Effect of Microwave Frying on Moisture Transport and Oil Uptake in Fried Foods

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Noviembre, 2019

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Special graduation project presented as partial requirement to obtain the Food Science and Technology Bachelor Degree.

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Abstract. The process of deep-frying potatoes dates from years around 1700 A.D. Despite being the most important method of preparations, deep-frying has remained the same since its origins. In the following study, microwave frying was compared against conventional frying at 177, 185 and 191 °C, furthermore, the addition of microwave energy after 1 minute of conventional frying was tested as well. Two different parameters were analyzed for each treatment: Oil Uptake and Moisture Transport. The effects of microwave energy in oil uptake were analyzed by measuring final fat content through Soxhlet extraction. Moisture transport was analyzed by measuring initial and final moisture content by freezing the samples in liquid nitrogen and then heating samples at 105 Celsius, with a posterior measurement weight loss. Microwave energy was found to increment moisture loss and oil uptake in the process of deep frying. It is speculated that microwave energy increases the energy inputted into the system, and thus it boosts water loss and therefore oil uptake after the frying finished. Temperature showed to have an impact in water loss but not in oil uptake. Said phenomenon can be explained by the fact that most of the oil absorbed by potatoes is absorbed after the frying process has been done. Further studies need to be done in order to give a deep and clear explanation of the effects of microwave energy on the complex process of deep frying.

Key words: Absorption, Deep-Frying, Fat, Microwave-Fryer, Potato, Water.

Resumen: El proceso de freído de papas data alrededor del siglo XVI. A pesar de ser uno de los métodos de preparación más importantes, el freído se ha mantenido igual desde sus orígenes. En el siguiente estudio, el freído por microondas fue comparado contra el freído convencional a 177, 185 y 191 grados Celsius, adicionalmente, se comparó la adición de energía microondas luego de 1 minuto de freído convencional. Dos parámetros diferentes se analizaron para cada tratamiento: Absorción de Grasa y Transporte de Humedad. Los efectos de la energía microonda en la absorción de grasa fueron analizados por medio de la extracción Soxhlet del contenido de grasa final de las papas. La humedad fue analizada por medio de la congelación de las muestras por nitrógeno líquido, para ser luego calentadas a 105°C y posteriormente pesar la pérdida de peso. La energía microonda incrementó la perdida de agua y la absorción de grasa en el proceso de freído. Se especula que la energía microonda aumenta la cantidad de energía introducida en el sistema, y por ende aumenta la perdida de agua y absorción de grasa luego del freído. La temperatura demostró tener un impacto en la perdida de agua, pero no en la absorción de grasa. Dicho fenómeno puede ser explicado por el hecho de que la mayoría del aceite se absorbe luego del freído. Se necesita realizar más estudios para dar una profunda y clara explicación de los efectos de la energía microondas en el complicado proceso de freído.

Palabras Clave: Absorción, Agua, Freído, Freidora Microondas, Grasa, Papa.

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1. INTRODUCTION

Around 16,000 million pounds of potatoes were processed on 2017 for french fries production in the United States, occupying more than 40% of total potatoes produced said year (USDA ERS 2018). The global market of frozen fries is worth 19 billion dollars and is predicted to keep growing around 3.8% each year (Mc Cain *et al.* 2017), making it one of the most prominent crop processing business on the world. Said growth can be attributed to the fact that humanity is leaning towards products that provide convenience, including fast food and frozen fries (Memehti and Xhoxhi 2014). Surprisingly enough, the method for the frying of fries has remained the same since the introduction of potatoes in Europe: Putting a basket of slices into hot oil, which fries through convective and conductive heat transfer.

With that being said, the frying process has not been fully understood by the scientific community (Oke *et al.* 2018), leading to the complication of the optimization of said common operation. The objective of this study is aimed at the identification of the effects of the addition of microwaves on the processing of French fries, in order to favor the implementation of said technology, which has proven to be up to 80% more energy efficient than conventional methods on the cooking of foods (Energy Star 2011).

Simulations on the addition of microwave energy have shown to increase the heat transfer coefficient on the frying process (Sensoy *et al.* 2013). Said increase is said to have an impact on oil uptake and water retention. In order to verify this assumption, the study will focus on the final oil content, and water loss of French fries prepared with microwave energy.

The results will aid at the understanding of the frying process, which has proven to be quite complicated due to the involvement of multiple variables and parameters that can alter the final attributes of the product (Parikh and Takhar 2016), the study will specifically help at the understanding of Water and Oil transport under microwave frying in potato slices. The result could also favor the implementation of microwave fryers at the fast food industry, which could lead to a reduction on power consumption at restaurants that serve French fries, and thus improve and optimize said unit operation.

For this study, we compared oil and water content on three different methods and temperatures. The methods included conventional heating, the implementation of microwave energy since the beginning of the frying process and the addition of microwave energy after a minute of conventional heating, temperatures used were 177, 185 and 191 °C in order to determine if different temperatures lead to different results.

The Objectives of this study were:

- To identify the effect of microwaves in oil uptake during potato frying.
- To identify the effects of microwaves in final moisture content caused by microwave frying.
- To identify the effects of increased temperature in moisture loss and oil uptake during frying.

2. MATERIALS AND METHODS

Sample preparation.

Russet potatoes where purchased at a local store on Urbana, Ill. USA. Potatoes were washed with cold water before being cut. A special cutter designed to yield round slices of 7mm in diameter was used to cut the potatoes. Slices without skin were selected and then standardized at 7cm of length. Special care was put on the origin of the slices by discarding slices coming from the center to standardize moisture as much as possible. This was done because the medulla of the potato has different microstructure and water content when compared with the perimedulla and cortex (Adu-Poku and Agbenorhevi 2017). The slices were washed with cold water in order to remove loose starch (Parikh and Takhar 2016).

Potato blanching and fryer preparation.

Potatoes slices were blanched at 100 °C for 2 minutes in order to cook the inside. Then slices were immediately placed in cold water with ice in order to prevent further cooking. For the whole experiment, 36 liters of Simply-Fry brand (Gordon Food Services, Wyoming, MI, U.S.A.) Of vegetable oil blend (canola oil, corn oil, and soybean oil) were placed on the microwave fryer (M346385, Highlight Technology Systems Corp., Taiwan, Republic of China). The microwave fryer had 2 magnetrons with a power of 750W working at a frequency of 2.45 Gigahertz each. The microwave fryer had a choice of turning off the magnetrons and working with the heating power of a thermal coil alone. (Parikh y Takhar 2016). All the frying methods described below were performed using said microwave fryer.

Potato frying.

Thirty blanched potato slices were placed in a basket per run. Potatoes were fried on a combination of the following methods and temperatures: Conventional frying (no microwave energy), Microwave Frying (with microwave energy) and Partial Microwave Frying (microwave energy input after 1 minute of conventional frying). The three following temperatures were used: 177, 185 and 191 °C. Potatoes were fried for 4 minutes and left to rest for a minute. The description of the treatments can be found at Table 1.

Table 1. Experimental Design.

Temperature / Frying Method	177 °C	185 °C	191 °C
Microwave Frying	MF177	MF185	MF191
Partial Frying	PF177	PF185	MF191
Conventional Frying	CF177	CF185	CF191
Experimental Units Total			27

MF = microwave frying; PF = partial frying; CF =frying.

Water content analysis.

Slices were then frozen with liquid nitrogen and ground with a coffee grinder. Moisture content was analyzed with a Moisture Meter (MB35, OHAUS, Ohaus, Switzerland) that was previously calibrated to follow the AOAC method 934.01 (AOAC 1995). Then 0.5 grams of potato powder were placed on the moisture meter.

The moisture meter heated the samples to a 105 °C temperature until the weight of the sample stayed stable. Water content was calculated by the moisture meter and results were stored in a Microsoft Excel Spreadsheet. Data was analyzed using SAS software (Base SAS® 9.3 TS1M2. SAS Institute Inc., Cary, NC.)

Fat content analysis.

The rest of the slices were left in a drying oven along with paper envelopes at 60 °C for 12 hours. After the drying period ended, the slices were ground with a coffee grinder. Around 3 to 4 grams of potato powder were placed inside each envelope. Fat was extracted with a Soxhlet extractor. Envelopes were weighted without a sample, with sample before/and after extracting. Fat content was calculated using Microsoft Excel 2016. Data was analyzed using SAS software (Base SAS® 9.3 TS1M2. SAS Institute Inc., Cary, NC.).

Experimental design.

For both fat and water content, a completely random design with bifactorial arrangement was done, the model proposed for the design goes as follows (Ecuation 1):

$$y_{ijk} = \mu + a_i + b_j + +(ab)_{ij} + \varepsilon_{ijk} \quad [1]$$

Where:

y= The analyzed parameter (oil and moisture content)

a= The effect of Temperature on the i-th treatment

b= The effect of frying method on the i-th treatment

(ab)=The possible interaction between temperature and frying method.

3. RESULTS AND DISCUSSION

Final moisture content.

For each of the treatments, Microwave Frying resulted significantly different from Conventional Frying, with Partial Frying resulting similar to both treatments. Full Microwave resulted having the lowest moisture content of all the treatments (Table 2).

Table 2. Average Moisture Content and Standard Deviation of fried slices per Method.

Frying Method	**177 °C**	**185 °C**	**191 °C**	**Tukey Grouping**	**Variation Coefficient**
Conventional	36.51 ± 0.47	32.51 ± 2.62	34.76 ± 0.74	A	3.84%
Partial	38.25 ± 0.55	25.66 ± 0.49	22.17 ± 0.55	B	1.69%
Microwave	31.85 ± 0.42	25.43 ± 0.99	21.93 ± 0.06	B	1.75%

The reduced moisture content can be attributed to the increased turbulence during frying , which increases the heat transfer coefficient of the frying process (Sensoy *et al.* 2013). The frying process involves conductive and convective heat transfer, with the former taking part at the formation of the crust of the slices, and the later taking part the moment water starts evaporating out of the potatoes (Halder *et al.* 2007). The moment water starts evaporating out of the slices, bubbles of steam start forming around the potatoes and create turbulence between the oil and the potatoes, and thus adding convective heat transfer to the process.

Microwaves are synchronized oscillations of the electromagnetic field that carry electromagnetic energy; microwaves can also be understood as photons carrying energy at a certain frequency and wavelength. Due to the polar nature of water molecules, water is easily excited (Akdoğan y Çiftçi 2016) when compared to non-polar molecules such as carbohydrates or triglycerides. Because of the increased rotation and vibration of water molecules, the turbulence heightens and therefore the heat coefficient transfer increases.

Water inside the potato also starts heating even before the heat coming from the outside of the slices reaches the center, this is due to microwaves This leads to a higher amount ofheat being transferred to the potatoes, which turns into more water being evaporated out of the slices. The penetration of 2.45 ghz microwaves in potatoes hovers around 9 mm (Tang 2015), so with 2 opposing magnetrons, potatoes were expected to receive a uniform amount of microwave energy. It is also important to note that the shape of food also affects the penetration of microwaves, with circular shapes having the most uniform heating in most cases (Zhang Z *et al.* 2018).

Now, when we compare the results obtained per temperature, the amount of moisture loss increases along with the increase of frying temperature(Table 3). The results match previous studies on conventional deep frying, with higher temperatures achieving a higher loss on moisture on deboned chicken breast (Kassama y Ngadi 2016). Statistically speaking, 177 °C resulted in significantly higher moisture content.

Table 3. Average Moisture Content and Standard Deviation of fried slices per Temperature

Temperature	**Conventional Frying**	**Microwave Frying**	**Partial Frying**	**Tukey Grouping**	**Variation Coefficient**
177 °C	36.51 ± 0.47	31.85 ± 0.42	38.25 ± 0.55	A	1.28%
185 °C	32.51 ± 2.62	25.43 ± 0.99	25.66 ± 0.49	B	4.56%
191 °C	34.76 ± 0.74	21.93 ± 0.06	22.17 ± 0.55	B	1.44%

Greater moisture loss happens because an increase in temperature increases moisture diffusivity due to the increased temperature difference between potato and oil increases the heat transfer coefficient (Pedreschi *et al.* 2005), due to the increased amount of energy being transferred, more water transforms into steam, with the increased amount of water exiting the slice. Because of that, convection increases and thus amplifies the evaporation effect.

It should be noted that on the Least Squared Means Separation test, the only individual treatments that were importantly different are those involving temperatures above 185 °C, and in the case of the conventional method, all temperatures are statistically similar between themselves. While some experiments found differences in moisture content on conventional frying (Pedreschi *et al.* 2005), their temperature range was from 120 to 180 °C, with differences existing predominantly between both ends.

Final Fat Content.

No significant differences in fat content were found between temperatures, the results can be seen on Table 4. Said results match with findings on a previous study (Ouchon *et al.* 2003) and predictions from a proposed model (Dana and Saguy 2006), on the other side, significant differences were found in a study were the gap between temperatures was 25 °C or more (Moreira *et al.* 1995).

Table 4. Average Fat Content and Standard Deviation of fried slices per Temperature

Temperature	**Conventional Frying**	**Microwave Frying**	**Partial Frying**	**Tukey Grouping**	**Variation Coefficient**
177 °C	16.73 ± 3.53	20.03 ± 2.06	19.54 ± 3.35	A	10.07%
185 °C	17.02 ± 1.35	25.15 ± 0.31	17.51 ± 2.28	A	4.38%
191 °C	14091 ± 1.31	24.91 ± 1.01	15.51 ± 3.21	A	6.77%

The results can be attributed to the fact that internal temperature of potatoes during frying reaches a maximum threshold of 100 °C and stops going further no matter the amount of temperature for the first 2 minutes of the frying process (Parikh y Takhar 2016), this phenomenon is expected to happen as long as there is enough water. This equilibrium can be attributed to the transformation of water into steam; water absorbs the incoming heat and keeps the internal thermal equilibrium from raising above water boiling temperature. Such thermal equilibrium was found to be present even at 10 minutes of frying at 185 °C on Pumpkin, Sweet Potato and Taro. (Ahromrit y Nema 2010).

Microwave Frying had significantly higher fat content when compared to PF and CF (Table 5). These results match a previous study where an increase in oil uptake was found with an increase in the amount of power applied (Pinthus *et al.* 1993) and also agree with an study on chicken fingers (Barutcu *et al.* 2009).

Table 5. Average Fat Content and Standard Deviation of fried slices per Method

Frying Method	**177°C**	**185°C**	**191°C**	**Tukey Grouping**	**Variation Coefficient**
Conventional	16.73 ± 3.53	17.02 ± 1.35	14.91 ± 1.31	A	8.16%
Partial	20.81 ± 2.06	22.64 ± 0.31	15.51 ± 1.01	A	9.04%
Microwave	20.03 ± 3.35	25.15 ± 2.28	26.75 ± 3.21	B	4.03%

The high numbers of fat content can be attributed to the increased amount of water loss and to pore uniformity. According to previous models (Moreira *et al.* 1995) most of the oil is absorbed after the slices are taken out of the oil. Previous X-ray imaging of MF slices yielded more uniform pores when compared to conventional frying (Parikh and Takhar 2016). Said pores are smaller, and thus can lead to an increased amount of oil uptake. After all, the mechanisms involved in oil uptake are not fully understood right now (Dana and Saguy 2006), so more experiments should help understanding the increase in oil uptake.

4. CONCLUSIONS

- Microwave frying increase oil uptake when compared to conventional frying if they start being applied at the beginning of the frying process.

- Using microwaves during the frying process increases the amount of water lost when compared to conventional frying.

- Water retention diminishes when temperature increases, this is due to the increase in heat transfer coefficient; in contrast, oil uptake is not affected by temperature unless there is a significant difference in temperatures being compared.

5. RECOMMENDATIONS

- Evaluate the behavior of other parameters involved in oil uptake such as capillarity, oil viscosity, pressure and pore formation will help explaining the differences obtained by microwave heating.

- Future studies should be aimed at the optimization of Microwave Frying times in order to achieve similar results in less time.

- Microwave frying should be implemented as a time and power saving alternative.

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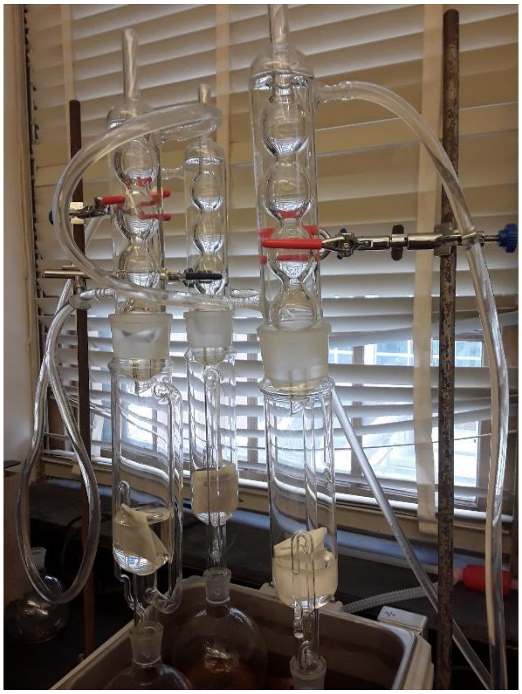
7. APPENDICES

Appendix 1. Soxhlet system.



Appendix 2. SAS code.

```
DATA Tesis;
INPUT method $ temp humedadI humedadF grasaS grasaH Wretention;
DATALINES;
Conventional 177 74.320 37.060 23.151 14.571 46.06
Conventional 177 79.460 36.230 30.137 19.218 40.47
Conventional 177 75.880 36.240 25.737 16.410 44.05
Conventional 185 76.520 35.520 25.879 16.687 43.02
Conventional 185 72.460 30.760 23.684 16.399 44.46
Conventional 185 76.300 31.230 26.154 17.986 40.88
Conventional 191 78.190 34.600 25.071 16.397 40.84
Conventional 191 76.930 34.110 21.149 13.935 41.83
Conventional 191 75.680 35.580 22.380 14.417 43.89
Full_Microwave 177 77.680 38.720 30.088   18.438 43.62
Full_Microwave 177 78.200 38.120 36.278   22.449 42.77
Full_Microwave 177 75.620 37.910 30.959   19.222 45.23
Full_Microwave 185 77.230 24.520 32.249   24.342 36.26
Full_Microwave 185 77.900 26.300 32.840   24.203 36.57
Full_Microwave 185 77.440 26.170 36.467   26.924 36.95
Full_Microwave 191 77.920 22.240 34.983   27.203 34.31
Full_Microwave 191 77.350 22.150 33.766   26.287 34.83
Full_Microwave 191 78.040 22.120 27.273   21.240 34.13
Partial_Microwave 177 74.760 34.600 34.416 22.508 44.27
Partial_Microwave 177 71.910 47.030 30.721 16.273 53.96
Partial_Microwave 177 75.920 34.760 30.422 19.847 43.20
Partial_Microwave 185 75.680 37.960 30.293 18.794 45.2
Partial_Microwave 185 76.360 27.960 30.818 22.201 39.02
Partial_Microwave 185 77.120 23.820 15.170 11.557 35.98
Partial_Microwave 191 78.180 29.640 23.099 16.252 38.12
Partial_Microwave 191 76.140 28.600 20.130 14.373 39.59
Partial_Microwave 191 72.060 29.440 22.572 15.927 44.13

Proc GLM;

class  method temp;

model humedadF grasaH Wretention = method temp method*temp;

Means method temp/tukey;

Lsmeans method*temp /stderr pdiff;

ODS HTML CLOSE;
ODS HTML;

Run;
```

Appendix 3. SAS Code Output.

The SAS System

The GLM Procedure

Dependent Variable: humedadF

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	786.929519	98.366190	7.85	0.0002
Error	18	225.662200	12.536789		
Corrected Total	26	1012.591719			

R-Square	Coeff Var	Root MSE	humedadF Mean
0.777144	11.07261	3.540733	31.97741

Source	DF	Type I SS	Mean Square	F Value	Pr > F
method	2	162.5537185	81.2768593	6.48	0.0076
temp	2	467.7747630	233.8873815	18.66	<.0001
method*temp	4	156.6010370	39.1502593	3.12	0.0408

Source	DF	Type III SS	Mean Square	F Value	Pr > F
method	2	162.5537185	81.2768593	6.48	0.0076
temp	2	467.7747630	233.8873815	18.66	<.0001
method*temp	4	156.6010370	39.1502593	3.12	0.0408

Cont. Appendix 3. SAS Code Output

Dependent Variable: grasaH

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	342.6918252	42.8364781	5.89	0.0009
Error	18	130.8322200	7.2684567		
Corrected Total	26	473.5240452			

R-Square	Coeff Var	Root MSE	grasaH Mean
0.723705	14.16025	2.696008	19.03926

Source	DF	Type I SS	Mean Square	F Value	Pr > F
method	2	260.5316172	130.2658086	17.92	<.0001
temp	2	10.4525747	5.2262874	0.72	0.5007
method*temp	4	71.7076333	17.9269083	2.47	0.0820

Source	DF	Type III SS	Mean Square	F Value	Pr > F
method	2	260.5316172	130.2658086	17.92	<.0001
temp	2	10.4525747	5.2262874	0.72	0.5007
method*temp	4	71.7076333	17.9269083	2.47	0.0820

Cont. Appendix 3. SAS Code Output

Dependent Variable: Wretention

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	360.3856519	45.0482065	4.91	0.0024
Error	18	165.0432000	9.1690667		
Corrected Total	26	525.4288519			

R-Square	Coeff Var	Root MSE	Wretention Mean
0.685889	7.341444	3.028047	41.24593

Source	DF	Type I SS	Mean Square	F Value	Pr > F
method	2	117.6536963	58.8268481	6.42	0.0079
temp	2	177.6116519	88.8058259	9.69	0.0014
method*temp	4	65.1203037	16.2800759	1.78	0.1778

Source	DF	Type III SS	Mean Square	F Value	Pr > F
method	2	117.6536963	58.8268481	6.42	0.0079
temp	2	177.6116519	88.8058259	9.69	0.0014
method*temp	4	65.1203037	16.2800759	1.78	0.1778

Cont. Appendix 3. SAS Code Output

Tukey's Studentized Range (HSD) Test for humedadF

Alpha	0.05
Error Degrees of Freedom	18
Error Mean Square	12.53679
Critical Value of Studentized Range	3.60930
Minimum Significant Difference	4.2599

Means with the same letter are not significantly different.

Tukey Grouping		Mean	N	method
	A	34.592	9	Conventi
	A			
B	A	32.646	9	Partial_
B				
B		28.694	9	Full_Mic

Tukey's Studentized Range (HSD) Test for grasaH

Alpha	0.05
Error Degrees of Freedom	18
Error Mean Square	7.268457
Critical Value of Studentized Range	3.60930
Minimum Significant Difference	3.2436

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	method
A	23.368	9	Full_Mic
B	17.526	9	Partial_
B			
B	16.224	9	Conventi

Cont. Appendix 3. SAS Code Output

Tukey's Studentized Range (HSD) Test for Wretention

Alpha	0.05
Error Degrees of Freedom	18
Error Mean Square	9.169067
Critical Value of Studentized Range	3.60930
Minimum Significant Difference	3.643

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	method
A	42.833	9	Conventi
A			
A	42.608	9	Partial_
B	38.297	9	Full_Mic

Tukey's Studentized Range (HSD) Test for humedadF

Alpha	0.05
Error Degrees of Freedom	18
Error Mean Square	12.53679
Critical Value of Studentized Range	3.60930
Minimum Significant Difference	4.2599

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	temp
A	37.852	9	177
B	29.360	9	185
B			
B	28.720	9	191

Cont. Appendix 3. SAS Code Output

Tukey's Studentized Range (HSD) Test for grasaH

Alpha	0.05
Error Degrees of Freedom	18
Error Mean Square	7.268457
Critical Value of Studentized Range	3.60930
Minimum Significant Difference	3.2436

Means with the same letter are not significantly different.

Tukey Grouping	Mean	N	temp
A	19.899	9	185
A			
A	18.771	9	177
A			
A	18.448	9	191