

Intraday Price and Volatility Spillovers between Japanese and Korean Stock Markets*

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This study investigates the intraday price and volatility spillover effect between the Japanese market and the Korean market, using a VAR-asymmetric BEKK GARCH model. In particular, the study considers three high-frequency (10-min, 30-min, and 1-hour) intraday datasets of TOPIX and KOSPI200 markets. The empirical results indicate a bi-directional price spillover effect in the 10-min intervals, but a uni-directional price spillover from the TOPIX market to KOSPI200 market in the 30-min and 1-hour time intervals. Regarding the volatility spillover effect, the estimation of the asymmetric BEKK GARCH model indicates evidence of bi-directional volatility spillover in the 10-min intervals, whereas the volatility spillover becomes weak with an increase in the length of time intervals (30-min and 1-hour). In addition, the cross-market asymmetric response is evident from the TOPIX market to the KOSPI200 market in all time intervals. These findings provide an important guideline on arbitrage strategies and risk management over very short time periods.

JEL Classification: C32, G12, G14, G15

Keywords: VAR-asymmetric BEKK GARCH model, intraday volatility, spillover effect, impulse response function, time-varying correlation coefficients

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1. INTRODUCTION

The issue of financial market integration is of interest in understanding market price spillover and volatility spillover effects from one market to another. Such a spillover effect in finance is the most important concept in building the optimal risk portfolios for international portfolio managers and risk managers (Kenourgios *et al.*, 2011; Syllignakis and Kouretas, 2011; Reboredo, 2014). In short, the dynamics of price spillover effects provide price predictions and an opportunity for an exploitable trading strategy, which constitutes evidence against market efficiency (Pati and Rajib, 2011; Dimpfl and Jung, 2012). In addition, information about volatility spillover effects may be useful for applications that rely on estimates of conditional volatility, such as option pricing, portfolio optimization, management of value-at-risk, and risk hedging (Arouri *et al.*, 2011, 2012; Aragón and Salvador, 2011).

Recent econometric studies have developed advanced techniques in capturing the spillover effects, i.e., multivariate generalized autoregressive conditional heteroskedasticity (GARCH)-type models (Bauwens *et al.*, 2006). In spite of these effects, prior studies are limited to detecting spillover effects as they utilize low frequency data that do not capture uncovered intraday information transmission among financial markets. With the development of information technology (IT), researchers easily access the high frequency data that provide more reliable information for examining the spillover effect within a very short time.

In this paper, we focus on the issue of price and volatility spillovers between the Tokyo Stock Price Index (TOPIX) and the Korea Composite Stock Price Index 200 (KOSPI200), in order to provide an important insight into the mechanism of information transmission between the two equity markets. In so doing, this paper utilizes the VAR-asymmetric BEKK GARCH model in three intraday datasets (10-min, 30-min, and 1-hour intervals).

This paper differs from the extant literature in the following ways. First,

some quantitative studies examine the relationship between an intraday single market, i.e., spot and futures markets. This study initially explores the intraday price and volatility spillover effects between two different equity markets. The evidence of spillover effect in different equity markets is an important factor in predicting the price and volatility direction in very short time intervals. Second, this paper first considers the high frequency data of Japanese and Korean equity markets. These two equity markets have homogenous trading times, common information transmission, and similar industry structures. These linkages indicate that market information in one market influences stock prices and volatility of its counterpart market in real time. Thus, intraday traders take into account the dynamic relationship between two markets over very short time intervals. Third, this study extends the multivariate GARCH with the asymmetric volatility effect, called the VAR-asymmetric BEKK GARCH model, which incorporates an asymmetric volatility transmission across two markets. Understanding the asymmetric volatility transmission offers an opportunity for arbitrage trading strategies (or program trading) for intraday traders.

Our empirical results support strong intraday linkages between Japanese and Korean stock markets. This information provides important implications for intraday traders in implementing arbitrage trading strategies, and also for portfolio managers in risk management. Intraday traders must take into account uni-directional asymmetric spillover effects in order to optimize arbitrage trading strategies in very short time intervals. In addition, risk-averse investors assess market portfolio risk by measuring the volatility spillover effects between two stock markets.

The rest of this paper is organized as follows. Section 2 briefly reviews the literature relating to spillover effects. Section 3 provides the descriptive statistics of 10-min intraday data. Section 4 discusses the econometric methodology used in this study. Section 5 provides the results, and several conclusions are discussed in section 6.

2. LITERATURE REVIEW

Numerous empirical studies have paid greater attention to the integration of, or contagion among, financial markets, especially in the wake of the October 1987 crash, which brought about correlated stock price movements across markets (Kanas, 1998). Early studies focused exclusively on the price spillover effect using the Granger-causality test (Eun and Shim, 1989; Jeon and von Furstenberg, 1990; Cumby, 1990).

Extensive empirical studies considered the information transmission or volatility spillover from one market to another (Hamao *et al.*, 1990; Koutmos and Booth, 1995; Kanas, 1998; In *et al.*, 2001). These volatility spillovers are usually attributed to cross-market hedging and changes in shared information, which may simultaneously alter expectations across markets (Arouri *et al.*, 2011, 2012; Aragó and Salvador, 2011). In addition, the existence of volatility spillover provides evidence of market contagion, i.e., a shock increases the volatilities not only in its own asset or market but also in other assets or markets as well (Chiang *et al.*, 2007; Poshakwale and Aquino, 2008; Dean *et al.*, 2010; Zhao, 2010; Ding and Pu, 2012).

Recently, empirical studies have tried to analyze the impact of the 2008 global financial crisis (GFC) on information transmission among equity markets. Syllignakis and Kouretas (2011) captured contagion effects among the US and German stock returns and the Central and Eastern Europe (CEE) stock returns during the GFC, using the Dynamic Conditional Correlation (DCC). Hwang *et al.* (2013) examined patterns of crisis spillover between stock returns of ten emerging economies and those of the US using the EGARCH-DCC model. Dimitriou *et al.* (2013) provided evidence of contagion effects on BRICS in different phases of the GFC, using the FIAPARCH-DCC model. Kang and Yoon (2013) revisited return and volatility spillover effect between the foreign exchange (KRW) and stock (KOSPI) markets in Korea, using the bivariate GJR-GARCH model. They found a uni-directional relationship from the KOSPI and KRW markets.

Another group of studies attempted to analyze the impact of sudden

changes on the volatility spillover across different markets. Ewing and Malik (2005, 2013) examined volatility transmission allowing for sudden change in variances using the MGARCH-BEKK model. Kang *et al.* (2011) suggested that ignoring structural changes may distort the direction of information inflow and volatility transmission between crude oil markets. In addition, a few studies have focused on the spillover effects in the intraday returns. Wu *et al.* (2005) found bi-directional volatility spillover between intraday US and UK futures markets. Chiang *et al.* (2009) found the positive dynamic conditional correlation between DJIA spot and NASDAQ futures markets, using both 10-min and 30-min interval returns. Park and Kim (2011) investigated the volatility behavior of ultra-high-frequency returns on Japanese Government Bond (JGB) futures transactions, using two-state Markov-switching volatility models. Pati and Rajib (2011) suggested that 5-min intraday futures prices lead to spot prices and then futures markets largely contribute to price discovery in the India market. Kang *et al.* (2013) and Kim and Ryu (2014) found that intraday bi-directional volatility spillover affects spot and futures markets of Korea.

Some studies have done the price and volatility spillover effects between Korean and Japanese stock markets. Kim and Rogers (1995) found the volatility spillovers from Japan and the U.S stock markets to the Korean stock market. Miyakoshi (2003) analyzed the price and volatility spillovers from Japan and US to Asian stock markets including Korea. This paper found a greater regional influence from Japan on Asian volatility than the world influence from the US and find a new adverse influence from Asia to Japan. Huyghebaert and Wang (2010) examined the co-movement in East Asian stock markets during the 1997-1998 Asian currency crisis. They suggested that price shocks in Hong Kong, Singapore, and Japan do have a significant effect on prices in the Korean stock market. Jeong *et al.*, (2012) provided no-evidence price spillover among Korea, China and Japan stock markets, but strong evidence of volatility spillover among them. Wang (2014) investigated the integration and causality of interdependencies in East Asian stock markets during the 2007-2009 global financial crisis. The global

financial crisis results in the integration of the Korean and Japanese stock markets and enhances both markets to be a more important regional market.

Many empirical studies have still considered the concept of spillover effects with mixed conclusions. This study also extends the in-depth concept of spillover effects with intraday returns.

3. DATA AND DESCRIPTIVE STATISTICS

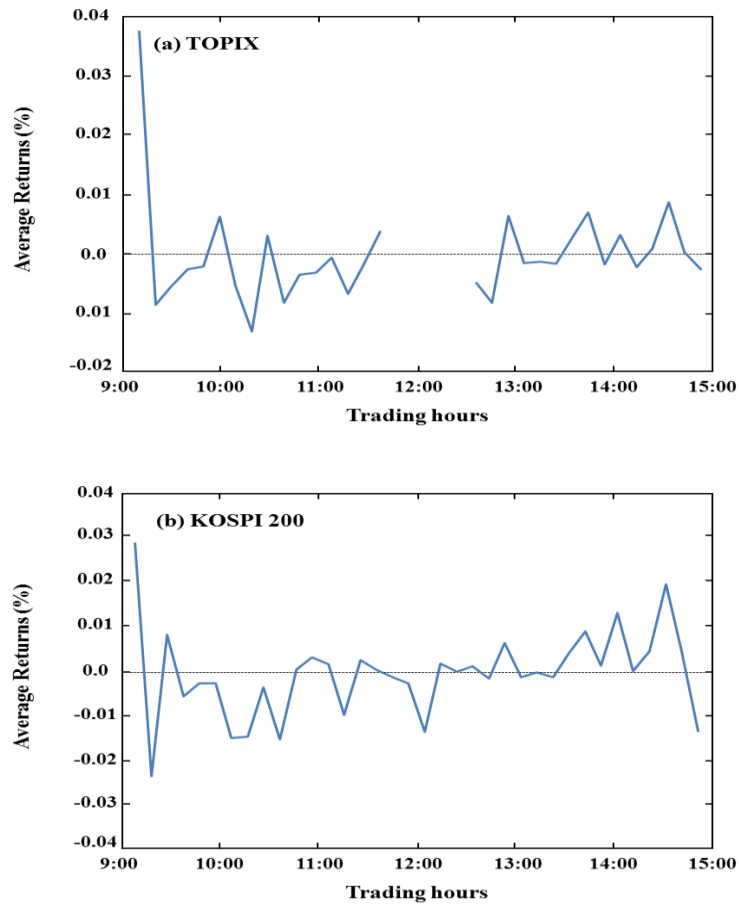
3.1. High Frequency Data of TOPIX and KOSPI200 Markets

With the advent of home trading systems and the rapid development of information technology (IT) techniques, investors can easily implement intraday trading strategies. The increase in intraday transactions requires academics to analyze the intraday behavior of the markets. High frequency data provide important implications regarding spillover effects within a very short time interval. In this context, this study considers three intraday time intervals, i.e., 10-min, 30-min, and 1-hour in both the TOPIX and KOSPI200 markets. These two equity markets have a homogenous trading time, from opening at 9:00 a.m. to closing at 15:00 p.m. The TOPIX market consists of two trading sessions: a morning session (9:00 a.m. to 11:30 a.m.) and an afternoon session (12:30 p.m. to 15:00 p.m.).

Figure 1 shows the average returns of TOPIX and KOSPI200 for each 10-min time interval. Both markets show a similar pattern of average returns. The initial 10-min interval from 9:00 a.m. to 9:10 a.m. shows the positive response of the market to overnight information. After this interval, the average returns across the time intervals center at zero and increase towards the end of the trading day. Both average returns show low returns at closing time (15:00 p.m.).

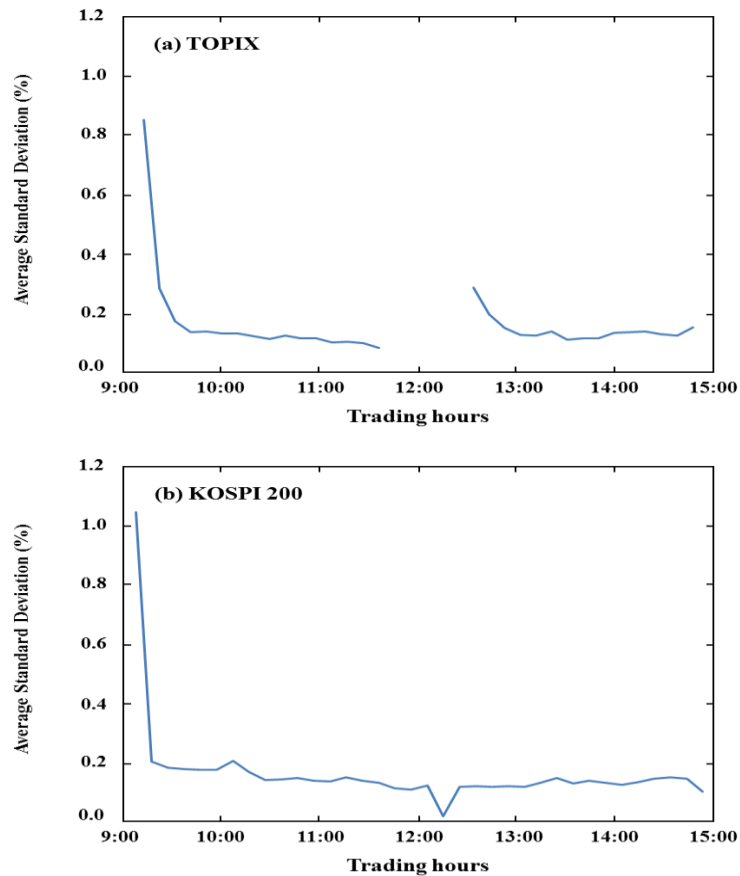
Figure 2 shows average standard deviation (volatility) across 10-min intervals. In the TOPIX market, starting out at about 0.90% in the morning session, they drop more than half during the afternoon session. The average

Figure 1 Average Returns for 10-min Intraday Data



Notes: The initial 10-min interval (from 9:00 to 9:10 a.m.) shows strong positive returns, reflecting the impact of both market opening effects. Following this, the average returns across the intervals center at zero.

volatility of TOPIX is significantly higher at the opening of the morning and afternoon sessions than during the closing-morning and closing-afternoon sessions. These features, combined with an increase in volatility immediately following the opening of each session, result in two distinct inverted J-shaped patterns: one in the morning and one in the afternoon.

Figure 2 Average Standard Deviation for 10-min Intraday Data

Note: The trading activity clearly exhibits a double inverted J-shaped pattern for the TOPIX market and single inverted J-shaped pattern for the KOSPI200 market.

In the KOSPI200 market, volatility starts at about 1.03% in the initial 10-min interval and then drops to the lowest level by midday, and rises slightly towards the close. Daily trading activities show an inverted *J*-shaped pattern across the 10-min intervals for every trading day as a result of the market opening effects. A similar pattern in intraday series can be also founded in Andersen *et al.* (2000), Wu *et al.* (2005), Haniff and Pok (2010), and Kang *et al.* (2013).

3.2. Descriptive Statistics for Sample Data

We considered three high frequency datasets (10-min, 30-min, and 1-hour time intervals) of the TOPIX and KOSPI200 markets. Intraday datasets cover the period from January 4, 2011 to December 28, 2012, obtained from the database of SIRCA.¹⁾ The high-frequency price series were then converted into logarithmic return series for all sample indices, that is, $R_{i,t} = \ln(P_{i,t}/P_{i,t-1}) \times 100$, where $R_{i,t}$ denotes the continuously compounded percentage returns for index i at time t and $P_{i,t}$ denotes the price level of index i at time t .

Table 1 shows the descriptive statistics and the results of the unit root tests for three intraday return series of both markets. As shown in Panel A of table 1, the return series show very similar descriptive statistics. According to skewness (Skew.) measured at the third standardized moment, excess kurtosis (Kurt.) measured at the deviation of the fourth moment from three of the normal distribution, and the Jarque-Bera (J-B) test results for Gaussian distribution of the observed probability distribution, the return series tend to follow a leptokurtic distribution with a higher peak and a fatter tail than the case of a normal distribution. The calculated values of the Ljung-Box statistic, $Q^2(12)$, for the squared return series are extremely high, indicating the rejection of the null hypothesis of no serial correlation. Thus, the return series seem to follow ARCH-type dependencies, confirming the appropriateness of our GARCH-type model formulation in analyzing intraday volatility.

Panel B of table 1 provides the results of two types of unit root tests for the stationarity of individual series: standard parametric augmented Dickey-Fuller (ADF) tests and non-parametric Phillips-Peron (PP) tests. These two ADF and PP test results with large negative values reject the null hypothesis of a unit root at the 1% level of significance, respectively. Thus, all the

¹⁾ We remove the observations of lunch break (11:30 a.m. to 12:30 p.m.) to couple trading time intervals between the TOPIX market and the KOSPI200 market. From the referee's point of view, the lunch break might affect the dynamics of the two markets. Note that this paper does not consider market micro-structure factors in both markets.

Table 1 Descriptive Statistics and Results of Unit Root Tests

	TOPIX			KOSPI200		
	10-min	30-min	1-hour	10-min	30-min	1-hour
Panel A: Descriptive Statistics						
Obs.	13,204	5,188	2,830	13,204	5,188	2,830
Mean	-0.0004	-0.0010	-0.0019	-0.0003	-0.0006	-0.0013
Std. Dev.	0.2126	0.3531	0.4801	0.2571	0.4005	0.5330
Maximum	3.2108	3.7668	4.7195	3.8755	3.6324	3.5996
Minimum	-3.5876	-6.1185	-6.8100	-5.1124	-5.5663	-5.7299
Skewness	-0.8812	-1.7602	-1.3550	-1.8412	-1.6815	-1.2817
Kurtosis	68.824	56.271	40.732	88.695	42.815	24.662
Jarque-Bera	2,385,489***	616,111***	168,750***	4,047,751***	345,123***	56,110***
$Q^2(12)$	2,698.6***	1,831.7***	1,457.0***	828.34***	822.44***	1,275.8***
Panel B: Results of Unit Root Tests						
ADF	-98.716***	-65.906***	-49.676***	-110.45***	-64.640***	-49.810***
PP	-98.461***	-65.784***	-49.758***	-110.41***	-68.674***	-49.828***

Notes: The Jarque-Bera (J-B) test was used for the null hypothesis of normality in the sample return distribution. The Ljung-Box statistic, $Q^2(12)$, was used to check for the presence of serial correlation in squared returns up to the 12th order. MacKinnon's 1% critical value is -3.435 for the ADF and PP tests. *** indicates the rejection of the null hypothesis at the 1% level of significance.

intraday return series used in this study could be regarded as stationary ones.

4. METHODOLOGY

This section introduces the VAR-asymmetric BEKK GARCH model that incorporates the price spillover and asymmetric volatility spillover between two market intraday variables (Engle, 2002). Consider the following

bivariate VAR(1) models to examine the Granger-causal relationship between two stock markets:²⁾

$$\begin{bmatrix} R_{1,t} \\ R_{2,t} \end{bmatrix} = \begin{bmatrix} \mu_1 \\ \mu_2 \end{bmatrix} + \begin{bmatrix} \gamma_{11} & \gamma_{12} \\ \gamma_{21} & \gamma_{22} \end{bmatrix} \begin{bmatrix} R_{1,t-1} \\ R_{2,t-2} \end{bmatrix} + \begin{bmatrix} \varepsilon_{1,t} \\ \varepsilon_{2,t} \end{bmatrix}, \quad (1)$$

where $R_{1,t}$ and $R_{2,t}$ are TOPIX and KOSPI200 intraday returns, respectively. μ_1 and μ_2 are constants and ε_1 and ε_2 are error terms. The coefficients, γ_{12} and γ_{21} capture the effect of the Grange-causal relationship between two markets. For example, the significance of γ_{21} means that TOPIX intraday returns Granger-cause the KOSPI200 intraday returns. The diagonal terms γ_{11} and γ_{22} measure their own lagged effects.

We further analyze the asymmetric volatility spillover between two markets, using the asymmetric BEKK GARCH model. By allowing the time-varying conditional variance of $\varepsilon_{i,t}$, H_t is a 2×2 matrix of conditional variance-covariance at time t . The market information available at time $t-1$ is represented by the information Ω_{t-1} in equation (2):

$$\begin{bmatrix} \varepsilon_{1,t} \\ \varepsilon_{2,t} \end{bmatrix} | \Omega_{t-1} \sim N(0, H_t). \quad (2)$$

An asymmetric BEKK GARCH model of Kroner and Ng (1998), which extended the GJR-GARCH approach of Glosten *et al.* (1993) to a multivariate setting to capture the asymmetric response to news on volatility, can be represented as follows:

$$H_t = C'C + A'\varepsilon_{t-1}\varepsilon'_{t-1}A + B'H_{t-1}B + D'\eta_{t-1}\eta'_{t-1}D, \quad (3)$$

²⁾ The optimal lag order of VAR model was determined by the Akaike information criterion (AIC).

$$\begin{aligned}
\begin{bmatrix} h_{11,t} & h_{12,t} \\ h_{21,t} & h_{22,t} \end{bmatrix} &= \begin{bmatrix} c_{11} & \\ c_{21} & c_{22} \end{bmatrix}' \begin{bmatrix} c_{11} & \\ c_{21} & c_{22} \end{bmatrix} \\
&+ \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}' \begin{bmatrix} \varepsilon_{1,t-1}^2 & \varepsilon_{1,t-1}\varepsilon_{2,t-1} \\ \varepsilon_{2,t-1}\varepsilon_{1,t-1} & \varepsilon_{2,t-1}^2 \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \\
&+ \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}' \begin{bmatrix} h_{11,t-1} & h_{12,t-1} \\ h_{21,t-1} & h_{22,t-1} \end{bmatrix} \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} \\
&+ \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix}' \begin{bmatrix} \eta_{1,t-1}^2 & \eta_{1,t-1}\eta_{2,t-1} \\ \eta_{2,t-1}\eta_{1,t-1} & \eta_{2,t-1}^2 \end{bmatrix} \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix}, \tag{4}
\end{aligned}$$

where H_t is a 2×2 matrix of conditional variance-covariance at time t ; C is a 2×2 lower triangular matrix with three parameters; A is a 2×2 square matrix of parameters and indicates the extent to which conditional variances are correlated to past squared errors; and B is a 2×2 squared matrix of parameters and indicates the extent to which current levels of conditional variances are related to those of past conditional variances. The off-diagonal elements of the matrices A and B capture cross-market effects, including shock spillovers (a_{12} and a_{21}) and volatility spillovers (b_{12} and b_{21}) between TOPIX and KOSPI200 markets.

In equation (4), $\eta_{t-1} = \begin{bmatrix} \max(0, -\varepsilon_{1,t-1}) \\ \max(0, -\varepsilon_{2,t-1}) \end{bmatrix}$, D is a 2×2 squared matrix of parameters and captures any asymmetry in variances and covariance through the definition of η_{t-1} . The significances of diagonal coefficients d_{11} and d_{22} capture evidence of an asymmetric response to negative shocks (bad news) to itself for both markets. Likewise, the significances of off-diagonal coefficients d_{21} and d_{12} examine the cross-market effect of volatility asymmetric response.

The parameters of the bivariate GARCH model can be estimated by the maximum likelihood estimation method optimized with the Berndt, Hall, Hall and Hausman (BHHH) algorithm. The conditional log likelihood function $L(\theta)$ is expressed as:

$$L(\theta) = -T \log 2\pi - 0.5 \sum_{t=1}^T \log |H_t(\theta)| - 0.5 \sum_{t=1}^T \varepsilon_t(\theta)' H_t^{-1} \varepsilon_t(\theta), \quad (5)$$

where T is number of observations and θ denotes the vector of all the unknown parameters.

5. EMPIRICAL RESULTS

This section considers both price spillover and volatility spillover effects between two market intraday returns (10-min, 30-min, and 1-hour), using the VAR-asymmetric BEKK GARCH model. Table 2 shows the estimation results of the VAR(1)-asymmetric BEKK GARCH model using intraday returns of three time intervals. The estimation results provide several interesting findings.

First, we consider the mean spillover effects between two markets in VAR(1) estimation results. The significance of coefficients, γ_{12} and γ_{21} , indicates a bi-directional relationship in the 10-min interval returns. This evidence suggests both intraday returns affect each other in the 10-min intervals. In addition, we find that only the coefficient γ_{21} is negatively significant, at least at the 10% level in all three intervals, indicating that the TOPIX intraday returns have a negative impact on the KOSPI200 intraday returns. This result can be explained by the geographic proximity and closer economic ties between Korea and Japan: Both macro-economics are very close and competitive in the IT, automobile, shipbuilding industries (Lim, 2004; Yoon and Yeo, 2007). Their similar trade structures suggest the good performance of Japanese firms negatively affect the performance of Korean firms. Thus, the price shocks of Japan do have a significant impact of the prices of Korea, which is in line with the strong macro-linkages between two countries (Huyghebaert and Wang, 2010).

Second, we now turn to volatility spillover effect between the two markets. Only for the case of the 10-min time interval, the diagonal parameters (i.e., b_{11} , b_{22} , a_{11} , a_{22}) of the matrix A and B are statistically significant, indicating

Table 2 Intraday Volatility Spillovers between TOPIX and KOSPI200

	10-min		30-min		1-hour	
Mean Equation: VAR(1) Model						
μ_1	-0.0047***	(0.0014)	0.0190	(0.0384)	0.0032	(0.0071)
μ_2	-0.0012	(0.0017)	0.0212	(0.0404)	0.0004	(0.0071)
γ_{11}	0.0333***	(0.0141)	0.0408***	(0.0148)	0.0469**	(0.0233)
γ_{12}	0.0207***	(0.0092)	0.0023	(0.0127)	-0.0018	(0.0190)
γ_{21}	-0.0571***	(0.0130)	-0.0549***	(0.0170)	-0.0361*	(0.0214)
γ_{22}	0.0659***	(0.0115)	0.0867***	(0.0170)	0.0902***	(0.0223)
Variance Equation: Bivariate Asymmetric GARCH Model						
c_{11}	0.1499***	(0.0012)	0.5163***	(0.0272)	0.0778***	(0.0056)
c_{21}	0.0521***	(0.0014)	0.1247***	(0.0198)	0.0179***	(0.0045)
c_{22}	0.0027***	(0.0009)	0.2223***	(0.0152)	0.0377***	(0.0034)
a_{11}	0.8727***	(0.0214)	0.0001	(0.0264)	0.0014	(0.0347)
a_{12}	0.2490***	(0.0110)	-0.0000	(0.0077)	0.0099	(0.0196)
a_{21}	-0.2867***	(0.0152)	-0.0000	(0.0184)	-0.0097	(0.0312)
a_{22}	0.0765***	(0.0074)	0.0000	(0.0173)	-0.0226	(0.0427)
b_{11}	0.0688***	(0.0085)	0.9713***	(0.0027)	0.9658***	(0.0044)
b_{12}	-0.3082***	(0.0104)	-0.0009	(0.0017)	0.0001	(0.0028)
b_{21}	0.4176***	(0.0020)	0.0144***	(0.0017)	0.0142	(0.0028)
b_{22}	1.1173***	(0.0037)	0.9928***	(0.0011)	0.9882***	(0.0019)
d_{11}	0.2546***	(0.0449)	0.1800***	(0.0121)	0.2158***	(0.0170)
d_{12}	0.0320***	(0.0143)	0.0044	(0.0075)	0.0033	(0.0112)
d_{21}	-0.1105***	(0.0273)	-0.0768***	(0.0118)	-0.0611***	(0.0132)
d_{22}	0.0711***	(0.0100)	0.1390***	(0.0090)	0.1698***	(0.0134)

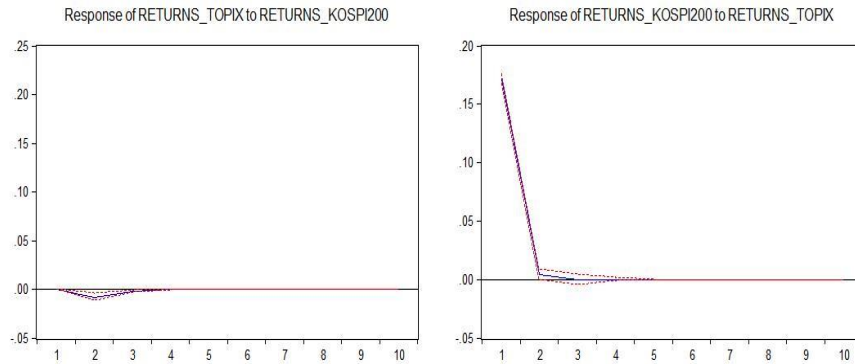
Notes: Standard errors are in parentheses. ***, **, * denote significance at the 1%, 5% and 10% levels, respectively.

ARCH and GARCH effects exist in both markets. This indicates that the current conditional variances of both intraday returns are considerably influenced by their own past shocks, respectively.

Third, the off-diagonal parameters of the matrices A and B measure cross-market impacts, capturing shock spillovers and volatility spillovers between Japanese and Korean stock markets, respectively. In the case of the 10-min interval, the estimate of a_{21} suggests a negative cross-effect running from the lagged KOSPI200 error to the TOPIX variance, while the estimate of a_{12} , which depicts a cross-effect in the opposite direction, shows a positive relation. It is noteworthy that the estimated off-diagonal parameters (i.e., a_{12} and a_{21}) of the matrix A are significant at the 1% level, respectively, indicating evidence of bi-directional shock spillovers between the two markets. Meanwhile, the shock spillover effects become weak in both markets as time intervals (30-min and 1-hour) increase.

Fourth, the off-diagonal elements in B (i.e., b_{12} and b_{21}) depict the extent to which the conditional variance of one variable is correlated with the lagged conditional variance of another variable. In the 10-min time intervals, the significance of b_{12} and b_{21} indicates a bi-directional volatility spillover between two markets. However, the estimation results of the 30-min interval suggest a uni-directional volatility spillover from the TOPIX market to the KOSPI200 market and then the volatility spillover effect disappears in the 1-hour time intervals.

Fifth, as far as matrix D is concerned, we find evidence of an asymmetric response to negative shocks (bad news) to itself for both markets due to the significance of coefficients d_{11} and d_{22} . This evidence suggests that negative shocks to itself have more effect than own positive shocks on the volatility of both markets. In addition, the cross-market asymmetric response is evident from the TOPIX market to the KOSPI200 market, as the coefficient d_{21} is negatively significant in all time intervals. This means that bad news in the TOPIX market leads to a smaller volatility in the KOSPI200 market than does good news in the TOPIX market. This evidence suggests that bad news in the TOPIX market should be good news in the KOSPI200

Figure 3 Impulse Response Function

market, but the reverse case is impossible. Thus, two competing markets transmit asymmetric volatility across markets. This finding provides an important implication on building the optimal portfolio between two markets.

Overall, the evidence of unidirectional spillover effects from the TOPIX market to the KOSPI200 market has become weak over an increase in time intervals from 10-min to 1-hour intraday returns. This implies that two equity markets share common information in real time and, thus, information in 10-min time intervals has more cross-market impact than in longer time intervals (30-min and 1-hour). In addition, this study finds asymmetric volatility response effects from the TOPIX market to the KOSPI200 market. Thus, we conclude that the TOPIX market leads the KOSPI200 market in price and asymmetric volatility over very short time intervals.

Figure 3 illustrates the impact of different shocks on TOPIX and KOSPI200 markets using the impulse response functions.³⁾ The results suggest that the impact of TOPIX shock is significant compared to the impact of KOSPI200 shocks, implying that the TOPIX intraday returns significantly affect the KOSPI200 intraday returns.

³⁾ The impulse response functions are based on Cholesky decomposition. We analyse the impulse response functions of three intraday returns. For save our spaces, we present the impulse response functions of 10-min intraday returns in this paper.

Figure 4 Time-Varying Correlation Coefficients

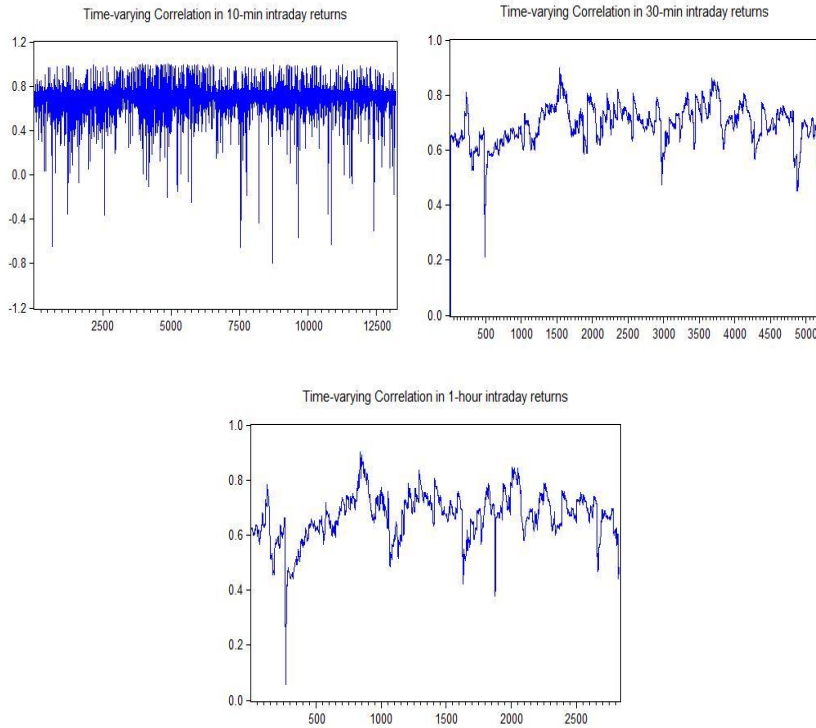


Figure 4 displays the conditional correlation coefficients in different time intervals, estimated from the VAR(1)-asymmetric BEKK GARCH(1, 1) model, which are calculated by $h_{12,t} / \sqrt{h_{11,t}} \sqrt{h_{22,t}}$. As shown in figure 3, the correlation coefficients are not constant, but vary greatly with time-varying changes and swings in all time intervals. Table 3 reports the descriptive statistics of correlation coefficients in different time intervals. Note that the 10-min intraday returns have the highest mean values, followed by the 30-min intraday returns, and the 1-hour intraday returns. This finding indicates that correlations become smaller as an increase in time-intervals. It seems that the common information is transmitted between two markets in very short time and this linkage become weak with an increase in time-intervals.

Table 3 Descriptive Statistics of Correlation Coefficients

Statistics	10-min	30-min	1-hour
Mean	0.7014	0.6931	0.6666
Maximum	0.9976	0.8995	0.9033
Minimum	-0.7961	0.0000	0.0585
Std. Dev.	0.1012	0.0728	0.0879
Skewness	-3.6696	-0.8744	-0.9684
Kurtosis	34.025	7.1044	6.26247

Note: This table reports the descriptive statistics of correlation coefficients in different time intervals.

6. CONCLUSIONS

This study has investigated the intraday price and volatility spillovers between the TOPIX and KOSPI200 using a VAR-asymmetric BEKK GARCH model. In this study, we considered three high-frequency intraday datasets (10-min, 30-min, and 1-hour intervals) in order to investigate the intraday spillover effects between the Japanese and Korean stock markets. This investigation of intraday spillover effects will provide intraday traders with a deeper understanding of short-time price and volatility transmission in both markets.

Our empirical results are summarized as follows. First, we found a bi-directional price spillover effect in the 10-min intervals, but a uni-directional price spillover from the TOPIX market to KOSPI200 market in the 30-min and 1-hour time intervals. Second, the estimation of the asymmetric BEKK GARCH model indicates evidence of bi-directional volatility spillovers between the two markets in the 10-min intervals. Meanwhile, the volatility spillover effects become weak as the time intervals (30-min and 1-hour) increase. Third, the cross-market asymmetric response is evident from the TOPIX market to the KOSPI200 market in all time intervals.

These intraday price and asymmetric volatility spillover effects may

provide an important guideline on arbitrage strategies and portfolio risk management in the Japanese and Korean stock markets. As intraday or program traders are eager to capture arbitrage opportunities, they must chase the price and volatility directions in very short-time trading intervals and change their positions to earn high returns without risk. In addition, risk-averse investors assess the portfolio risk by analyzing the direction of asymmetric volatility spillover effects between the two stock markets.

A limitation of our paper is that we do not consider the micro-structures of intraday stock markets. The TOPIX market consists of two trading sessions: a morning session (9:00 a.m. to 11:30 a.m.) and an afternoon session (12:30 p.m. to 15:00 p.m.). Two trading sessions might generate different volatility regimes in the intraday data and ignoring this macro-structure factor lead to biased results regarding volatility spillover effect between two intraday equity markets. In this context, we suggest that this study can be extended with volatility spillover effects in different regimes using a Markov switching GARCH approach (Gray, 1996).

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