Drying Biomass for Energy Use of *Eucalyptus urophylla* and *Corymbia citriodora* Logs

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Brazil is the world's largest producer of charcoal, mainly for the steel industry. Fresh wood has high moisture content, which reduces its use for energy. Thereby, drying is a fundamental step for charcoal production. This work aimed to determine longitudinal variation in stem diameter, wood basic density, moisture content, and calorific value of *Eucalyptus urophylla* and *Corymbia citriodora* logs. These logs were taken from different longitudinal positions on the trees and dried for 90 d; the net calorific value was determined based on the gross calorific value and moisture content. Curves and models were generated based on this data for moisture content and net calorific value during the 90-d period. The logs from the base and middle of *C. citriodora* trees had lower initial moisture content, and, after 90 d of drying, all logs from the top reached the equilibrium moisture. Drying the logs increased the wood calorific value, with an increase of 49.36%, 63.86%, and 85.98% for those of the base, middle, and top, respectively. The models generated had a high coefficient of determination and a low standard error.

Keywords: Gross and net calorific values; Growth; Moisture content; Wood density

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INTRODUCTION

The main source of energy in the world is derived from fossil fuels, and their use increases CO_2 emissions, contributing to the greenhouse effect (Zhu *et al*. 2011). Biomass is an alternative replacement for these sources (Rousset *et al*. 2013; Protásio *et al*. 2013); however, its production is not sufficient to meet the demand.

Harvesting, drying, transportation, and distribution methods are the biggest challenges in obtaining energy from biomass (Casal *et al*. 2010; Gonzalez *et al*. 2011; Zhu *et al*. 2011). The bioenergy industry in Brazil uses mainly *Eucalyptus camaldulensis*, *Eucalyptus globulus*, *Eucalyptus grandis*, and *Eucalyptus urophylla* to produce charcoal for the steel mill industry, with a consumption of nearly 17 million m^3 of eucalyptus wood in 2011 (ABRAF 2012).

All freshly cut timber has large quantities of water (Skaar 1972), which reduces its use in generating power. The charcoal industry requires raw materials with humidity around 35% (Brand *et al*. 2011). Outdoor storage is the most commonly used method to reduce wood moisture with low cost, but it requires a long drying period.

The drying rate of logs presents the highest values during the first 15 days due to the loss of free water; thereafter, there is a tendency toward lower values until the equilibrium moisture content is reached (Rezende *et al*. 2010). Wood factors such as anatomy, density, and dimensions, and environmental factors such as temperature, relative humidity, and wind speed affect wood drying (Engelund *et al*. 2013; Mugabi *et al*. 2010; Moya *et al*. 2012; Berberovic and Milota 2011; Watanabe *et al*. 2012; Muñoz and Moya 2008).

The chemical composition, moisture content, and environmental conditions affect the energetic properties of wood (Sotelo Montes *et al*. 2003; Brand *et al*. 2011; Sotelo Montes *et al*. 2011; Cetinkol *et al*. 2012; Sotelo Montes *et al*. 2012; Wang *et al*. 2012). Wood with high lignin and extractives contents has higher calorific value (Shebani *et al*. 2008; Silva *et al*. 2012). The calorific value is reduced by 2 MJ/kg for each 10% increase in wood moisture content (Swithenbank *et al*. 2011). However, wood does not need to be completely dry, because increasing the calorific value after a certain value does not compensate for the effort required for the continued drying, depending on the species and the environmental conditions (Brand *et al*. 2011).

The drying of logs has variable outcomes, and its effects on the energy stored in the wood need further studies. Thus, the objective of this study was to evaluate the variation of moisture content and calorific values of *Eucalyptus urophylla* and *Corymbia citriodora* logs during a 90-days drying period.

EXPERIMENTAL

Nine trees, each seven years old, were selected. Three were from each clone VM4 and Mn463 of *Eucalyptus urophylla*, and three from *Corymbia citriodora* plants that originated from seed. Logs 1.1 m in height were cut from the base (15 cm above ground) and at 50% and 100% of the commercial height of the tree. Variation longitudinal of the diameter, and height mean value of *Eucalyptus urophylla* clones and *Corymbia citriodora* are showed in Table 1.

Table 1. Mean Diameter at the Base, Middle, and Top of Logs, and Mean Height of *Eucalyptus urophylla* Clones and *Corymbia citriodora*

Material	Base Diameter (cm)	Middle Diameter (cm)	Top Diameter (cm)	Height (m)
Mn463 (*E. urophylla*)	20.34 (6.02)	14.23 (3.69)	4.6 (2.45)	30.45 (11.32)
Vm4 (*E. urophylla*)	19.45 (5.14)	13.34 (4.08)	4.7 (2.67)	29.45 (10.15)
Corymbia citriodora	17.88 (8.13)	12.56 (9.56)	4.3 (3.22)	22.65 (14.99)

The coefficient of variation is given in parentheses.

A 5-cm disk was removed from the transverse surfaces of each log, its moisture content was determined, and the average moisture was inferred as the log moisture. The same sample was used to determine basic wood density (ABNT 2003). *E. urophylla* and *C. citriodora* logs were grouped without contact with each other, and their transverse surfaces were waterproofed to ensure that the small size of the samples did not affect the results.

Logs were weighed every alternate day during the first 20 days, every 4 days during the next 30 days, and weekly for the last 40 days of the total 90-days drying period**.**

The drying rate was calculated using the following equation,

$$DR = (U_i - U_f)/\text{ days} \quad (1)$$

where DR is the drying rate, U_i (%) is the initial wood moisture content, U_f (%) is the final wood moisture content, and *days* = number of drying days.

The gross calorific value of the wood from base, middle, and top of each log was evaluated according to standard NBR8633 (ABNT 1984), and the net calorific value was calculated using the following equation (Tillman *et al*. 1989),

$$PC_i = PC_s - [0.0114 \times U \times PC_s\ (\%)] \quad (2)$$

where PC_i is the net calorific value, PC_s is the gross calorific value, and U (%) is the wood moisture content.

The regression model utilized to predict the moisture content and net calorific value was,

$$y = a + b \times \text{days} + c \times days^{0.5} \quad (3)$$

where y is the moisture in percent or net calorific value (cal/g), a is the intercept, b is the regression coefficient for days, c is the regression coefficient for $\text{days}^{0.5}$, and *days* is the number of drying days. The model proposed was based on the coefficient of determination.

RESULTS AND DISCUSSION

Mean values of initial moisture content and wood basic density of *Eucalyptus urophylla* clones and *Corymbia citriodora* are shown in Table 2. *Corymbia citriodora* and Vm4 (*E. urophylla*) had the highest average initial moisture contents at the base, and Mn463 (*E. urophylla*) had it at the top. The amount of moisture and its distribution in the longitudinal direction varies among species and individuals of *Corymbia citriodora*, *Eucalyptus cloeziana*, *Eucalyptus grandis*, *Eucalyptus paniculata*, *Eucalyptus pilularis*, *Eucalyptus urophylla*, and *Eucalyptus tereticornis* (Engelund *et al*. 2013; Oliveira *et al*. 2005).

The initial moisture content was consistent with previously reported values from 59.6% to 159% for *Eucalyptus cloeziana*, *Eucalyptus globulus*, *Eucalyptus grandis*, *Eucalyptus paniculata*, *Eucalyptus pellita*, *Eucalyptus regnans*, and *Eucalyptus urophylla* and *Pinus dunnii* (Oliveira *et al*. 2005; Hansmann *et al*. 2008; Studhalter *et al*. 2009; Rezende *et al*. 2010; Redman and McGavin 2010; Brand *et al*. 2011).

C. citriodora had the highest values, and Mn463 (*E. urophylla*) had the lowest values of wood basic density in all longitudinal positions. The densities of *E. urophylla* and *C. citriodora* were similar to the previously reported values of 0.429 to 0.596 g/cm³ for *Eucalyptus cloeziana*, *Eucalyptus grandis*, *Eucalyptus paniculata*, and *Eucalyptus urophylla* (Rezende *et al*. 2010; Oliveira *et al*. 2005; Santos *et al*. 2012; Sette *et al*. 2012), but they were lower than the reported values of 0.73 and 0.756 for *C. citriodora* (Oliveira *et al*. 2005).

Table 2. Initial Moisture Content and Density of Wood at the Base, Middle, and Top of Logs of *Eucalyptus urophylla* Clones and *Corymbia citriodora*

Material	Initial moisture content (%)		
	Base	Middle	Top
Mn463 (*Eucalyptus urophylla*)	121.52 Cb (3.56)	112.59 Ca (3.55)	126.15 Cc (4.13)
Vm4 (*Eucalyptus urophylla*)	94.54 Ba (4.44)	82.52 Bb (5.45)	80.99 Bb (4.77)
Corymbia citriodora	78.47 Ac (6.88)	75.43 Ab (5.54)	67.72 Aa (6.61)
Material	Wood basic density (g/cm^3)		
Mn463 (*Eucalyptus urophylla*)	0.497 Aa (3.35)	0.507 Aa (3.98)	0.517 Aa (4.05)
Vm4 (*Eucalyptus urophylla*)	0.528 Ba (3.76)	0.571 Bb (3.12)	0.567 Bb (3.12)
Corymbia citriodora	0.665 Ca (6.13)	0.683 Cb (7.45)	0.673 Cab (6.29)
Means with the same capital letter per column and lower case per line are not significantly different (P>0.05)			

The coefficient of variation is given in parentheses.

Drying rates of *E. urophylla* and *C. citriodora* logs are shown in Table 3. Samples from the top, with their smaller diameters, showed high drying rates in the first month. Logs of Mn463 (*E. urophylla*), with higher initial moisture, dried easily due to the short distance traveled by water and reached a drying rate of 3.52% in the first month. Vm4 (*E. urophylla*) and *C. citriodora* logs had drying rates of 1.9% and 1.59% in the same period, respectively. These rates were lower in the second and third months, showing that the logs were near the equilibrium conditions of the environment. The moisture content of *C. citriodora* logs reached 35% within 6 days, while Vm4 (*E. urophylla*) and Mn463 (E. *urophylla*) took 14 days (Table 3). The maximum moisture content recommended for carbonization is 35% (Brand *et al*. 2011).

The middle logs of Mn463 (*E. urophylla*), VM4 (*E. urophylla*), and *C. citriodora* showed average moisture contents after a 90-day drying period lower than the 35% moisture content recommended for carbonization (Brand *et al*. 2011). However, *C. citriodora* logs reached 35% moisture within 16 days of drying, while those of Mn463 (*E. urophylla*) and VM4 (*E. urophylla*) required 78 days and 65 days, respectively.

Table 3. Drying Rate of Logs in Different Periods and Final Moisture Content after 90-day Drying and Its Coefficient of Variation

Material	Position	DR 1 (%/day)	DR 2 (%/day)	DR 3 (%/day)	DR 4 (%/day)	Final Moisture of Logs (%)
Mn 463 (*Eucalyptus urophylla*)	Base	1.31 a	0.449 b	0.221 c	0.67	61.28
	Middle	1.94 a	0.467 b	0.186 c	0.88	33.15
	Top	3.52 a	0.037 b	0.005 b	1.22	15.98
Vm 4 (*Eucalyptus urophylla*)	Base	1.19 a	0.359 b	0.229 c	0.60	40.47
	Middle	1.36 a	0.229 b	0.153 c	0.59	29.24
	Top	1.90 a	0.204 b	0.001 c	0.72	15.87
Corymbia citriodora	Base	1.14 a	0.26 b	0.144 c	0.52	31.13
	Middle	1.47 a	0.22 b	0.094 c	0.61	20.49
	Top	1.59 a	0.01 b	0.037 b	0.56	17.07
Means with the same letter per line are not significantly different (P>0.05); DR1, drying rate in the first 30 days; DR2, drying rate in the second 30 days; DR3, drying rate of the last 30 d; DR4, drying rate over 90 days						

Drying of the base log after 90 days was more difficult due to its larger diameter (Table 3). *C. citriodora* logs showed moisture contents below 35% after 71 days of drying, while the logs of the other species needed longer drying periods to reach this level. Factors such as a smaller diameter and higher density favored the drying of *C. citriodora* logs.

The gross and net calorific values of the wood are show in Table 4. Gross calorific values were similar to those reported for *Eucalyptus dunnii*, *Eucalyptus grandis*, *Pinus pinaster*, and *Pinus taeda*, between 4,250 and 4,796 cal/g (Brand *et al*. 2011; Telmo and Lousada 2011; Musinguzi *et al*. 2012).

Table 4. Gross and Net Calorific Values of Wood (Mean and Coefficient of Variation) During 90 Days of Drying

Material	Position	GCV (cal/g)	NCV 1 (cal/g)	NCV 2 (cal/g)	NCV 3 (cal/g)	NCV 4 (cal/g)
Mn463 (*Eucalyptus urophylla*)	Base	4781(4.3) a	1791(3.3) e	2343(4.4) d	2532(4.2) c	2711(3.5) b
	Middle	4731(4.3) a	1875(3.1) e	2879(2.9) d	3162(3.6) c	3390(4.3) b
	Top	4745(5.3) a	1728(4.1) c	3958(3.4) b	3999(4.6) b	4000(2.8) b
Vm4 (*Eucalyptus urophylla*)	Base	4722(4.3) a	2106(3.2) e	2755(3.3) d	2954(3.1) c	3173(3.4) b
	Middle	4755(3.8) a	2304(3.6) e	3195(4.2) d	3344(3.3) c	3528(3.5) b
	Top	4731(4.8) a	2318(4.2) c	3963(3.4) b	3969(4.5) b	3994(2.3) b
Corymbia citriodora	Base	4631(8.4) a	2315(7.2) e	3045(6.3) d	3215(6.9) c	3381(8.2) b
	Middle	4598(7.6) a	2351(6.4) e	3396(7.7) d	3577(7.1) c	3707(7.6) b
	Top	4575(8.1) a	2474(7.2) c	3759(7.4) b	3784(7.3) b	3814(3.5) b

Means with the same letter per line are not significantly different (P>0.05)
GCV, gross calorific value of wood
NCV 1, net calorific value of freshly cut wood
NCV 2, net calorific value of wood after 30 days of drying
NCV 3, net calorific value of wood after 60 days of drying
NCV 4, net calorific value of wood after 90 days of drying

The net wood calorific value increased by 31.1%, 45.6%, and 81.1% in 30 days of drying; 6.9%, 6.6%, and 2.4% in the next 30 days; and 6.5%, 3.8%, and 0% in the final 30 days for base, middle, and top section logs, respectively. This increase results in a gain in gravimetric yield and carbonization time (Arruda *et al*. 2011).

Corymbia citriodora had the lowest gross calorific value, but the lower moisture content of logs from the base and middle during the evaluations resulted in higher net calorific value, indicating the importance of drying for better use of biomass. The logs from the top of all species had similar moisture contents after 90 days of drying. This resulted in higher net calorific value for Mn463 (*E. urophylla*) and VM4 (*E. urophylla*) because of their higher gross calorific value.

The curves for moisture showed a higher drying rate in the first 15 days (Fig. 1), which is similar to that reported for *Cryptomeria japonica* lumber and *Betula papyrifera* flakes (Bedane *et al*. 2011; Hermawan *et al*. 2012). *Eucalyptus urophylla* logs with similar diameters in the base and middle logs showed average moisture contents of 63% and 43%, respectively, after 80 days of drying (Rezende *et al*. 2010). Drying logs of *Eucalyptus* sp. with diameters greater than 12 cm had moisture contents of about 55% after 175 days of drying in open air, and the moisture content was 16% to 27% for logs with diameters of 4 to 12.0 cm after this period (Vital *et al*. 1985).

The curves of the net calorific value followed a reverse trend from that of drying. Top logs showed high moisture losses in the first month, resulting in a higher gain of net calorific value and stabilization at the consecutive periods. Base and middle logs showed a tendency toward increasing net calorific value during the evaluation period (Fig. 1).

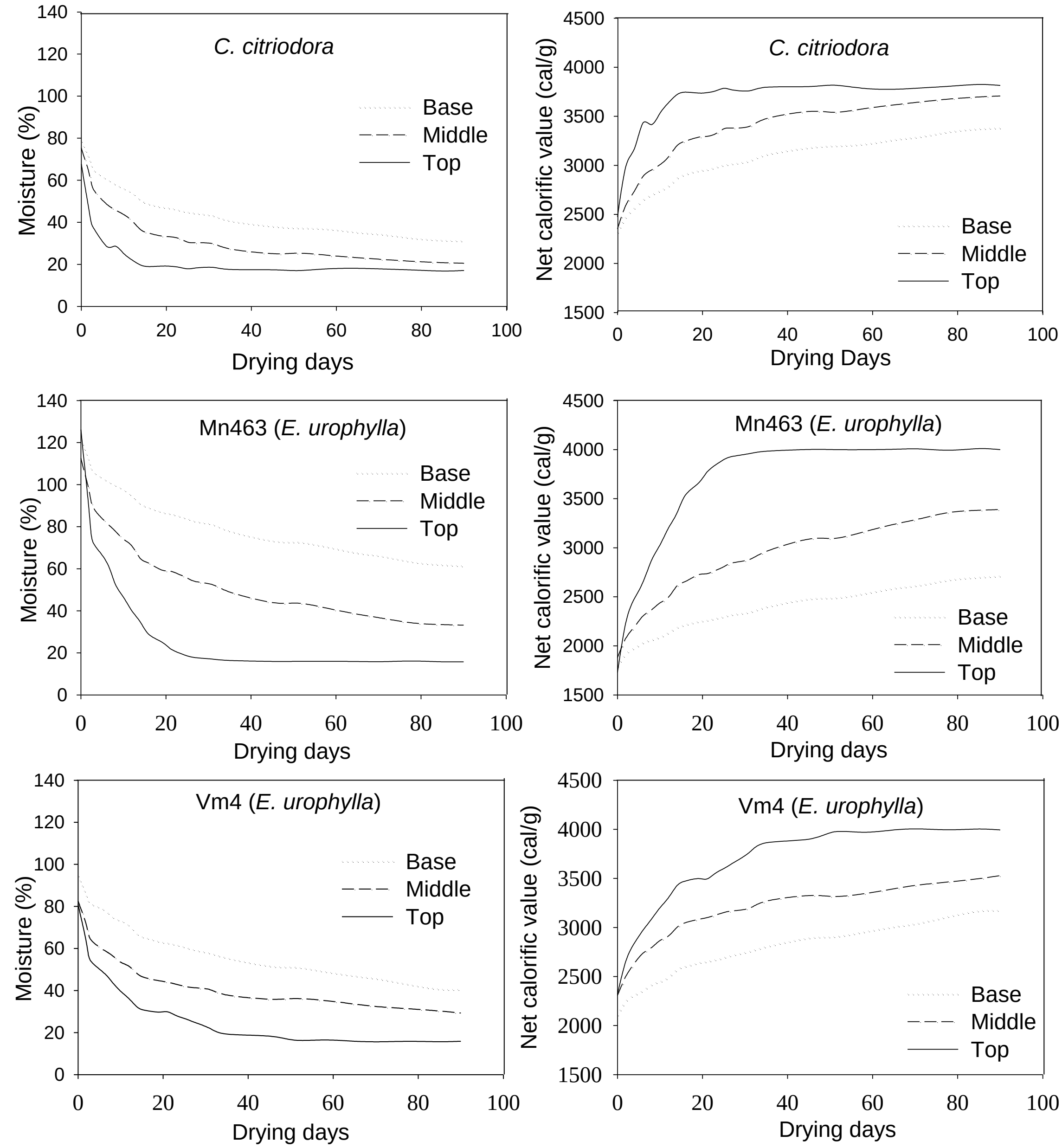

Fig. 1. Moisture and net calorific value of *Eucalyptus urophylla* and *Corymbia citriodora* as functions of drying time

The regression models showed a coefficient of determination higher than 0.85, indicating that at least 85% of the variations can be explained by the model. The highest standard error was 5.12 (Table 5).

Table 5. Regression Models for Moisture Contents of *Eucalyptus* and *Corymbia* Logs, Coefficient of determination (C.D.), and Standard Error (SE) as Functions of Drying Time

Material	Position	Estimated Model for Moisture During Drying Time	C.D.	SE
Mn 463 (*Eucalyptus urophylla*)	Base	$y = 122.1611 + 0.281281 \times d - 9.09789 \times d^{0.5}$	0.9805	2.24
	Middle	$y = 114.5736 + 0.711272 \times d - 15.2864 \times d^{0.5}$	0.9689	3.73
	Top	$y = 125.393 + 2.225017 \times d - 31.9889 \times d^{0.5}$	0.9819	3.73
Vm4 (*Eucalyptus urophylla*)	Base	$y = 95.59872 + 0.266067 \times d - 8.29966 \times d^{0.5}$	0.9367	3.71
	Middle	$y = 83.17181 + 0.603682 \times d - 11.1904 \times d^{0.5}$	0.9873	1.5
	Top	$y = 81.46459 + 0.976169 \times d - 16.0773 \times d^{0.5}$	0.9748	2.68
Corymbia citriodora	Base	$y = 79.6023 + 0.420152 \times d - 9.01448 \times d^{0.5}$	0.8517	5.12
	Middle	$y = 75.97072 + 0.738466 \times d - 12.659522 \times d^{0.5}$	0.9351	3.63
	Top	$y = 55.88981 + 0.853124 \times d - 11.8366 \times d^{0.5}$	0.8847	4.28

Corymbia citriodora that had been produced via seeds showed higher moisture variation, and it was therefore more difficult to generate models for it, thereby reducing the coefficient of determination and increasing the standard errors values.

The models presented for the net calorific values of wood showed coefficient of determination from 0.8515 to 0.9872 and standard error from 36.07 to 123.92 (Table 6).

Table 6. Regression Models for Net Calorific Value of *Eucalyptus* and *Corymbia* Logs, Coefficient of determination (C.D.), and Standard Error (SE) as Functions of Drying Time

Materials	Position	Estimated Model for Net Calorific Value During Drying Time	C.D.	SE
Mn 463 (*Eucalyptus urophylla*)	Base	$y = 1776.121 - 1.06684 \times d + 109.4079 \times d^{0.5}$	0.9749	40.42
	Middle	$y = 1807.509 - 6.28686 \times d + 228.8758 \times d^{0.5}$	0.9611	84.82
	Top	$y = 1466.576 - 43.3353 \times d + 673.1356 \times d^{0.5}$	0.9646	123.92
Vm 4 (*Eucalyptus urophylla*)	Base	$y = 2081.855 - 1.41121 \times d + 128.3836 \times d^{0.5}$	0.9294	80.37
	Middle	$y = 2260.328 - 10.1563 \times d + 226.1257 \times d^{0.5}$	0.9872	36.07
	Top	$y = 2211.351 - 20.3673 \times d + 384.6185 \times d^{0.5}$	0.9629	91.47
Corymbia citriodora	Base	$y = 2274.954 - 6.1539 \times d + 174.3076 \times d^{0.5}$	0.8513	119.63
	Middle	$y = 2321.62 - 13.4797 \times d + 271.92 \times d^{0.5}$	0.9490	87.36
	Top	$y = 2533.475 - 27.9292 \times d + 388.4773 \times d^{0.5}$	0.9192	107.76

The models for the net calorific value followed the same trend as for the drying models. *Corymbia citriodora* produced via seeds had the highest variation, and gave lower coefficient of determination and higher standard errors.

CONCLUSIONS

1. Base and middle logs from *C. citriodora* had lower moisture contents after 90 days of drying than those from *E. urophylla*. Top logs of all species reached the equilibrium moisture content after this period.

2. The average calorific value of wood increased during the 90-days drying period to 49.3%, 63.9%, and 86.0% for the base, middle, and top logs, respectively.

3. Drying and calorific value models showed high coefficient of determination and low standard errors for the drying of *C. citriodora* and *E. urophylla* logs.

ACKNOWLEDGMENTS

Thanks to Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), V&M Florestal, Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), and Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) for financial support. Global Edico Services rewrote and edited the English version of this manuscript.

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Article submitted: May 30, 2013; Peer review completed: July 10, 2013; Revised version received and accepted: July 22, 2013; Published: August 21, 2013.