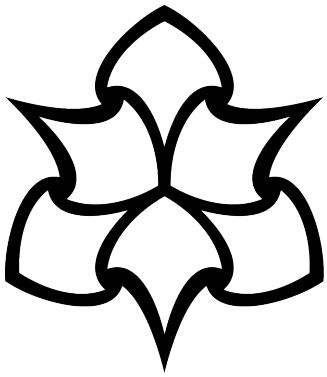

Thermal decomposition kinetics of the antiparkinson drug "entacapone"

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Abstract

The thermal decomposition kinetics of entacapone (ENT) have been investigated via thermogravimetric analysis (TGA) under non-isothermal and isothermal conditions which provide useful stability information for their processing in the pharmaceutical industry and also for predicting shelf life and suitable storage conditions. The determination of the kinetic parameters for the decomposition process under non-isothermal conditions in a nitrogen atmosphere at four heating rates (5, 10, 15, and 20 $^{o}C\ min^{-1}$) was performed. Kinetic parameters of the decomposition process for ENT were calculated through Friedman, Flynn– Wall–Ozawa, Kissinger–Akahira–Sunose, and Li–Tang methods. This work demonstrates that the activation energies calculated from the decomposition reactions by different methods are consistent with each other. Moreover, the thermodynamic functions of the decomposition reaction were also calculated.

Keywords

Entacapone, thermal analysis, activation energy, isothermal and non-isothermal conditions

Introduction

Entacapone, (ENT), (see figure 1) is an adjunct to standard preparations of levodopa/benserazide or levodopa/carbidopa for use in patients with Parkinson's disease who have end-of-dose motor fluctuations which cannot be stabilized on those combinations [1]. ENT (Fig. 1) is a specific and mainly peripherally-acting catechol-O-methyl transferase (COMT) inhibitor which decreases the metabolic loss of levodopa to 3-O-methyldopa and it is reported that ENT increases the bio-availability of levodopa to the brain by 5 - 10% [2]. ENT is practically insoluble in water, but slightly soluble in organic solvents. The aqueous solubility of ENT is very low at acidic pH but increases strongly with increasing pH; it is also slightly soluble in organic solvents [3].

Various analytical methods have been used for ENT determination such as spectrophotometric [4, 5], HPLC [6-9], micellar capillary chromatography [10, 11] and electrochemical methods [12-15]. While mainly used for the analytical determination of target analytes, thermal analytical techniques can provide important data regarding the storage and stability of drugs [16-18]. The most widely used thermal analysis techniques are thermogravimetry / derivative thermogravimetry (TG/DTG), differential thermal analysis (DTA) and differential scanning calorimetry (DSC) [18-20]. These techniques are widely used in the pharmaceutical sciences for the characterization of solid drugs and excipients. The application of thermo-analytical methods may provide new information about the temperature and energy associated with events, such as melting, oxidation and reduction reactions, glass transition, boiling, sublimation, decomposition, crystallization, or gel to liquid crystal transitions [21-23]. TG can be considered as a quantitative and comparative analytical technique which can generate fast and reproducible data which leads to the utilization of TG in the quality control of drugs to enhance the final products and for the determination of drug quality via technical parameters [24]. The identification of pharmaceutical and organic compounds can be also be performed by differential thermal analysis (DTA) [25].

TG and DTA techniques involve the continuous measurement of physical properties such as weight, volume, heat capacity, etc., as the sample temperature is increased at a predetermined rate, it is possible to calculate the kinetic constants from these techniques by making a number of patterns at different heating rates. TG and DTA is used in the pharmaceutical industry as an

analytic tool of high importance, to identify and to test the purity of the active substances with quick and efficient results [26]. Also, DTA can be used to control the quality of the raw materials used to obtain pharmaceutical products [27].

The recommendations of the International Confederation for Thermal Analysis and Calorimetry (ICTAC) offer guidance for the reliable evaluation of kinetic parameters from data obtained by thermogravimetry, differential scanning calorimetry and differential thermal analysis [28]. The measurement of kinetics and the associated Arrhenius parameters are the essential aspects of the characterization of drug and related compounds [29]. The thermal decomposition of drugs allows the prediction of the degradation rates at marketing temperatures from data collected on accelerated processes that are studied at elevated temperatures. The temperature may increase the chemical reactions, providing sufficient energy (activation energy) required to break chemical bonds and starts the decomposition process [30, 31]. In this work, the thermal behavior of ENT is investigated under non-isothermal and isothermal conditions allowing kinetic information to be readily deduced. From isothermal experiments, the activation energy (E) can be obtained from slope of ln t *vs*. $1/T$ at a constant conversion level. According to the ICTAC recommendations on isothermal analysis, isothermal kinetics data usually are easier to analyze and interpret, gaining worthy isothermal data typically consumes more time and effort than in case of non-isothermal runs [32].

The methods proposed for the kinetic study of thermal decomposition are generally classified as model-fitting and model-free methods. In each case, data from isothermal and/or non-isothermal experiments can be used [33, 27]. The kinetic analysis based on an isoconversional method is frequently referred to as ‘‘model free’’ because it is possible to obtain the apparent activation energy (E) as a function of the conversion degree (α) which has a specific interest when the thermal decomposition occurs in more than one step [27].

In this paper we report the study of the thermal behavior of ENT via TGA under non-isothermal and isothermal conditions. Kinetic parameters are deduced which are of importance to the pharmaceutical industry. The thermo-analytical techniques cannot replace the classical stability studies that usually require weeks or months, but it can provided an early idea to direct the process

toward the most successful formulation [34]. Furthermore, to the best our knowledge, there is no report on the thermal behavior and decomposition kinetic of this target drug, ENT.

Experimental Section

ENT was kindly supplied from Novartis Pharmaceuticals, Egypt. Thermo-gravimetry and differential thermal analysis were carried out using simultaneous Shimadzu Thermo-gravimetric Analyzer TGA-60 H with TA 60 software in a dry nitrogen atmosphere at a flow rate of 30 mL min^{-1} in a platinum crucible. The experiments were performed from room temperature up to 800^{o}C at different heating rates (5, 10, 15 and 20^{o}C min^{-1}). The sample mass was about 5 mg of the drug without any further treatment. In the isothermal condition, the temperatures were 160, 170, 180, 190 and 200^{o}C with 10 ^{o}C temperature increments, under dynamic nitrogen atmosphere with the flow rate of 30 mL min^{-1}. These values were chosen since according to ICTAC recommendation to isothermal analysis, when selecting the temperature range for kinetic experiments one should be mindful of possible phase transitions that a reactant may undergo within that range. A solid compound can melt. Consequently, we chose temperatures around the melting point as ENT melting point is 162-163°. The respective rates and Arrhenius parameters for solid and liquid state decomposition can differ significantly. The isothermal holding was monitored based on the time to a mass loss of 5.0 % decomposition. The instrument was calibrated at each heating rate considered using a dedicated aluminum oxide standard in a platinum crucible.

Results and discussions

Thermal behavior of ENT

The thermo-analytical graphs of ENT are presented in Fig. 2 which show that ENT decomposes during three steps. The first step shows a mass loss (Δm = 23.4 %) in the interval of 185–250ºC, suggesting the release of a diethyl amine molecule (23.6 %, calc.). The second decomposition step shows a mass loss (Δm = 14.9 %) in the temperature range 251–400 ºC, suggesting the release of a nitrite molecule (15.1 %, calc.). The third decomposition step shows a mass loss (Δm = 61.6 %) in the temperature range 401–800 ºC, suggesting complete decomposition of ENT. The DTA curve shows key thermal event when this temperature range is applied. The endothermic peak observed at 163 ºC [3] is likely due to the melting of the compound while the exothermic peak at 230 ºC is attributed to the first decomposition process corresponding to the first mass loss observed in TG/DTG thermogram curves as shown in Fig. 2. The sharp exothermic peak at 600 ºC is due to the pyrolysis of the compound. The suggested pathway of thermal decomposition of ENT is depicted within Scheme 1.

Kinetic analysis

The kinetic parameters were determined from the TG/DTG curves using the following kinetic methods: Friedman(Fd) [35, 36], Flynn–Wall–Ozawa (FWO) [37-39], Kissinger–Akahira–Sunose (KAS) [40, 41] and Li-Tang (LT) [42]. Figure 3 depcits the α–T curves for the non-isothermal decomposition of ENT at different heating rates. The model-free methods (*e.g*. isoconversional, KAS and Friedman) allow one to evaluate the activation energy without determining the reaction model [43]. These methods yield the effective activation energy as a function of the extent of conversion allowing the reaction kinetics over a wide temperature region to be predicted [44, 43]. The isoconversional methods give comparable (but not identical) dependences of E on the extent of conversion for isothermal and non-isothermal experiments [45].

Generally, the kinetics of many reactions (*e.g.* decomposition, crystallization, polymerization, etc.) can be described by the following rate equation [46, 47]:

$$d\alpha/_{dt} = k(T).f(\alpha) = A.exp\left(-\frac{E}{R.T}\right).f(\alpha) \qquad (1)$$

where t is time, α is the extent of conversion, $k(T)$ is the Arrhenius rate constant, A and E are the Arrhenius parameters (pre-exponential factor and activation energy, respectively), R is the gas constant, and $f(\alpha)$ is the reaction model associated with a certain reaction mechanism. In the case of non-isothermal conditions $d\alpha/dt$ is replaced with $\beta d\alpha/dT$, where β is the heating rate, giving:

$$\beta.\frac{d\alpha}{dT} = A.exp(\frac{E}{R.T}).f(\alpha) \qquad (2)$$

Taking the logarithmic form of eq. (2), the iso-conversional Friedman method is based on the following equation:

$$ln\left(\beta\frac{d\alpha}{dT}\right) = ln[A.f(\alpha)] - \frac{E}{R.T} \qquad (3)$$

In order to evaluate the activation energy more precisely, the term $\ln(\beta d\alpha/dT)$ was obtained by numeric a derivation of the curve α vs. T with respect to T and by subsequently taking logarithms. In the case of α = constant, and using various heating rates, the plot $\ln(\beta d\alpha/dT)$ *vs.* $(1/T)$ is linear, as shown in figure 4). The values of the activation energy as obtained from the slopes of the straight lines are listed in Table 1. The general equation of the reaction rate for non-isothermal conditions at constant heating rate is generally written as:

$$g(\alpha)=\frac{A.E}{R.\beta}p(x) \qquad (4)$$

where $g(\alpha)$ is the the conversion integral, $p(x)$ the temperature integral, $x = E/(R.T)$. The dependence on α is defined by the reaction model, $f(\alpha)$, which can take a variety of mathematical forms [48, 32]. Experimentally the measured rate is adequate to the actual process kinetics only when the process variables (α, T, and $p(x)$) are controlled accurately and precisely [32].

Many approximations of the temperature integral *p(x)* have been suggested in the literature and as a consequence, it can be approximately represented via different empirical interpolation formulas in terms of Doyle, Agrawal, Gorbatchev and Frank–Kameneskii approximation [49]. All these methods involve the plot of a logarithmic function (which depends on the approximation for the temperature integral used) versus $1/T_\alpha$, :

$$ln\frac{\beta}{T_\alpha^k} = -B\frac{E_\alpha}{R.T_\alpha} + C \qquad (5)$$

where k is a function describing the temperature dependence of the reaction rate, B and C are constants and the subscript α designates values related to a given extent of conversion. The literature has considered four linear integral iso-conversional methods as the most accurate and promised methods which were used in this article. Equation (5) has been derived assuming a constant activation energy [38]. This assumption obviously introduces some systematic error in estimating E_α, if the latter varies with α. This error does not appear in the differential iso-conversional method of Friedman. For this reason one can estimate the systematic error of an integral iso-conversional method by comparing it against the Friedman method [50].

Flynn–Wall–Ozawa (FWO) method:

The FWO method is based on Doyle's approximation for the temperature integral, $p(x) = \exp(-1.052.\mathrm{x} - 5.331)$. For this method, $k = 0$ and for constant conversion a, the general linear Eq. (5) becomes:

$$ln\beta = -1.052.\frac{E_\alpha}{R.T_\alpha} + C \qquad (6)$$

Utilizing the FWO method, the activation energies were calculated from the slope of the linear fitted function of $\ln\beta$ versus $1/T$ (as shown within figure 5A). The values of the activation energy (E_α) are included in Table 1. The order of reaction was determined by Ozawa's plots in which slope of log heating rate versus $1/T$ was found to be first order.

Kissinger–Akahira–Sunose (KAS) method:

This method sometimes called the generalized Kissinger method is one of the best iso-conversional methods [51] and it is based on the equation:

$$ln\frac{\beta}{T_\alpha^2} = -\frac{E_\alpha}{RT_\alpha} + C \qquad (7)$$

This method utilizes the adequate temperatures (T_α) to certain values of the conversion α for experiments effectuated to different rates of heating, β. From the slopes of the straight lines obtained by the graphic representation of the ln β/T_α^2 vs. ($1/T_\alpha$) the activation energy was determined (Figure 5B). The values of activation energy calculated by means of the integral methods are listed in Table 1.

Li–Tang (LT) method:

The approximation proposed by LT for the temperature integral is: *-ln p(x) = 0.37774+1.89466 ln x - 1.00145x.* For this method (k = 1.89466) and at constant conversion α, the general linear Eq. (4) becomes:

$$ln\frac{\beta}{T_\alpha^{1.894661}} = -1.00145\frac{E_\alpha}{RT_\alpha} + C \qquad (8)$$

For α = constant, the values of E (Table 1) were determined from the slope of the linear fitted function of $ln\frac{\beta}{T_\alpha^{1.894661}}$versus $1/T_\alpha$, (see Figure 5C).

Table 1 Values of the activation energy obtained by the Friedman (Fd), Flynn–Wall–Ozawa (FWO), Kissinger–Akahira–Sunose (KAS) and Li–Tang (LT) methods for ENT

Method	E/kJ mol^{-1}, for conversion degree, α										
	0.05	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	Mean
FR	126.20	119.90	114.05	115.66	126.20	107.24	104.03	114.13	115.50	121.52	116.44±7.29
FWO	119.80	118.86	117.10	111.44	110.05	109.15	110.1	118.50	118.49	122.54	115.60±4.64
KAS	116.92	116.90	118.5	118.64	108.55	108.58	113.62	118.14	118.05	116.39	115.43±3.89
Li-Tang	117.48	117.46	119.14	109.07	109.08	109.09	114.15	119.14	119.21	117.48	115.13±4.42

The values of the activation energy *(E)* obtained by the four methods are in good agreement, and the weak variation of E vs. α. The values of E show a considerable thermal stability of the ENT-active substance. According to Galwey [52], the numbers of reactions for which the reported E values occurred within steps of equal increment (30.0 kJ mol^{-1}) through distribution of magnitudes of activation energies graph, a broad flat maximum, for which 65% were between $100 < E < 230$ kJ mol^{-1}. No particularly preferred magnitude of E can be identified. The overall mean magnitude of E was 175 kJ mol^{-1}. There was a small proportion (8%) of relatively large E values, > 300 kJ mol^{-1}.

The change in entropy (ΔS), enthalpy (ΔH), and free energy (ΔG) were calculated using the following relations [53, 54]:

$$\Delta S^* = R\,[\ln (Ah/KT)] \qquad (9)$$

$$\Delta H = E_a - RT \qquad (10)$$

$$\Delta G = H - T\Delta S \qquad (11)$$

where h is the Planck constant, K is the Boltzmann constant and T is the temperature, A is the Arrhenius constant. The calculated kinetic parameters for ENT are also included in Table 2. A comparison between the results obtained by applying different kinetic methods reveal that the values of activation energies calculated for ENT are very close to each other. The obtained kinetic parameters were used to evaluate the thermodynamic parameters of activation. The entropy values (ΔS) for the ENT decomposition are negative. In terms of the activated complex theory (transition theory) [55, 56], a negative value of ΔS indicates a highly ordered activated complex. The result may be interpreted as a ‘‘slow’’ stage. The positive values of ΔH and ΔG for the decomposition show that it is connected with the introduction of heat and it is a non-spontaneous process.

It is known that the thermal decomposition of drugs is a complex process which tends to take place in many steps with different heating rates [26]. Through this complex process, simultaneously competitive and consecutive reactions (parallel) could occur. For ENT-active substance, the competitive reactions can be excluded because the total mass lost for the four heating rates is the same. It is difficult to specify the nature of the decomposition products because of a possible process of condensation between reacted and non-reacted molecules of the ENT, followed by their decomposition process [26].

The isothermal TG curves superimposed of ENT are illustrated in Figure 6 and were recorded at 160, 170, 180, 190 and 200°C. These curves show mass loss rate dependence in temperature function of isothermal, the higher the temperature lower will be the necessary time so that occur the same mass loss. The curves were used to obtain the graphic of ln*t* versus $1/T$ (K^{-1}) at a constant conversion level 5.0% [57, 19]. From this linear regression method, the equation for the line is $y = -13800.3x + 25.47$ and $R = 0.9993$ are obtained. The value of the activation energy can be calculated from the product of the slope with the molar gas constant (R = 8.314). The calculated activation energy was found to be 114.73kJ mol^{-1}. This result is in agreement with the values obtained from the dynamic methods, and this is an important experimental finding, Figure 6.

Table 2. Kinetic parameters for ENT using Friedman (Fd), Flynn–Wall–Ozawa (FWO), Kissinger–Akahira–Sunose (KAS), and Li–Tang (LT) methods

Parameters	FR	FWO	KAS	Li-Tang
A(s^{-1})	11.10 x10^{11}	8.97 x10^{11}	8.60 x10^{11}	8.34 x10^{11}
ΔS (kJ mol^{-1})	-18.54	-20.30	-20.66	-20.91
ΔH (kJ mol^{-1})	112.32	111.48	111.31	111.19
ΔG (kJ mol^{-1})	121.68	121.53	121.54	121.54
k(s^{-1})	4.09x10^{-9}	4.64 x10^{-9}	4.76x10^{-9}	5.22x10^{-9}

Calculation of Rate Constant:

The values of rate constants (*k*) for thermal decomposition of ENT were calculated at the room temperature of 25°C using the following equation and the previously mentioned values for activation energies (*E*) and Arrhenius factors (*A*) [58]:

$$\log k = \log A - \frac{E}{2.3RT} \qquad (9)$$

The calculated *k* values are listed in Table 2. Through using the calculated values of *k*, the half-life of ENT at 25°C was estimated and found to be 4.73 years and deviation from this temperature; say as a consequence of storing ENT at higher temperatures will result in reducing its half-life progressively. ENT is a more heat-sensitive drug compared with other drugs [59], which require more care during storage.

Conclusions

We have explored the thermal decomposition of ENT via TGA allowing thermal decomposition kinetics to be readily deduced. The thermal decomposition mechanism of ENT is deduced to proceed through three key steps (see Scheme 1). The half-life of ENT (at 25^{o}C) was deduced to be 4.73 years indicating that it is largely unaffected by heat in comparison to other drugs – this information is valuable to the pharmaceutical industry.

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