in SCs, and the effect of altruistic preferences on SC management.

First, many relevant researches were mainly focused on SC pricing strategies and contract design considering social concern from the viewpoint of enhancing consumer surplus (Goering, 2007, 2008a, 2008b; Goering, 2012; Panda, 2014; Panda 2015; Bian et al., 2016; Brand & Grothe, 2015; Panda, Modak & Cárdenas-Barrónc, 2017). Specially, a mixed duopoly setting is examined in which a private non-profit firm competes with a private profit-maximizer (Goering, 2007). Then, a simple linear demand with two-period durable goods is studied in which the durable good is provided by a socially concerned firm (Goering, 2008a). Then, Goering (2008b) extends Goering (2007) to examine a mixed oligopoly setting where a non-profit firm's rival is a pure profit maximizer, a public social welfare maximizer, or both in a mixed market Cournot setting. Moreover, some researches assume that a firm's CSR is accounted through consumer surplus of its stakeholders (Goering, 2012; Panda, 2014; Panda, 2015). Specially, a simple bilateral monopoly SC coordination model is examined, and the impact of CSR on the optimal two-part tariff scheme is analyzed (Goering, 2012). A coordination mechanism of a SC with CSR retailer and CSR manufacturer is studied (Panda, 2014). Then, Panda (2014) is extended to a three-stage SC and the coordination mechanism of the SC is also analyzed (Panda, 2015). Recently, a linear bilateral monopoly is introduced to analyze the effects of firms' social concern in which both the SC members can be socially concerned (Brand & Grothe, 2015). Then, a strategic analysis is

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examined to incorporate CSR considerations into managerial incentive design in a duopoly where each firm consists of an owner and a manager (Bian et al., 2016). Lastly, Panda et al. (2017) study the effects of CSR and explores channel coordination in a socially responsible manufacturer-retailer closed-loop SC. Consumer surplus is more important in a medical SC compared to others, so we focus on it. However, the above researches don't worry about quality.

The second stream focuses on contract design with effort-dependent demand. Mukhopadhyay, Su and Ghose (2009) investigate a distribution channel with a manufacturer selling through a sales agent in which the agent exerts an appropriate marketing effort level to influence and increase the demand. Kaya (2011) compares several contracts and analyzes the effort and pricing decisions in a decentralized SC where one of the members can exert costly effort to increase demand. He finds the optimal contract parameters in each model. Ma, Wang and Shang (2013) study the channel coordination for a two-stage SC with one retailer and one manufacturer in which the demand is dependent on the retailer's sales effort and manufacturer's quality improvement effort. Seifbarghy, Nouhi and Mahmoudi (2015) consider demand is dependent on the price and quality degree of the product, and address the centralized model and the decentralized SC with revenue-sharing contract. Niu, Jin and Pu (2016) address two contract farming structures (i.e., firm– farmer and firm-cooperative-farmer) to assess how each contract type impacts the coordination of production efforts and utilities by SC members. Giri, Roy and Maiti (2017) assume the market demand is dependent on the retail price and the quality of the product, and address a three-stage SC with one supplier, one manufacturer and one retailer for trading a single product. Yang, Tang and Chen (2017) study option contracts in a supplier-retailer agricultural SC where the market demand depends on sales effort. Different with the literature above, we not only compare different contracts with the quality effort level, but also introduce the patient concern into the model.

Third, our model is related to the literature on medical SC management. Several studies have addressed network design and optimization in medical SCs (Fahimnia, Jabbarzadeh, Ghavamifar & Bell, 2017; Fleischhacker, Ninh & Zhao, 2015; Masoumi, Yu & Nagurney, 2017; Nagurney & Nagurney, 2012; Pishvaee, Razmi & Torabi, 2014). Atasu, Toktay, Meng Yeo and Zhang (2017) investigated the effective medical surplus recovery in not-for-profit Medical Surplus Recovery Organizations (MSROs). Differs with above papers, our research focuses on the manufacturer's capacity to invest in quality efforts to increase market demand while considering patients' welfare constraints. Moreover, most popular contract in the medical SCs is a revenue-sharing contract, this is the reason why we adopt it.

The fourth strand of related research lies in quality management in the medical SC. Quality is important in medical SC. However, some researches only focus on quality for one single hospital without considering SC dynamic (Kong, Xu, Yang & Ma, 2015; McGinty, Baller, Azrin, Juliano-Bult & Daumit, 2015; Nageswaran et al., 2017). Quality issues can be solved by collective efforts of all parties among the SC. Due to health and cost is high in medical SC, thus it's very important to manage the quality in medical SC. On the other hand, SC quality management has received much attention in other fields in recent years. Garvin (1987) described product quality under eight dimensions: performance, aesthetics, reliability, durability, special features, perceived quality, conformance, and serviceability. Sosa, Mihm and Browning (2013) empirically linked cyclicality to quality and identified aspects of cyclicality that significantly affect quality. Several studies have examined pricing and quality decision by considering quality competition (Banker, Khosla & Sinha, 1998; Chen, Liang, Yao & Sun, 2017; El Ouardighi & Kim, 2010; Gans, 2002; Giri, Chakraborty & Maiti, 2015; Ha, Long & Nasiry, 2016; Xie, Wang & Lai, 2011a). Xie, Yue, Wang and Lai (2011b) extended Banker et al. (1998)'s demand function and investigated quality and pricing decisions in risk-averse SCs. Moreover, several authors have addressed quality uncertainty in manufacturing and remanufacturing (Liang, Pokharel & Lim, 2009; Teunter & Flapper, 2011). In keeping with the literature on quality, we focused on how patient concern levels impact quality efforts and medical SC performance.

Last, many researches focus on the effect of altruistic preferences on SC management (Hosoda & Disney, 2006; Loch & Wu, 2008; Disney and Hosoda, 2009; Liu, Yan, Wei, Xie & Wang, 2018; Yenipazarli, 2019). Hosoda and Disney (2006) study the influences of altruistic behavior on the governing dynamics of SCs and show that the altruistic behavior can mitigate the bullwhip effect. Loch and Wu (2008) provide experiment evidence that social preferences systematically influence economic decision making in SC transactions. Then, Disney and Hosoda (2009) find that the unmatched controller generalized Order-Up-To policy dominates the matched controller case with an altruistic retailer who is concerned with minimizing the global SC inventory costs. Recently, Liu et al. (2018) use the ex-post payment contract and 'revenue sharing + franchise fee' contract to solve the SC coordination when both the logistics service integrator and the functional logistics service provider have altruistic preferences. Yenipazarli (2019) considers the consumers have intrinsic or altruistic preferences for the environmental bad created by the manufacturing process of the product. When the retailer or the manufacturer cares the patient benefits, which is similar to that the retailer or the manufacturer has some altruistic behavior. Different from them, we focus on the retailer and the manufacturer consider the patient benefits.

3. Model description and research design

3.1. Model description

We considered a demand function that depended on both retail price and product quality:

$$q = a - bp + \gamma\theta, \quad a > 0, \quad \theta > 0. \tag{1}$$

Here, a is the base market size, b is the price elasticity of demand, θ is the medical equipment manufacturer's quality effort level (Kaya, 2011; Xie et al., 2011b), and γ measures the influence of quality efforts on demand, where the influence is assumed to be positive, i.e., $\gamma \geq 0$. We used $\xi\theta^2/2$ to capture the quality effort costs, where ξ is the quality effort's cost parameter; the quadratic form implies increasing marginal cost of quality effort levels (see Banker et al., 1998; Xie et al., 2011b for a similar demand function and cost structure). The unit manufacturing cost is denoted by c. We made the following assumptions: $a - bc > 0$ and $b\xi > \gamma^2$. If $a < bc$, the whole SC is not economically feasible. If $b\xi < \gamma^2$, no quality effort is meaningful.

The wholesale price that the retailer pays is w, and the retail price of the product is p. V_m, V_r, and V_{sc} stand for the objective functions of the manufacturer, the retailer, and the overall SC, respectively. Moreover, we used π_i for the profits of the manufacturer ($i = m$), the retailer ($i = r$), and the SC ($i = sc$).

In contrast to profit-maximizing firms with an objective of maximizing profits, a socially responsible firm seeks to maximize its profits plus some fraction of consumer surplus (Goering, 2007, 2008a, 2008b, 2012). In the healthcare industry, the end users are patients and, compared to other industries, their benefits are more critical to societal sustainability and fairness. Consumer surplus (i.e., patient benefits in our case) is:

$$CS(p,\theta) = \int_p^{p_{\max}} (a - bx + \gamma\theta)dx = \frac{1}{2b}(a - bp + \gamma\theta)^2. \tag{2}$$

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Here, $p_{\max}$ is $\frac{a+\gamma\theta}{b}$, which can be derived from $a-bp+\gamma\theta=0$; and the surplus depends on both the price p and the quality level θ.

The research design of our paper can be seen in Appendix A.

3.2. Wholesale price contract with no patient concern (Model I)

Under a wholesale price contract, the profit functions of the manufacturer and the retailer, respectively, are

$$\pi_m = (w-c)(a-bp+\gamma\theta) - \frac{\xi\theta^2}{2}, \quad and \tag{3}$$

$$\pi_r = (p-w)(a-bp+\gamma\theta). \tag{4}$$

The following proposition summarizes both SC members' optimal solutions under the wholesale price contract with no patient concern.

Proposition 1. *In the wholesale price contract with no patient concern, the manufacturer's optimal wholesale price (w^{I*}) and quality effort level (θ^{I*}), the retailer's optimal retail price (p^{I*}), the optimal sales quantity (q^{I*}), the manufacturer's profits (π_m^{I*}), the retailer's profits (π_r^{I*}), and the SC's profits (π_{sc}^{I*}) are as follows:*

$$w^{I*} = \frac{-2bc\xi + c\gamma^2 - 2a\xi}{-4b\xi+\gamma^2}, \quad \theta^{I*} = \frac{\gamma(a-bc)}{4b\xi-\gamma^2},$$

$$p^{I*} = \frac{bc\xi - c\gamma^2 + 3a\xi}{4b\xi-\gamma^2}, \quad q^{I*} = \frac{\xi b(a-bc)}{4b\xi-\gamma^2},$$

$$\pi_m^{I*} = \frac{\xi(a-bc)^2}{2(4b\xi-\gamma^2)}, \quad \pi_r^{I*} = \frac{\xi^2(a-bc)^2 b}{\left(4b\xi-\gamma^2\right)^2}, \quad and$$

$$\pi_{sc}^{I*} = \frac{\xi(a-bc)^2\left(6b\xi-\gamma^2\right)}{2\left(4b\xi-\gamma^2\right)^2}, \quad respectively.$$

Proof. Please see the Appendix C.

3.3. Wholesale price contract with patient concern (Model II)

In the decentralized model with a wholesale price contract, the medical equipment manufacturer and the healthcare equipment retailer make their decisions independently. As the Stackelberg leader, the manufacturer decides its quality effort level (θ) and wholesale price (w) first. The retailer, the follower, then chooses retail prices to maximize profits. The profits of the manufacturer (π_m) and the retailer (π_r) are

$$\pi_m = (w-c)(a-bp+\gamma\theta) - \frac{\xi\theta^2}{2}, \quad and \tag{5}$$

$$\pi_r = (p-w)(a-bp+\gamma\theta). \tag{6}$$

Since both the manufacturer and the retailer care about patients' benefits, the objective functions of the manufacturer and the retailer are

$$V_m = (w-c)(a-bp+\gamma\theta) - \frac{\xi\theta^2}{2} + \frac{\alpha_m}{2b}(a-bp+\gamma\theta)^2, \text{ and} \tag{7}$$

$$V_r = (p-w)(a-bp+\gamma\theta) + \frac{\alpha_r}{2b}(a-bp+\gamma\theta)^2. \tag{8}$$

Where $\alpha_i (i=m,r)$ indicate the fraction of patient benefits considered in the objective functions of the manufacturer and the retailer respectively (Goering, 2008; Panda, 2014, Modak). In our paper, α_m and α_r respectively represent the patient concern levels of the manufacturer and the retailer (Brand & Grothe, 2015). The retailer or the manufacturer operates like a profit maximizer without any patient concern if $\alpha_i = 0$ while the whole patient benefits are considered in the retailer's or manufacturer's objective function if $\alpha_i = 1$.

We used a backward induction to solve this two-stage problem. Taking the first derivative of Eq. (8) with respect to p, we obtained the first order condition of

$$p(w,\theta) = \frac{(a+\gamma\theta)(1-\alpha_r)+bw}{(2-\alpha_r)b}. \tag{9}$$

Substituting Eq. (9) into Eq. (7), we obtained

$$V_m = (w-c)\left(\frac{-\gamma\theta\alpha_r - a\alpha_r + bw + \gamma\theta + a}{\alpha_r - 2} + \gamma\theta + a\right) - \frac{1}{2}\xi\theta^2 + \frac{1}{2}\frac{\alpha_m(-bw+\gamma\theta+a)^2}{(\alpha_r-2)^2 b}. \tag{10}$$

We managed to obtain the optimal equilibrium solution of the Stackelberg game between the retailer and the manufacturer. Proposition 2 summarizes our findings.

Proposition 2. *In the wholesale price contract with patient concern, the manufacturer's optimal wholesale price (w^{II*}) and quality effort level (θ^{II*}), the retailer's optimal retail price (p^{II*}), the optimal sales quantity (q^{II*}), the medical equipment manufacturer's optimal profits with patient concern (V_m^{II*}), the medical equipment manufacturer's optimal profits (π_m^{II*}), the retailer's optimal profits with patient concern (V_r^{II*}), the retailer's optimal profits (π_r^{II*}), and the SC's optimal profits (π_{sc}^{II*}) are*

$$w^{II*} = \frac{bc\xi\alpha_r + a\xi\alpha_m + a\xi\alpha_r - 2bc\xi + c\gamma^2 - 2a\xi}{b\xi\alpha_m + 2b\xi\alpha_r - 4b\xi + \gamma^2},$$

$$\theta^{II*} = \frac{(a-bc)\gamma}{4b\xi - b\xi\alpha_m - 2b\xi\alpha_r - \gamma^2},$$

$$p^{II*} = \frac{a\xi\alpha_m + 2a\xi\alpha_r - bc\xi + c\gamma^2 - 3a\xi}{b\xi\alpha_m + 2b\xi\alpha_r - 4b\xi + \gamma^2},$$

$$q^{II*} = \frac{b\xi(a-bc)}{4b\xi - b\xi\alpha_m - 2b\xi\alpha_r - \gamma^2},$$

$$V_m^{II*} = \frac{1}{2}\frac{\xi(a-bc)^2}{4b\xi - b\xi\alpha_m - 2b\xi\alpha_r - \gamma^2},$$

$$\pi_m^{II*} = \frac{(a-bc)^2\xi\left(2\xi(2-\alpha_m-\alpha_r)b-\gamma^2\right)}{2\left(\xi(4-\alpha_m-2\alpha_r)b-\gamma^2\right)^2},$$

$$V_r^{II*} = \frac{\xi^2 b(a-bc)^2(2-\alpha_r)}{2\left(b\xi\alpha_m + 2b\xi\alpha_r - 4b\xi + \gamma^2\right)^2},$$

$$\pi_r^{II*} = \frac{\xi^2(1-\alpha_r)b(a-bc)^2}{\left(4b\xi - b\xi\alpha_m - 2b\xi\alpha_r - \gamma^2\right)^2}, \quad and$$

$$\pi_{sc}^{II*} = \frac{(a-bc)^2\xi\left(2\xi(3-\alpha_m-2\alpha_r)b-\gamma^2\right)}{2\left(\xi(4-\alpha_m-2\alpha_r)b-\gamma^2\right)^2}, \quad respectively.$$

Proof. Please see the Appendix C.

3.4. Revenue-sharing contract with no patient concern (Model III)

A revenue-sharing contract can be characterized by two parameters (Cachon & Lariviere, 2005): w, the wholesale price the retailer pays per unit, and ρ_r, the retailer's share of revenue generated from each unit. The medical equipment manufacturer's share is $1-\rho_r$. In other words, the retailer pays the medical equipment manufacturer a wholesale price for each unit purchased, plus a percentage of the revenue the retailer generates. Under the revenue-sharing contract, the profit functions of the manufacturer and the retailer, respectively, are

$$\pi_m = [(1-\rho_r)p + w - c](a-bp+\gamma\theta) - \frac{\xi\theta^2}{2}, \quad and \tag{11}$$

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$$\pi_r = (\rho_r p - w)(a - bp + \gamma\theta). \tag{12}$$

Taking the second derivative of π_r in Eq. (12) with respect to p, we obtained $\frac{d^2\pi_r}{dp^2} = -2b\rho_r < 0$. Then, we solved the first-order condition of $\frac{d\pi_r}{dp} = 0$ and obtained

$$p(w,\theta) = \frac{\gamma\theta\rho_r + a\rho_r + bw}{2b\rho_r}. \tag{13}$$

Substituting Eq. (13) into Eq. (11), we derived

$$\pi_m = \frac{-(\gamma\theta + a)^2\rho_r^3 + \left(\left(-2\xi\theta^2 - 2\gamma(c-w)\theta - 2a(c-w)\right)b + (\gamma\theta + a)^2\right)\rho_r^2 + b^2(2c-w)w\rho_r - b^2w^2}{4b\rho_r^2}. \tag{14}$$

The following proposition summarizes both SC members' optimal solutions under the revenue-sharing contract.

Proposition 3. *In the revenue-sharing contract with no patient concern, the manufacturer's optimal wholesale price (w^{III*}) and quality effort level (θ^{III*}), the retailer's optimal retail price (p^{III*}), the optimal sales quantity (q^{III*}), the manufacturer's profits (π_m^{III*}), the retailer's profits (π_r^{III*}), and the SC's profits (π_{sc}^{III*}) are as follows:*

$$w^{III*} = \frac{\rho_r\left(2a\xi\rho_r + 2bc\xi - c\gamma^2\right)}{2b\xi\rho_r + 2b\xi - \gamma^2},\quad \theta^{III*} = \frac{\gamma(a-bc)}{2b\xi\rho_r + 2b\xi - \gamma^2},$$

$$p^{III*} = \frac{(2a\rho_r + bc + a)\xi - c\gamma^2}{2b(\rho_r+1)\xi - \gamma^2},\quad q^{III*} = \frac{b\xi(a-bc)}{2b(\rho_r+1)\xi - \gamma^2},$$

$$\pi_m^{III*} = \frac{(a-bc)^2\xi}{4b(\rho_r+1)\xi - 2\gamma^2},\quad \pi_r^{III*} = \frac{\rho_r\xi^2(a-bc)^2b}{\left(2b(\rho_r+1)\xi - \gamma^2\right)^2},\quad \textit{and}$$

$$\pi_{sc}^{III*} = \frac{\left(2b(2\rho_r+1)\xi - \gamma^2\right)(a-bc)^2\xi}{2\left(2b(\rho_r+1)\xi - \gamma^2\right)^2},\ \textit{respectively.}$$

Proof. Please see the Appendix C.

3.5. Revenue-sharing contract with patient concern (Model IV)

When both the manufacturer and the retailer care about patients' benefits, the objective functions of the manufacturer and the retailer are as follows:

$$V_m = [(1-\rho_r)p + w - c](a - bp + \gamma\theta) + \frac{\alpha_m}{2b}(a - bp + \gamma\theta)^2 - \frac{\xi\theta^2}{2}, \tag{15}$$

$$V_r = (\rho_r p - w)(a - bp + \gamma\theta) + \frac{\alpha_r}{2b}(a - bp + \gamma\theta)^2. \tag{16}$$

Taking the second derivative of V_r in Eq. (16) with respect to p, we obtained $\frac{d^2V_r}{dp^2} = b\alpha_r - 2b\rho_r < 0$ if $\alpha_r < 2\rho_r$. Next, we solved the first-order condition of $\frac{dV_r}{dp} = 0$ and obtained

$$p(w,\theta) = \frac{(\gamma\theta + a)(\rho_r - \alpha_r) + wb}{b(2\rho_r - \alpha_r)}. \tag{17}$$

Substituting Eq. (17) into Eq. (15), we derived

$$V_m = -\frac{\left((\gamma\theta+a)\rho_r^2 + ((-\gamma\theta - a)\alpha_r - a - \gamma\theta + (2c-w)b)\rho_r + (a + \gamma\theta + (-c+w)b)\alpha_r - wb\right)((\gamma\theta+a)\rho_r - wb)}{b(2\rho_r - \alpha_r)^2}$$
$$+\frac{1}{2}\frac{((\gamma\theta+a)\rho_r - wb)^2\alpha_m}{(2\rho_r - \alpha_r)^2b} - \frac{1}{2}\xi\theta^2 \tag{18}$$

The following proposition summarizes both SC members' optimal solutions under the revenue-sharing contract.

Proposition 4. *In the revenue-sharing contract with patient concern, the manufacturer's optimal wholesale price (w^{IV*}) and quality effort level (θ^{IV*}), the retailer's optimal retail price (p^{IV*}), the optimal sales quantity (q^{IV*}),the manufacturer's profits with patient concern (V_m^{IV*}), the manufacturer's profits (π_m^{IV*}), the retailer's profits with patient concern (V_r^{IV*}), the retailer's profits (π_r^{IV*}), , and the SC's profits (π_{sc}^{IV*}) are as follows:*

$$w^{IV*} = \frac{a\xi\alpha_m\rho_r + 2a\xi\alpha_r\rho_r - 2a\xi\rho_r^2 + bc\xi\alpha_r - 2bc\xi\rho_r + c\gamma^2\rho_r - a\xi\alpha_r}{b\xi\alpha_m + 2b\xi\alpha_r - 2b\xi\rho_r - 2b\xi + \gamma^2},$$

$$\theta^{IV*} = \frac{(a-bc)\gamma}{2b\xi\rho_r + 2b\xi - b\xi\alpha_m - 2b\xi\alpha_r - \gamma^2},$$

$$p^{IV*} = \frac{a\xi\alpha_m + 2a\xi\alpha_r - 2a\xi\rho_r - bc\xi + c\gamma^2 - a\xi}{b\xi\alpha_m + 2b\xi\alpha_r - 2b\xi\rho_r - 2b\xi + \gamma^2},$$

$$q^{IV*} = \frac{b\xi(a-bc)}{2b\xi\rho_r + 2b\xi - b\xi\alpha_m - 2b\xi\alpha_r - \gamma^2},$$

$$V_m^{IV*} = -\frac{1}{2}\frac{\xi(a-bc)^2}{b\xi\alpha_m + 2b\xi\alpha_r - 2b\xi\rho_r - 2b\xi + \gamma^2},$$

$$\pi_m^{IV*} = \frac{(a-bc)^2\left(2\xi(\rho_r - \alpha_m - \alpha_r + 1)b - \gamma^2\right)\xi}{2\left(b(2\rho_r - \alpha_m - 2\alpha_r + 2)\xi - \gamma^2\right)^2},$$

$$V_r^{IV*} = -\frac{1}{2}\frac{\xi^2b(a-bc)(-bc\alpha_r + 2bc\rho_r + a\alpha_r - 2a\rho_r)}{\left(b\xi\alpha_m + 2b\xi\alpha_r - 2b\xi\rho_r - 2b\xi + \gamma^2\right)^2},$$

$$\pi_r^{IV*} = \frac{\xi^2(\rho_r - \alpha_r)(a-bc)^2b}{\left(b(2\rho_r - \alpha_m - 2\alpha_r + 2)\xi - \gamma^2\right)^2},\ \textit{and}$$

$$\pi_{sc}^{IV*} = \frac{\left(\xi(4\rho_r - 2\alpha_m - 4\alpha_r + 2)b - \gamma^2\right)(a-bc)^2\xi}{2\left(b(2\rho_r - \alpha_m - 2\alpha_r + 2)\xi - \gamma^2\right)^2},\ \textit{respectively.}$$

Proof. Please see the Appendix C.

We investigated how the revenue-sharing fraction (ρ_r) influences the profits of the overall SC, the retailer, and the manufacturer. We obtained the following propositions.

Proposition 5. *(i) If $0 \le \rho_r \le \frac{\alpha_m + 2\alpha_r}{2}$, $\frac{d\pi_{sc}^{IV*}}{d\rho_r} \ge 0$; (ii) If $\frac{\alpha_m+2\alpha_r}{2} < \rho_r \le 1$, $\frac{d\pi_{sc}^{IV*}}{d\rho_r} < 0$; (iii) Specifically, if $\rho_r = 1$, then $\pi_{sc}^{II*} = \pi_{sc}^{IV*}$; Otherwise, if $\rho_r = \frac{1}{2}\alpha_m + \alpha_r$, then $\pi_{sc}^{IV*} = \frac{\xi(a-bc)^2}{2(2b\xi - \gamma^2)}$.*

Proof. Please see the Appendix C.

Proposition 6. *(i) If $0 \le \rho_r \le \frac{b\xi(2\alpha_r+2-\alpha_m)-\gamma^2}{2b\xi}$, then $\frac{d\pi_r^{IV*}}{d\rho_r} \ge 0$; (ii) If $\frac{b\xi(2\alpha_r+2-\alpha_m)-\gamma^2}{2b\xi} < \rho_r \le 1$, then $\frac{d\pi_r^{IV*}}{d\rho_r} < 0$.*

Proof. Please see the Appendix C.

Proposition 7. *(i) If $0 \le \rho_r \le \frac{b\xi(3\alpha_m+2\alpha_r-2)+\gamma^2}{2b\xi}$, then $\frac{d\pi_m^{IV*}}{d\rho_r} \ge 0$; (ii) If $\frac{b\xi(3\alpha_m+2\alpha_r-2)+\gamma^2}{2b\xi} < \rho_r \le 1$, then $\frac{d\pi_m^{IV*}}{d\rho_r} < 0$.*

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Proof. Please see the Appendix C.

Combining Propositions 5 through 7, we derived Proposition 8.

Proposition 8. *(i) If* $\rho_r = \frac{\alpha_m+2\alpha_r}{2}$, *the SC's profits* (π_{sc}^{IV*}) *reach the maximum value; (ii) If* $\rho_r = \frac{b\xi(2\alpha_r+2-\alpha_m)-\gamma^2}{2b\xi}$, *the retailer's profits* (π_r^{IV*}) *reach the maximum value; (iii) If* $\rho_r = \frac{b\xi(3\alpha_m+2\alpha_r-2)+\gamma^2}{2b\xi}$, *the manufacturer's profits* (π_m^{IV*}) *reach the maximum value.*

Proof. Please see Appendix C.

Proposition 8 shows that the overall SC profits reach a maximum when the revenue-sharing fraction is equal to half of the patient concern level in the revenue-sharing contract. We obtain $\frac{b\xi(2\alpha_r+2-\alpha_m)-\gamma^2}{2b\xi} \le \frac{b\xi(3\alpha_m+2\alpha_r-2)+\gamma^2}{2b\xi} \Leftrightarrow \alpha_m \ge 1-\frac{\gamma^2}{2b\xi}$. Thus, if $1-\frac{\gamma^2}{2b\xi} \le \alpha_m \le 1$, the retailer prefers a relatively low revenue-sharing fraction, whereas if $0 \le \alpha_m < 1-\frac{\gamma^2}{2b\xi}$, then the retailer prefers a relatively high revenue-sharing fraction and the medical equipment manufacturer needs a relatively low revenue-sharing parameter.

4. Pareto improvement condition (Model II vs. Model IV)

The wholesale price contract is widely applied in practice (Cachon, 2003). If profits from the revenue-sharing contract with patient concern (Model IV) are greater than those of the wholesale price contract with patient concern (Model II), the healthcare equipment retailer will be motivated to work with the medical equipment manufacturer and to accept the revenue-sharing contract proposed in Section 3.5. A contract is said to be a "Pareto improvement contract" when both SC members benefit from the contract, compared with the wholesale price contract (Gao, Zhao & Geng, 2014). Comparing the profits of SC members in Model IV with those in Model II, we obtain Proposition 9.

Proposition 9.

(i) When $\sqrt{2b\xi(1-\alpha_m)} \le \gamma \le \sqrt{-3b\xi\alpha_m - 2b\xi\alpha_r + 4b\xi}$, then $\pi_m^{IV*} \ge \pi_m^{II*}$ and $\pi_r^{IV*} \ge \pi_r^{II*}$ if $\rho_r \in [\rho_{r1}, 1]$, i.e., a revenue-sharing contract can make the healthcare equipment retailer and the medical equipment manufacturer reach Pareto improvement.

(ii) When $\sqrt{-b\xi\alpha_m + 2b\xi\alpha_r} \le \gamma < \sqrt{2b\xi(1-\alpha_m)}$, then $\pi_m^{IV*} \ge \pi_m^{II*}$and $\pi_r^{IV*} \ge \pi_r^{II*}$ if $\rho_r \in [\rho_{r3}, 1]$, i.e., a revenue-sharing contract can make the healthcare equipment retailer and the medical equipment manufacturer reach Pareto improvement,

where $\rho_{r1} = \frac{1}{2}\frac{3b^2\xi^2\alpha_m^2 + 8b^2\xi^2\alpha_m\alpha_r + 4b^2\xi^2\alpha_r^2 - 12b^2\xi^2\alpha_m - 12b^2\xi^2\alpha_r + 4b\gamma^2\xi\alpha_m + 4b\gamma^2\xi\alpha_r + 8b^2\xi^2 - 6b\gamma^2\xi + \gamma^4}{b\xi(2b\xi\alpha_m + 2b\xi\alpha_r - 4b\xi + \gamma^2)}$

and $\rho_{r3} = \frac{b^2\xi^2\alpha_m^2 - 4b^2\xi^2\alpha_r^2 - 4b^2\xi^2\alpha_m + 4b^2\xi^2\alpha_r + 2b\gamma^2\xi\alpha_m + 4b^2\xi^2 - 4b\gamma^2\xi + \gamma^4}{4b^2\xi^2(1-\alpha_r)}$.

Proof. Please see the Appendix C.

Proposition 9 gives the Pareto improvement condition and shows that the retailer and the manufacturer will accept the revenue-sharing contract under certain conditions. Proposition 9 also shows that the region of revenue-sharing fraction for the manufacturer and the retailer will change with the quality effort coefficient. Moreover, the revenue-sharing contract can adjust the relationship between the manufacturer and the retailer according to the different values of the manufacturer's quality effort coefficient, which makes the revenue-sharing contract better than the wholesale price contract.

5. Analysis

In this section, we present the impact of the manufacturer's and retailer's patient concern level on retail prices, sales quantity, the quality effort level, the SC's profits, and the patient benefits.

5.1. Effects of patient concern level on the retail prices

We first investigated the effects of the manufacturer's and retailer's patient concern level on retail price respectively and obtained Proposition 10.

Proposition 10. *(i) For all* $\alpha_m \in [0,1]$, *we have* $\frac{\partial p^{II*}}{\partial \alpha_m} < 0$, $\frac{\partial p^{IV*}}{\partial \alpha_m} = \frac{\partial p^{V-1*}}{\partial \alpha_m} < 0$, and $\frac{\partial p^{V-2*}}{\partial \alpha_m} > 0$; *(ii) For all* $\alpha_r \in [0,1]$, *we have* $\frac{\partial p^{II*}}{\partial \alpha_r} < 0$, $\frac{\partial p^{IV*}}{\partial \alpha_r} = \frac{\partial p^{V-1*}}{\partial \alpha_r} < 0$, and $\frac{\partial p^{V-2*}}{\partial \alpha_r} = 0$.

Proof. Please see the Appendix C.

Proposition 10 shows that the retail price will always decrease with the manufacturer's and retailer's patient concern levels in Models II, IV and V-1. In Model V, the retail price will always increase with the manufacturer's patient concern levels when the constraint Eq. (B2) is binding while the retailer's patient concern level has no impact on the retail price when the constraint Eq. (B2) is binding.

Moreover, in Proposition 10, when the manufacturer considers patient benefits in its objective function in Models II and IV, the manufacturer will decrease its wholesale price, which encourages the retailer to decrease the retail price of the products. However, when the constraint Eq. (B2) is binding, the retail price increases with manufacturer's patient concern level while the retailer's patient concern level has no impact on the retail price.

5.2. Effects of patient concern level on sales quantity

We then studied the effects of the manufacturer's and retailer's patient concern level on the product's sales quantity respectively and obtained Proposition 11.

Proposition 11. *(i) For all* $\alpha_m \in [0,1]$, *we have* $\frac{\partial q^{II*}}{\partial \alpha_m} > 0$, $\frac{\partial q^{IV*}}{\partial \alpha_m} = \frac{\partial q^{V-1*}}{\partial \alpha_m} > 0$, and $\frac{\partial q^{V-2*}}{\partial \alpha_m} < 0$. *(ii) For all* $\alpha_r \in [0,1]$, we have $\frac{\partial q^{II*}}{\partial \alpha_r} > 0$, $\frac{\partial q^{IV*}}{\partial \alpha_r} = \frac{\partial q^{V-1*}}{\partial \alpha_r} > 0$, and $\frac{\partial q^{V-2*}}{\partial \alpha_r} = 0$.

Proof. Please see the Appendix C.

Proposition 11 shows that the product's sales quantity increases with manufacturer's and retailer's patient concern level in Models II and IV respectively. Proposition 11 also shows that the product's sales quantity increases with manufacturer's and retailer's patient concern level in Model V when the constraint Eq. (B2) is not binding. On the other hand, the product's sales quantity decreases with the manufacturer's patient concern level when the constraint Eq. (B2) is binding while the retailer's patient concern level has no impact on product's sales quantity when the constraint Eq. (B2) is binding.

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5.3. Effects of patient concern level on quality effort level

We studied the effects of the manufacturer's and the retailer's patient concern level on product quality respectively and then compared the quality effort levels among Models I, II, IV and V.

Proposition 12. *(i) For all* $\alpha_m \in [0,1]$, *we have* $\frac{\partial\theta^{II*}}{\partial\alpha_m} > 0$, $\frac{\partial\theta^{IV*}}{\partial\alpha_m} = \frac{\partial\theta^{V-1*}}{\partial\alpha_m} > 0$, *and* $\frac{\partial\theta^{V-2*}}{\partial\alpha_m} < 0$; *(ii) For all* $\alpha_r \in [0,1]$, *we have* $\frac{\partial\theta^{II*}}{\partial\alpha_r} > 0$, $\frac{\partial\theta^{IV*}}{\partial\alpha_r} = \frac{\partial\theta^{V-1*}}{\partial\alpha_r} > 0$, *and* $\frac{\partial\theta^{V-2*}}{\partial\alpha_r} = 0$. *(iii) The quality effort levels in Models I, II, III, IV and V are related as follows:* $\theta^{I*} < \theta^{II*} < \theta^{III*} < \theta^{IV*} = \theta^{V-1*}$ *if* $\frac{2-\alpha_m-2\alpha_r}{2} < \rho_r \le 1$; otherwise $\theta^{I*} < \theta^{III*} \le \theta^{II*} < \theta^{IV*} = \theta^{V-1*}$ if $0 \le \rho_r \le \frac{2-\alpha_m-2\alpha_r}{2}$.

Proof. Please see the Appendix C.

Proposition 12 shows that the quality effort level increases with manufacturer's and retailer's patient concern level in Models II, IV and V-1. In Model V, when the constraint Eq. (B2) is binding, the product's quality effort level decreases with manufacturer's patient concern level while the retailer's patient concern level has no impact on the quality effort level.

The quality effort level is highest in Model IV and is lowest in Model I. The quality effort level under wholesale price contract with patient concern (Model II) can be same as that under the revenue-sharing contract with no patient concern (Model III). If the retailer's revenue-sharing fraction is relatively large (i.e., $\frac{2-\alpha_m-2\alpha_r}{2} < \rho_r \le 1$), revenue-sharing contract can make the manufacturer determine higher quality effort level. On the other hand, if the retailer's revenue-sharing fraction is relatively small (i.e., $0 \le \rho_r \le \frac{2-\alpha_m-2\alpha_r}{2}$), the wholesale price contract can make the manufacturer determine higher quality effort level.

5.4. Effects of patient concern level on SC's profits

We investigated the effects of the manufacturer's and the retailer's patient concern level on SC profits.

Proposition 13. *(i) For all* $0 \le \alpha_m \le 1$, *we have* $\frac{\partial\pi_{sc}^{II*}}{\partial\alpha_m} > 0$; $\frac{\partial\pi_{sc}^{IV*}}{\partial\alpha_m} \ge 0$ *if* $\alpha_m \le 2(\rho_r - \alpha_r)$, *and* $\frac{\partial\pi_{sc}^{IV*}}{\partial\alpha_m} < 0$ *if* $\alpha_m > 2(\rho_r - \alpha_r)$; $\frac{\partial\pi_{sc}^{V-1*}}{\partial\alpha_m} = 0$; $\frac{\partial\pi_{sc}^{V-2*}}{\partial\alpha_m} \ge 0$ *if* $0 \le \alpha_m \le \frac{1}{2}\left(\frac{\sqrt{CS_0}(4b\xi-2\gamma^2)}{b\xi(a-bc)}\right)^2$, *and* $\frac{\partial\pi_{sc}^{V-2*}}{\partial\alpha_m} < 0$ *if* $1 \ge \alpha_m > \frac{1}{2}\left(\frac{\sqrt{CS_0}(4b\xi-2\gamma^2)}{b\xi(a-bc)}\right)^2$.

(ii) For all $0 \le \alpha_r \le 1$, *we have* $\frac{\partial\pi_{sc}^{II*}}{\partial\alpha_r} > 0$; $\frac{\partial\pi_{sc}^{IV*}}{\partial\alpha_r} \ge 0$ *if* $0 \le \alpha_m \le 2(\rho_r - \alpha_r)$, *and* $\frac{\partial\pi_{sc}^{IV*}}{\partial\alpha_r} < 0$ *if* $1 \ge \alpha_m > 2(\rho_r - \alpha_r)$; $\frac{\partial\pi_{sc}^{V-1*}}{\partial\alpha_r} \ge 0$ *if* $0 \le \alpha_r \le \rho_r$, *and* $\frac{\partial\pi_{sc}^{V-1*}}{\partial\alpha_r} < 0$ *if* $1 \ge \alpha_r > \rho_r$; $\frac{\partial\pi_{sc}^{V-2*}}{\partial\alpha_r} = 0$.

Proof. See the Appendix C.

Proposition 13 (i) shows that the SC's profits always increase with manufacturer's patient concern level in Model II. In Model IV, as the manufacturer's patient concern increases, the SC's profits increase when the manufacturer's patient concern level is relatively low (i.e., $\alpha_m \le 2(\rho_r - \alpha_r)$) and decrease when the manufacturer's patient concern level is relatively high (i.e., $\alpha_m > 2(\rho_r - \alpha_r)$). In Model V, the manufacturer's patient concern level has no impact on the SC's profits when the constraint Eq. (B2) is not binding while the SC's profits also increase when the constraint Eq. (B2) is binding and the manufacturer's patient concern level is relatively low (i.e., $0 \le \alpha_m \le \frac{1}{2}\left(\frac{\sqrt{CS_0}(4b\xi-2\gamma^2)}{b\xi(a-bc)}\right)^2$). Similar analyses result in Proposition 13 (ii).

5.5. Effects of patient concern level on patient benefits

In the wholesale price contract with no patient concern (Model I), we can derive the actual patient benefits:

$$CS^{I*} = \frac{b\xi^2(a-bc)^2}{2\left(4b\xi-\gamma^2\right)^2}. \tag{19}$$

In the wholesale price contract with patient concern (Model II), we can obtain the actual patient benefits:

$$CS^{II*} = \frac{b\xi^2(a-bc)^2}{2\left(b\xi\alpha_m + 2b\xi\alpha_r - 4b\xi + \gamma^2\right)^2}. \tag{20}$$

Similarly, we can also obtain the actual patient benefits in the revenue-sharing contract with no patient concern (Model III):

$$CS^{III*} = \frac{b\xi^2(a-bc)^2}{2\left(2b(\rho_r+1)\xi-\gamma^2\right)^2}. \tag{21}$$

Similarly, we can also obtain the actual patient benefits in the revenue-sharing contract with patient concern (Model IV):

$$CS^{IV*} = \frac{b\xi^2(a-bc)^2}{2\left(b\xi\alpha_m + 2b\xi\alpha_r - 2b\xi\rho_r - 2b\xi + \gamma^2\right)^2}. \tag{22}$$

Lastly, in the revenue-sharing contract with constraint condition of patient concern (Model V), we can also obtain the patient benefits of the two cases as follows:

$$CS^{V-1*} = CS^{IV*} = \frac{b\xi^2(a-bc)^2}{2\left(b\xi\alpha_m + 2b\xi\alpha_r - 2b\xi\rho_r - 2b\xi + \gamma^2\right)^2}, \quad \textit{and}$$

$$CS^{V-2*} = \frac{CS_0}{\alpha_m} \tag{23}$$

As we know that $CS_0 > \frac{b\xi^2\alpha_m(a-bc)^2}{2(\xi(2\rho_r-\alpha_m-2\alpha_r+2)b-\gamma^2)^2}$. Thus, we have

$$CS^{V-2*} > \frac{b\xi^2(a-bc)^2}{2\left(\xi(2\rho_r-\alpha_m-2\alpha_r+2)b-\gamma^2\right)^2} = CS^{V-1*}. \tag{24}$$

Combining Eqs. (20), (22), and (23), we can derive Proposition 14.

Proposition 14. *(i) For any* $0 \le \alpha_m \le 1$, *we have* $\frac{\partial CS^{II*}}{\partial\alpha_m} > 0$, $\frac{\partial CS^{IV*}}{\partial\alpha_m} = \frac{\partial CS^{V-1*}}{\partial\alpha_m} > 0$ *and* $\frac{\partial CS^{V-2*}}{\partial\alpha_m} < 0$; *(ii) For any* $0 \le \alpha_r \le 1$, *we have* $\frac{\partial CS^{II*}}{\partial\alpha_r} > 0$, $\frac{\partial CS^{IV*}}{\partial\alpha_r} = \frac{\partial CS^{V-1*}}{\partial\alpha_r} > 0$, *and* $\frac{\partial CS^{V-2*}}{\partial\alpha_r} = 0$.

Proof. See the Appendix C.

Proposition 14 shows that all the patient benefits under Models II, IV and V-1 increase with manufacturer's and retailer's patient concern respectively. In the Model V (Case 2), the patient benefits decrease with the manufacturer's patient concern while the retailer's patient concern has no impact on the patient benefits. This is because that the sales quantity decreases with the manufacturer's patient concern level, which results in the decrease of the patient benefits.

6. Case study

We first used data from a patented automated medical equipment system produced by a medical equipment manufacturer to test our model and conducted a sensitivity analysis to further investigate the impacts of model parameters. The manufacturer produces this system with a constant unit manufacturing cost and also invests in quality efforts.

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Table 1
Optimal values of Models I, II, IV, V with real data.

	Model I	Model II	Model III	Model IV/Model V (Case 1)
Quality effort level (θ)	7795	12,486	9772	18,472
Sales quantity (q)	107	171	134	253
Retail price (p)	241,364	222,869	233,570	199,269
Wholesale price (w)	174,579	158,683	97,401	89,960
SC's profit (π_{sc})	19,482,815	26,185,214	22,767,369	29,257,456
Retailer's profit (π_r)	7,136,336	10,986,137	7,289,733	10,018,486
Manufacturer's profit (π_m)	12,346,480	15,199,077	15,477,636	19,238,970
Patient Benefits	3,568,168	9,155,114	5,607,487	20,036,972

Note. $a=435.354$, $b=0.0016$, $c=41{,}009.25$, ρ_r=0.65, α_m=0.5, α_r=0.4, $\gamma=0.0074$ and $\xi=0.0634$.

Table 2
Optimal decisions of Model IV ($\alpha_m=0.1$, 0.2, 0.3, 0.4, and 0.5; $\alpha_r=0.5$).

	$\alpha_m=0.1$	$\alpha_m=0.2$	$\alpha_m=0.3$	$\alpha_m=0.4$	$\alpha_m=0.5$
Quality effort level (θ)	16,247	17,288	18,472	19,830	21,404
Sales quantity (q)	223	237	253	272	293
Retail price (p)	208,043	203,937	199,269	193,915	187,711
Wholesale price (w)	114,349	110,342	105,786	100,560	94,506
SC's profit (π_{sc})	28,832,846	29,137,259	29,257,456	29,099,313	28,520,509
Retailer's profit (π_r)	4,650,025	5,265,219	6,011,092	6,927,454	8,070,521
Manufacturer's profit (π_m)	24,182,821	23,872,040	23,246,364	22,171,859	20,449,988
Patient Benefits	15,500,084	17,550,731	20,036,972	23,091,513	26,901,737

6.1. Case background and parameter estimation

We first collected data (i.e., sales quantity, retail price, wholesale price, quality efforts cost, manufacturing cost of product, and the healthcare equipment retailer's revenue-sharing fraction) from a newly patented automated medical system from a medical equipment manufacturer.

We used real 8-year time-series data for an Automated Medical System from 2008 to 2015 for optimizing quality efforts. We used real data to estimate the relevant parameters of real demand for the product. First, based on 8-year time-series data of quality effort costs, we can obtain 8-year values of quality effort levels. Then, we use 8-year time-series data of retail price (p) and quality effort level (θ) as independent variables, and the sales quantities (q) as the dependent variable to conduct a regress analysis, and obtain $q=435.354-0.0016p+0.0074\theta$. We get $a=435.354$, $b=0.0016$, $\gamma=0.0074$. $R^2=0.965$, which shows our model has strong explaining power. The p-value of Significance F is 2.33535E-04, less than 0.001, which shows the regress model is significant. After that, we use $\xi\theta^2/2$ to get the corresponding value of ξ. Then we use the average value of ξ during 8 years and then get $\xi=$ 0.0634. We also use average value of unit manufacturing cost during 8 years as the manufacturing cost.

Next, we use these estimated parameters to carry out the corresponding calculations. We can obtain the optimal values of Models I, II, III, and IV respectively (See Table 1). Compared with the results above, we found that optimization of Model IV can improve SC profits. From Table 1, we also find that the SC obtains the highest profits under the Models IV and V (Case 1), and the quality effort levels can also obtain the highest under the Models IV and V (Case 1). For Model V (Case 2), if we set different values of CS_0, the model V (Case 2) will get different results. Thus, we here omit the analysis of Model V (Case 2).

We then assume $\alpha_r=0.5$ to investigate the effects of α_m and obtain Table 2. We find that the quality effort level, the sales quantity and the patient benefits always increase with the manufacturer's patient concern, which results in that SC's profits increase with manufacturer's patient concern first, and then decrease with it. Table 2 also shows that when the retailer uses the strategy that considering the patient concern level is 0.5, the manufacturer's best strategy is not considering the same patient concern level as the retailer does. Because the manufacturer also should invest in the quality, which also need much cost. Then, we assume $\alpha_m=0.5$ to investigate the effects of α_r and obtain Table 3. We can also do similar analysis for Table 3.

6.2. Effects of α_r on the wholesale price, retail price, quality effort and sales quantity

Recall that, Model V (Case 1) is the same as Model IV. On the other hand, the optimal values of Model V (Case 2) have the parameter CS_0. Given different values of CS_0, we can obtain different values of Model V (Case 2). Thus, in this subsection, we do not compare Model V with other models. We now again use the parameters $a=435.354$, $b=0.0016$, $c=41{,}009.25$, $\rho_r=0.65$, $\gamma=0.0074$, $\xi=0.0634$ and $\alpha_m=0.5$ to investigate the effects of α_r on the wholesale price, the retail price, the quality effort and the sales quantity. Similarly, we can set the value of α_r to investigate the effects of α_m. However, we omit it here and put them on the Appendix E.

Fig. 1 shows that the effects of the retailer's patient concern on the wholesale price. It shows that the wholesale prices obtain the highest in the wholesale price contract with no patient concern (Model I) while the wholesale prices obtain the lowest in the revenue-sharing contract with patient concern (Model IV). This is because revenue-sharing contract can make the manufacturer lower the wholesale price. Fig. 2 shows that the retail price will obtain the lowest in Model IV, which make total patient benefits become higher than other models. On the other hand, the total sales quantities are obtained the lowest in Model I (See Fig. 4), which makes the total patient benefits obtain the lowest under Model I among the models. Moreover, the retail prices under Model II are lower than those under Model III if $\alpha_r \geq \tilde{\alpha}_r \approx 0.1$.

Fig. 3 shows that the quality effort levels obtain the lowest under the wholesale price contract with no patient concern (i.e., Model I). The quality effort levels under Model II will be higher than these under Model III if $\alpha_r \geq \tilde{\alpha}_r \approx 0.1$. Moreover, the quality effort levels increase with the retailer's patient concern

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Table 3
Optimal decisions of Model IV (α_r = 0.1, 0.2, 0.3, 0.4, and 0.5; α_m = 0.5).

	$\alpha_r = 0.1$	$\alpha_r = 0.2$	$\alpha_r = 0.3$	$\alpha_r = 0.4$	$\alpha_r = 0.5$
Quality effort level (θ)	13,092	14,500	16,247	18,472	21,404
Sales quantity (q)	179	199	223	253	293
Retail price (p)	220,479	214,929	208,043	199,269	187,711
Wholesale price (w)	81,619	83,801	86,510	89,960	94,506
SC's profit (π_{sc})	26,775,857	27,904,606	28,832,846	29,257,456	28,520,509
Retailer's profit (π_r)	11,072,001	11,111,601	10,850,059	10,018,486	8,070,521
Manufacturer's profit (π_m)	15,703,857	16,793,005	17,982,787	19,238,970	20,449,988
Patient Benefits	10,065,455	12,346,223	15,500,084	20,036,972	26,901,737

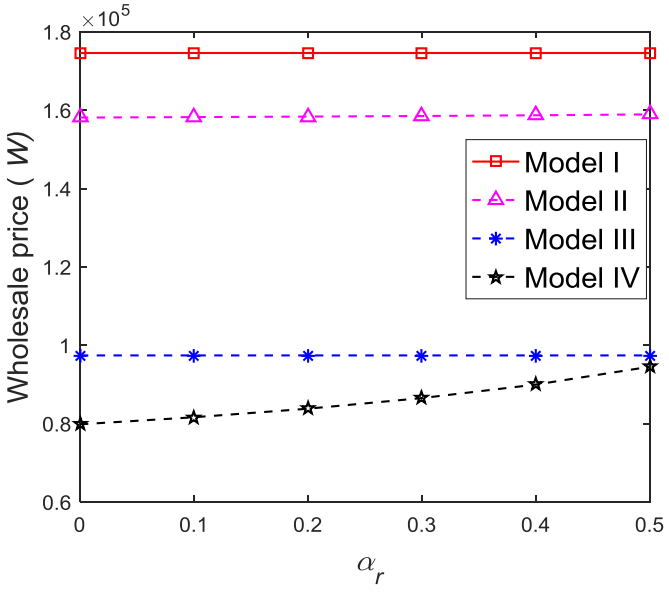

Fig. 1. Effects of α_r on the wholesale price.

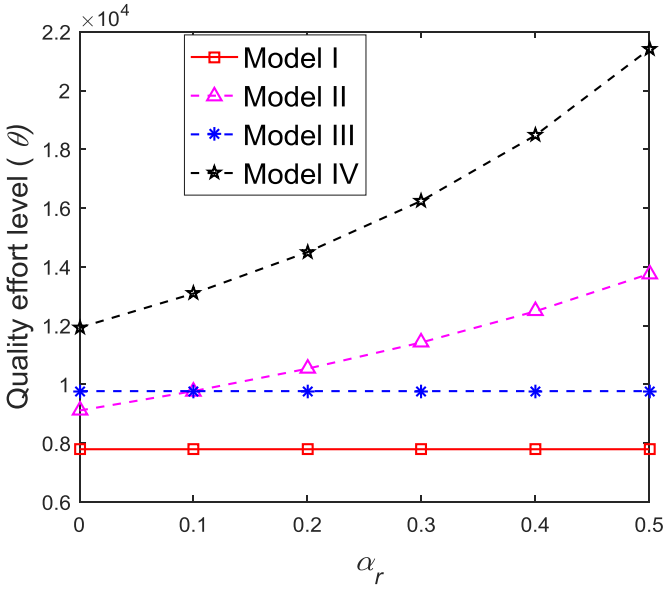

Fig. 3. Effects of α_r on the quality effort level.

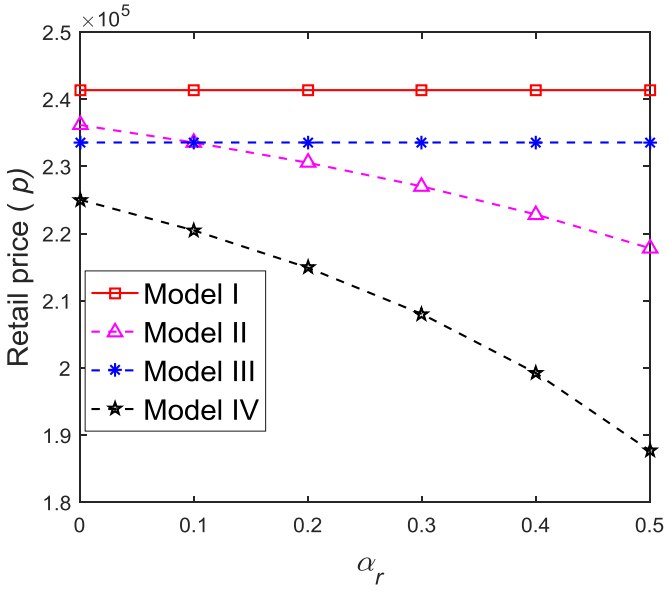

Fig. 2. Effects of α_r on the retail price .

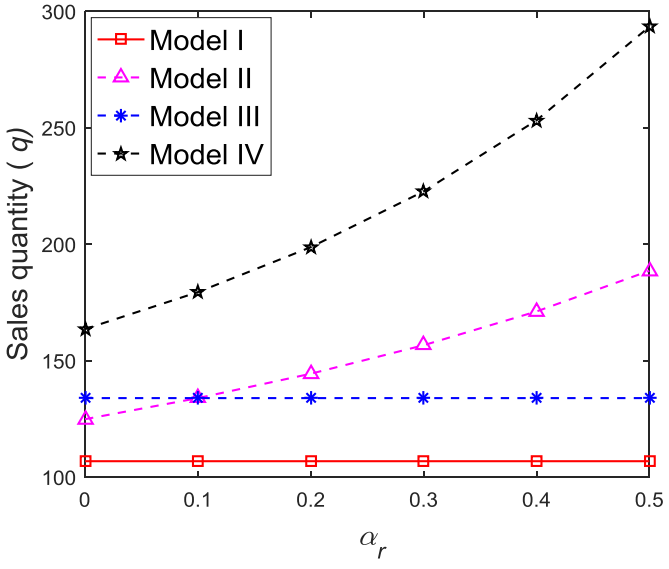

Fig. 4. Effects of α_r on the sales quantity.

under Models II and IV. This is because that the manufacturer wants the retailer to care more patient concern, and when the retailer improves its patient concern level, the manufacturer will improve its quality effort level to increase the sales quantity. Lastly, Fig. 4 shows that the sales quantities under Models II, III and IV are larger than those of the wholesale price contract with no patient concern (i.e., Model I). Fig. 4 also shows that the revenue-sharing contract can increase the sales quantities compared to the wholesale price contracts. The sales quantities increase with the retailer's patient concern under Models II and IV. Moreover, the

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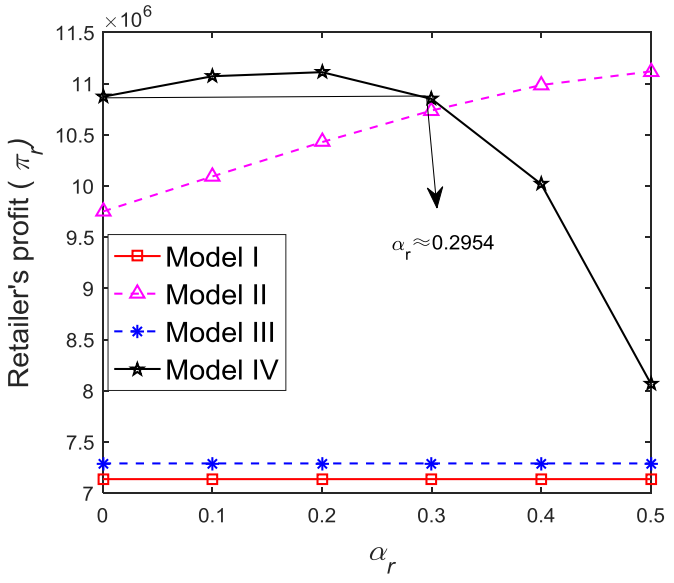

Fig. 5. Effects of α_r on the retailer's profits.

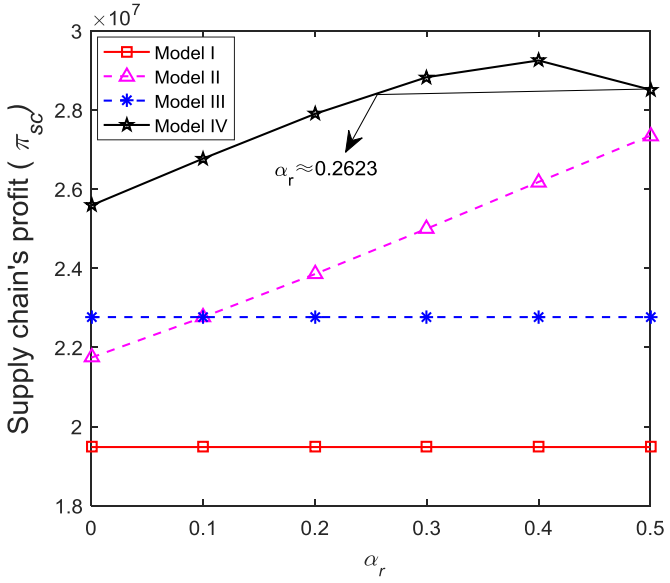

Fig. 7. Effects of α_r on the SC's profits.

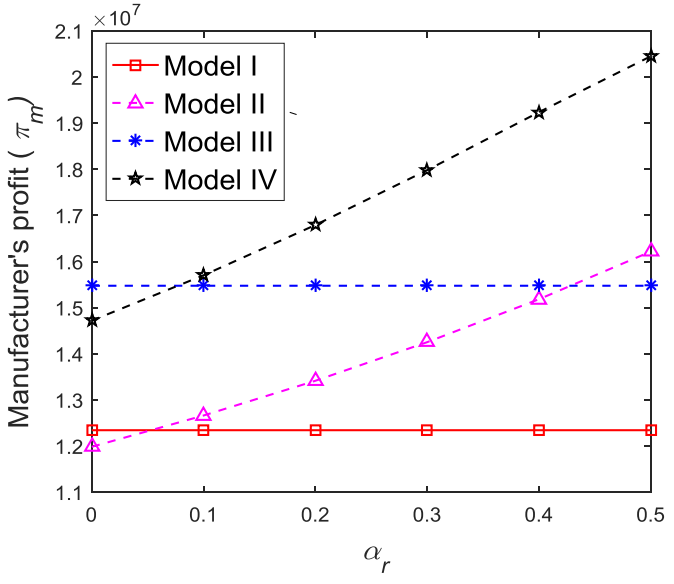

Fig. 6. Effects of α_r on the manufacturer's profits.

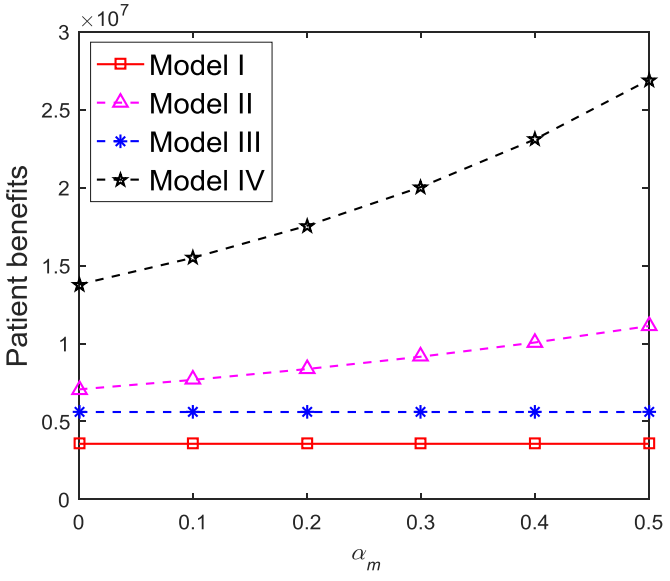

Fig. 8. Effects of α_m on the patient benefits.

sales quantities under model II are larger than these under Model III if $\alpha_r \geq \bar{\alpha}_r \approx 0.1$.

6.3. Effects of parameter α_r on the profits of the retailer, the manufacturer and the SC

Based on the same parameters used in Section 6.2, we will study the effects of α_r on the profits of the retailer, the manufacturer and the SC in this subsection. Fig. 5 shows that the retailer will consider less patient concern level than that the manufacturer will do (From Fig. 5, we can also find that the retailer obtains the highest profits in models IV when $\alpha_r \approx 0.1699$). From the perspective of the manufacturer, the manufacturer's profits increase with the retailer's patient concern under Models II and IV, and the manufacturer will obtain the highest profits under Model IV if $\alpha_r \geq \bar{\alpha}_r \approx 0.078$ (See Fig. 6). Fig. 5 also shows that the retailer will obtain the same profits when $\alpha_r = 0$ and $\alpha_r \approx 0.2954$. On the other hand, the manufacturer will also want the retailer to choose the case ($\alpha_r \approx 0.2954$). This is because the manufacturer's profits will always increase with the retailer's patient concern level (See Fig. 6). Moreover, the case ($\alpha_r \approx 0.2954$) can make the customer obtain higher patient benefits (See Tables 2 and 3). Thus, the retailer will choose the case ($\alpha_r \approx 0.2954$) to care the patient benefits.

Fig. 7 shows that the SC will obtain the highest in Model IV with $\alpha_m = 0.5$ and $\alpha_r \approx 0.4$. The SC's profits in Model III are higher than those of Model II when the retailer's patient concern level is relatively small. If the manufacturer introduces the fraction of patient benefits into its objective function is 0.5, the retailer's best strategy is not considering the same fraction of patient benefits as the manufacturer does. Fig. 7 also shows that the SC will obtain the same profits when the $\alpha_r \approx 0.2623$ and $\alpha_r = 0.5$. From the perspective of profits, there is no difference between $\alpha_r \approx 0.2623$ and $\alpha_r = 0.5$. However, the case ($\alpha_r = 0.5$) can make the customer

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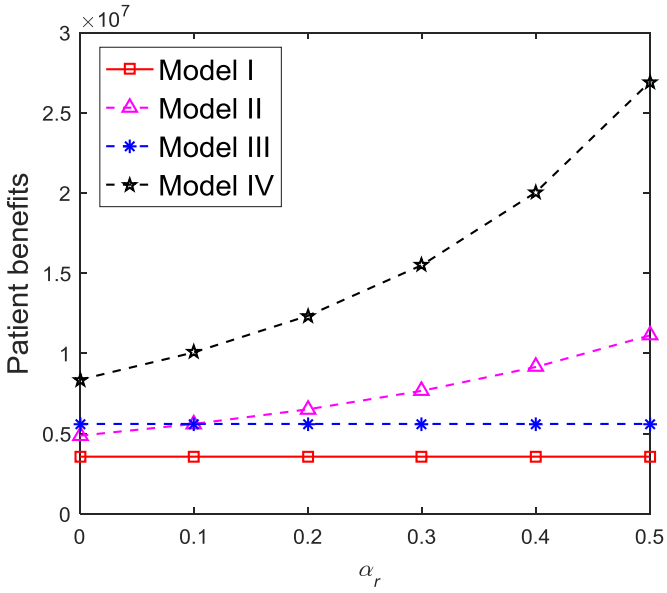

Fig. 9. Effects of α_r on the patient benefits.

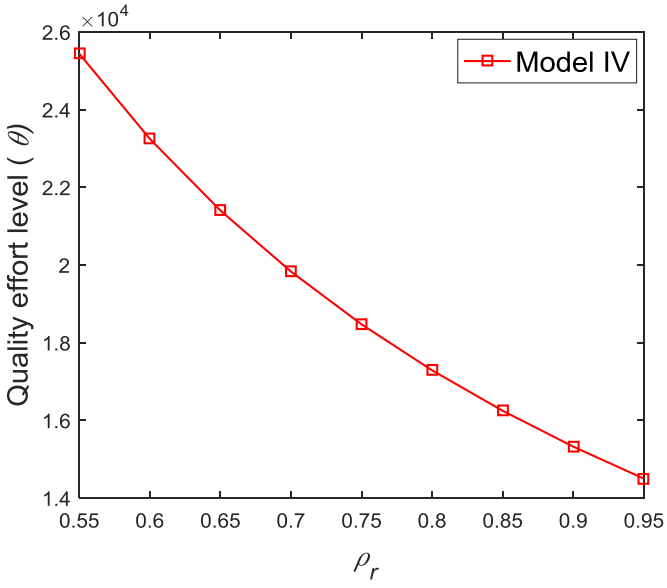

Fig. 10. Effects of ρ_r on the quality effort level.

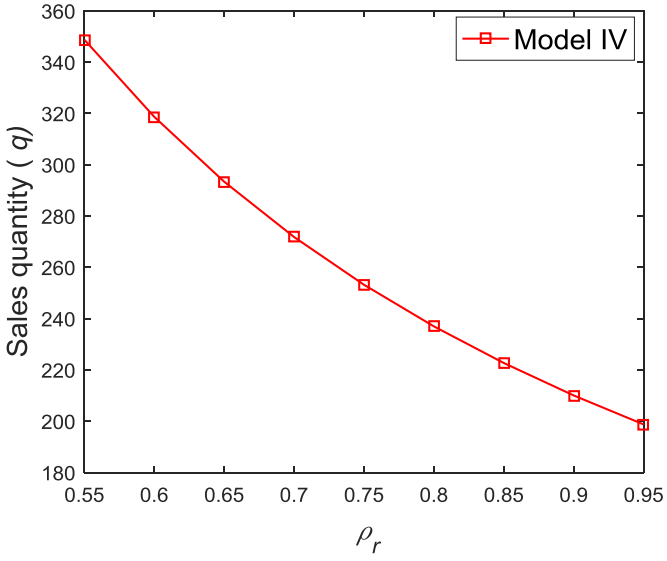

Fig. 11. Effects of ρ_r on the sales quantity.

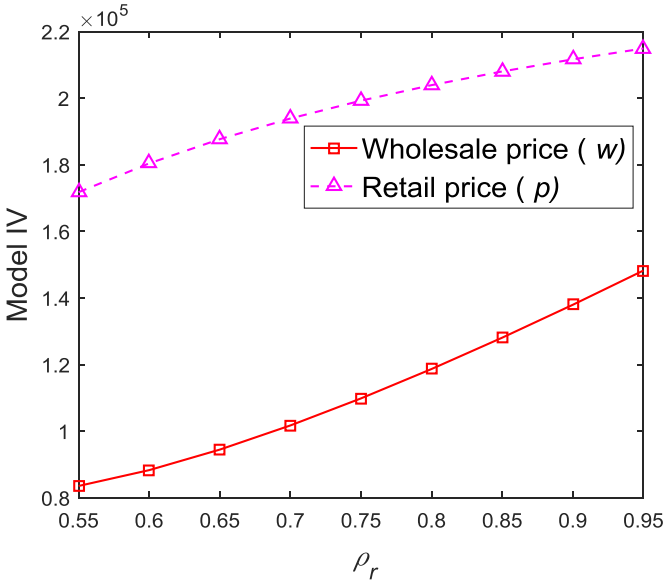

Fig. 12. Effects of ρ_r on the wholesale and retail prices.

obtain higher patient benefits (See Tables 2 and 3). Thus, the case ($\alpha_r = 0.5$) is better than the case ($\alpha_r \approx 0.2623$). Similarly, we can set the value of α_r to investigate the effects of α_{m}. However, we omit it here and put them on the Appendix E.

6.4. Effects of α_{m} and α_{r} on the patient benefits

Recall that the values of parameters: $a = 435.354$, $b = 0.0016$, $c = 41{,}009.25$, $\rho_r = 0.65$, $\gamma = 0.0074$, $\xi = 0.0634$. Assume $\alpha_r = 0.5$ to investigate the effects of α_m on the patient benefits and we obtain Fig. 8. Fig. 8 shows that the patient benefits in Model IV always increase with manufacturer's patient concern. This is also the reason why the SC's profits in Model IV cannot always increase with the manufacturer's patient concern (See Fig. e7). Then, we set $\alpha_m = 0.5$ to investigate the effects of α_r on the patient benefits and obtain Fig. 9. Fig. 9 also shows that the patient benefits obtain the highest under Model IV and increase with retailer's patient concern very quickly when the parameter α_r is relatively large. Moreover, patient benefits under the wholesale price contract with patient concern (Model II) will be higher than that under the revenue-sharing contract with no patient concern (Model III) if the retailer's patient concern level is larger than a threshold value (i.e., $\alpha_r > \bar{\alpha}_r \approx 0.1$).

6.5. Effects of parameter ρ_{r} on the optimal decisions ($\alpha_{\mathrm{m}} = \alpha_{\mathrm{r}} = 0.5$)

Now, we again use the parameters $a = 435.354$, $b = 0.0016$, $c = 41{,}009.25$, $\gamma = 0.0074$, $\xi = 0.0634$, $\alpha_m = 0.5$ and $\alpha_r = 0.5$ to investigate the effects of ρ_r on the quality effort, the sales quantity, the wholesale price, the retail price, and the profits of the retailer, the manufacturer and the SC. From Figs. 10–13, we find that: (1) The quality effort level and the sales quantity decrease with the retailer's revenue-sharing fraction; (2) Both the retail price and the wholesale price increase with the retailer's revenue-sharing fraction, and as the retailer's revenue-sharing fraction increases, the difference between the retail price and the wholesale price will be smaller; (3) The profits of the manufacturer are higher than those of the retailer, and the retailer's profits increase with

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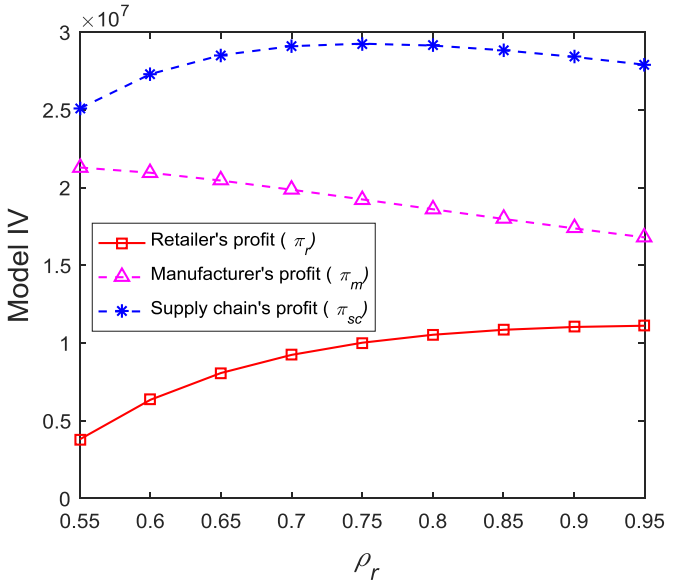

Fig. 13. Effects of ρ_r on the profits of the retailer, the manufacturer, and the SC.

retailer's revenue-sharing fraction while the manufacturer's profits decrease with it. Moreover, the SC can obtain the highest profits when $\rho_r = 0.75$.

7. Conclusions

We studied how the quality effort level of the medical equipment manufacturer is linked to its patient concern level and how the patient concern levels affect the quality effort level, the wholesale price, the retail price, the sales quantity and the profits of the manufacturer, the retailer, and SC. By developing models of five scenarios (i.e., wholesale price contract with no patient concern, wholesale price contract with patient concern, revenue-sharing contract with no patient concern, and revenue-sharing contract with patient concern, and revenue-sharing contract with constraint condition of patient concern), we obtain the optimal values under five different models.

Some key insights from our study are as follows: (1) we found the Pareto improvement conditions under which the revenue-sharing contract can allow the retailer and the manufacturer to achieve a win-win situation; (2) the retail price will always decrease with manufacturer's and retailer's patient concern levels while the product's sales quantity and the quality effort level increase with manufacturer's and retailer's patient concern level in Models II and IV respectively; (3) the SC's profits always increase with retailer's and manufacturer's patient concern level in Model II. In Model IV, the SC's profits increase with retailer's patient concern when the retailer's patient concern level is relatively low and decrease with it when the retailer's patient concern level is relatively high; (4) all the patient benefits under Models II and IV increase with manufacturer's and retailer's patient concern respectively; (5) In Model V, the influences of manufacturer's and retailer's patient concern on the retail price, the sales quantity, the quality effort level, the SC's profits and the patient benefits depend on whether the consumer-welfare constraint is binding or not; (6) we used case study to address the proposed models and validate our analytical results. Even though this study was motivated by a SC in the medical equipment industry and used data from that SC, all analyses and insights are also applicable to more general settings where the customer demand depends on effort and altruistic preferences may happen. Actually, more and more SCs are becoming concerned about sustainability and social welfare.

This research can be extended in several ways. One possible future research opportunity is to consider the contract coordination problem in SCs by taking patient benefits into account. SCs often have multiple manufacturers, so another possible direction is to examine the optimal quality and pricing decisions with competing manufacturers.

Acknowledgments

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ejor.2019.06.030.

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